SPECIAL ISSUE: The Science You Don't See

SCIENCE FOR THE CURIOUS

Discover®

July/August 2015

Invisible Planet

24-page bonus section

Powering the Future

PLUS

BONUS ONLINE CONTENT CODE p.5

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SPECIAL ISSUE: INVISIBLE PLANET

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This wind park, built last year outside the Faroe Islands' capital city of Tórshavn, is part of an initiative to generate more of the country's electricity from renewable resources.

ON THE COVER *SPS-Alpha solar satellite concept created by John Mankins.*

FEATURES


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COLUMNS & DEPARTMENTS

FROM TOP: RICHARD T. NOWITZ/SCIENCE SOURCE; KAREN WARKENTIN

Editor's Note

Things Made Visible

WILLIAM ZUBACK/DISCOVER

Uncovering the past and powering the future.

Welcome to our annual Invisible Planet issue, focusing on the little known, the hidden or hard to understand, the science we don't see. As in previous years, I like to use this page to praise the hard work of the invisible planners — the *Discover* staffers and contributors who work hard to bring you the stories you'll find in this extra-large issue.

Our "Powering the Future" section (page 50) deserves special commendation. The concept was initially developed by Contributing Editor Dan Ferber. Associate Editor April Reese and Associate Art Director Alison Mackey spent many weeks coordinating the words and pictures for this impressive 24-page extravaganza, which showcases innovative renewable energy technologies.

Another contributing editor, Jeff Wheelwright, and Managing Editor Kathi Kube also deserve shout-outs for their parts in launching History Lessons, a new regular column devoted to uncovering lost, forgotten or seldom-visited moments of science in history. Jeff begins the column with a bang as he writes about a lost volcano from the 1800s. Check it out on page 86.

NEXT ISSUE: *Stunning archaeological finds from subway tunnels around the globe, the hunt for supersized Earth-like worlds and much more. See you in September!*

Stephen C. George, **EDITOR IN CHIEF**

YOUR REPLY

In our May issue, I asked you to share what you believe is the greatest science achievement or failure of all time. We were flooded with responses — with more coming in even as I write this. Reader Stuart Lynn went for the big-picture answer:

I believe the greatest science story of all time is science itself, as the most reliable procedure for learning about the universe and its parts. The development of this method with its emphasis on investigation, reproducibility and openness is one of humanity's greatest achievements.

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THE CRUX

The Latest Science News & Notes

Pluto Comes Into Focus

With the arrival of the New Horizons probe, it's the planetary reject's time to shine.

BY **COREY S. POWELL**

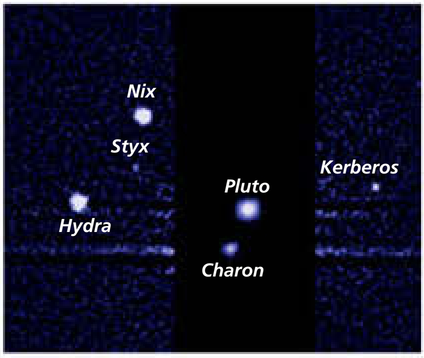
An artist's conception of New Horizons' July arrival and the latest images of Pluto (inset).

NASA/JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY/SOUTHWEST RESEARCH INSTITUTE (JHUAPL/SWRI)

Being stripped of planetary status may be the best thing that ever happened to Pluto. For decades, it seemed like little more than a celestial misfit, much farther out than the solid, Earth-like worlds and far smaller than the giant, gassy ones. But in the nine years since Pluto's demotion, astronomers have come to appreciate that its oddity is actually an indication of its importance.

When the New Horizons spacecraft flies past Pluto on July 14, it will arrive not at the smallest planet but at the brightest and most intriguing member of the Kuiper Belt, the unexplored outer territory of the solar system. Alan Stern — principal investigator on New Horizons and the No. 1 Pluto booster out there — proudly calls his once-maligned target "the belle of the ball."

The story of Pluto's rehabilitation begins, improbably, with the discoveries that dethroned it. Starting in 1992, astronomers Dave Jewitt and Jane Luu identified a succession of objects with orbits similar to Pluto's. These bodies, along with Pluto, are members of the Kuiper Belt, a population of rocky potential comets orbiting beyond Neptune. Then on Jan. 5, 2005, Michael Brown of Caltech discovered



A 2012 Hubble photo shows Pluto, its largest moon, Charon, and its four other known moons.

Alan Stern, the principal investigator of New Horizons, is also one of Pluto's biggest fans.

Eris, a Kuiper Belt object roughly the same size as Pluto. Less than two years later, the International Astronomical Union decided that Pluto was no longer lonely enough (technically, its orbit wasn't empty enough) to be called a proper planet.

But that was just the beginning of Pluto's transformation. Planetary scientists started to recognize that Pluto's neighborhood is as rich and complex as the more familiar regions filled by the rocky and gas giant planets. It fills a region vastly larger than that occupied by all of the traditional planets. It is home to countless objects — estimates range from hundreds of thousands to more than a billion — that collectively outweigh the asteroid belt many times over.

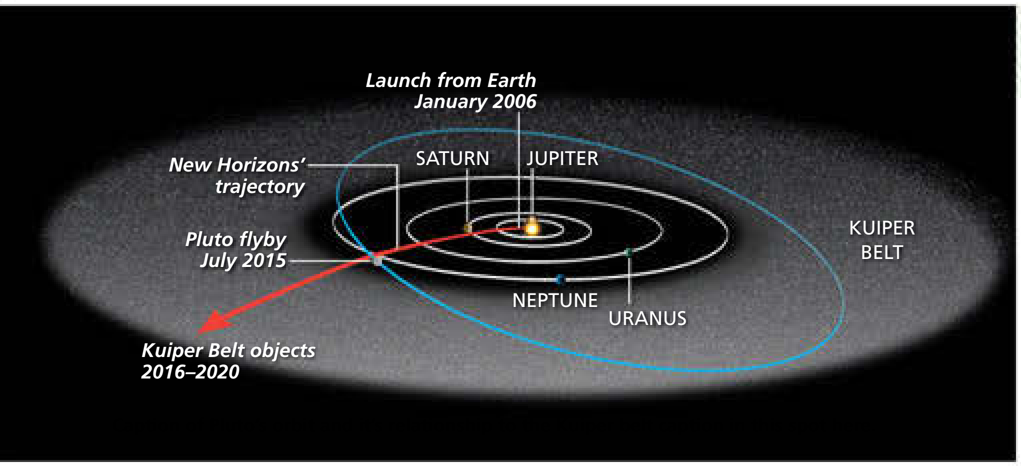
Residents of the Kuiper Belt also have diverse colors and shapes, suggesting eclectic compositions and histories. Researchers increasingly began referring to the Kuiper Belt and its environs as the solar system's "third zone."

Separately, a group of theorists led by Alessandro Morbidelli at the Observatoire de la Cote d'Azur was beginning to understand the reasons behind the belt's tremendous complexity. They realized that the early solar system was not an orderly place where planets formed neatly in their present locations, as scientists had long assumed. Conditions around the infant sun were more akin to cosmic pinball, with planets bouncing around and migrating wildly before settling down.

According to the new models,

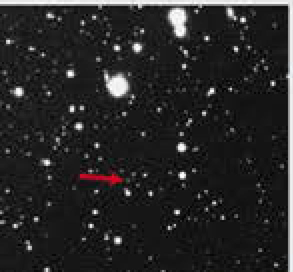
NASA hopes to map Pluto's surface, investigate its atmosphere, study its geology and more.

THIS PAGE FROM TOP: NASA/ESA/M. SHOWALTER (SETI INSTITUTE); NASA/JOEL KOWSKY; NASA/JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY/SOUTHWEST RESEARCH INSTITUTE (JHUAPL/SWRI).
OPPOSITE FROM TOP: ROEN KELLY/DISCOVER; LOWELL OBSERVATORY ARCHIVES (2); RVLSOFT/SHUTTERSTOCK



New Horizons' long journey through the solar system spans more than 3 billion miles and nine years. After its flyby of Pluto in July, the probe will continue to explore the distant Kuiper Belt.

Jupiter drifted inward toward the sun, then tacked back out. As Jupiter moved away, its gravity acted like a giant snowplow, flinging comets and baby planets out into the deep freeze of the Kuiper Belt. If this "Grand Tack" model is correct, Pluto preserves key clues about the solar system's early days.



Clyde Tombaugh, who discovered Pluto in 1930 by spotting a moving "star" in astronomical photographs (top), sits at the Lowell Observatory telescope where he first saw the onetime ninth planet.

In the updated picture, Pluto has a strange dual status, as both the leading representative of the Kuiper Belt and a unique denizen within it. Stern ticks off Pluto's standout qualities. It has an intricate family of five known satellites, including giant Charon, which is nearly half Pluto's diameter. "On its own, Charon is one of the largest objects in the Kuiper Belt," he notes.

Unlike any of the other objects out there, Pluto has a wispy but enormous atmosphere composed of nitrogen, methane and other gases that evaporate off its surface when it nears the sun. New Horizons co-investigator Michael Summers estimates the volume of the atmosphere is 350 times the volume of Pluto itself. And the vague markings visible from Earth show that Pluto has extreme contrasts of light and dark, indicating highly varied terrain.

We will have to wait for the summer arrival of New Horizons to make sense of that tantalizing landscape. Then comes a bonus second act. After the probe's encounter with Pluto, Stern and his team want to continue on and check out a smaller member of the Kuiper Belt that could be reached within three years. If that happens, scientists will be able to do the first compare-and-contrast in the solar system's unexplored outer zone. It will be as momentous as the discovery of Uranus by William Herschel in 1781, an event that similarly expanded the scope of the known solar system.

That still leaves one issue unsolved: What do we call Pluto, this ambassador to the undiscovered country? I suggest classifying all Kuiper Belt objects as "Plutoids," with Pluto the archetype of the whole population. When Stern hears this, he makes a sour face. "Please never use that term. It sounds like *hemorrhoid*," he says. Maybe *dwarf planet* will have to do for now. But there is nothing dwarf about the leading world of the solar system's third zone.

Follow along with New Horizons' discoveries at **www.DiscoverMagazine.com/Pluto**

Stylish Spuds

Per capita potato consumption dropped to an all-time low recently. To boost consumer interest, American potato breeding programs are selectively breeding smaller, more colorful varieties. The flashier hues mean more phytonutrients, compounds linked to a variety of health benefits, and their compact size means shorter cooking times. Breeding those traits takes 12 to 14 years, says Texas A&M program director J. Creighton Miller Jr., but you won't have to wait that long to see one of the program's newest creations, a variety called peppermint. It sports white skin speckled with red, and it could arrive in stores later this year. Don't worry; the name only reflects the potato's color, not its flavor. —LEAH SHAFFER

The Element That Shaped Our World

"URANIUM — TWISTING THE DRAGON'S TAIL"
8 p.m. EDT July 28, PBS (check local listings)

Host Derek Muller visiting the Titan Missile Museum in Tucson, Ariz.

Physicist Derek Muller found his way into numerous classrooms, homes and office cubicles via Veritasium, his YouTube science channel. But Muller's latest project, hosting a documentary about uranium, took him even further afield. His travels included the ghost town of Pripyat, Ukraine, near the site of the 1986 Chernobyl disaster, a uranium mine in Australia's remote Kakadu region and Marie Curie's old lab in Paris. Muller chatted with *Discover* Senior Associate Editor Gemma Tarlach about the world's most controversial element.

Q *Telling uranium's story in two hours is ambitious. Where do you start?*

A We go back more than 5 billion years to this rock's source, an exploding supernova. The rock contains that trapped energy. So when you detonate a nuclear weapon, for example, you're releasing energy that's been trapped for billions of years.

Q *What makes the discovery of uranium so significant, in a nutshell?*

A With its discovery, our understanding of matter shifted. Things we thought were inert rocks were really powerful energy sources. It's mind-blowing to think of how one element has shaped the modern world. Uranium has a strong yin yang. It's the most destructive power on Earth, but when it splits into pieces, or fissions, it can be used to diagnose and treat cancer.

Uranium ore

Q *There's a segment where you explore the derelict Pripyat hospital, abandoned shortly after the Chernobyl disaster. Workers and firefighters who suffered acute radiation poisoning died there, and as you walk past their belongings, still in situ 29 years later, your Geiger counter crackles wildly. Was that the most memorable moment during filming?*

A That experience at Pripyat was incredibly memorable, but so was being out in the New Mexico desert, where the first nuclear weapon was dropped. You could still find pieces of green glass that had been melted by the blast, 70 years after it went off. And they were still radioactive. It was a powerful place to be.

Q *How does the show tackle the debate about nuclear power?*

A The film doesn't have an agenda. [But] it is a super-divisive issue. What we can say for sure about nuclear power is that it doesn't produce carbon dioxide, which is an important thing today. And, after the initial capital investment, it's cost effective and economical to run. But there are other issues: the question of waste storage and weaponization, which are not quantifiable. There's a big gap in the research that could have been done in the '80s and '90s, but that didn't happen because of Chernobyl.

Q *What kind of research should have been done?*

A Research into small, modular designs that could be mass produced at lower cost, and reactor designs that are walkaway safe — they shut themselves down, with no risk of explosion. One of the young researchers I met while filming — I don't think she's even 30 — joked that there are young nuclear engineers and old nuclear engineers, and no one in the middle. I do believe that has set the industry back.

INBOX

Standing on Einstein's Shoulders

The cover of our April issue boasted the cover line "Outsmarting Einstein," part of our special section celebrating the 100th anniversary of the general theory of relativity.

"Outsmarting Einstein," while catchy, is an unfortunate phrase. Modifying his general theory of relativity would be an enormous intellectual achievement, and the people trying to do so are by no means dummies. But, in place of his pencil and paper, they have a century of experiments upon which to build, as well as incredible instruments and budgets. If his theory is eventually modified, he certainly will not have been outsmarted.

Al Wagner *Shoreline, WA*

Species Resurrection

March's "Jurassic Ark" feature explored the science and ethics of de-extinction for animals such as the woolly mammoth, dodo, ibex and Steller's sea cow.

I don't believe creatures [brought back from extinction] would survive for long. Some very powerful, very rich person would find his/her life incomplete without the head of a woolly mammoth on his/her wall. We might not even be able to keep the elephant or rhinoceros from being hunted to extinction; a brought-back-from-extinction creature would be much more rare, and its head would be all that more interesting on a wall.

Chuck Farmer *Broomfield, CO*

FROM TOP: JOSEPHINE WRIGHT/GENEPOOL PRODUCTIONS PTY LTD; ABADONIAN/ISTOCK

Take 20 Worms and Call Me in Six Months

An Englishman is infected with parasites. That's the good news.

In 2007, John Scott, who had extreme food and environmental allergies, chronic fatigue and Crohn's disease, participated in a Nottingham University study to test the safety of hookworms (*Necator americanus*) on Crohn's patients. It was a placebo-controlled study, but Scott assumed he received worms because his condition improved. So when the study ended, he wanted the worms back.

Scott's idea to infect himself with roughly centimeter-long worms was not an outlandish plan: Do-it-yourself worm therapy as a way to treat autoimmune disorders has become more common in the past decade. Since humans evolved with parasites and bacteria, some scientists believe the immune system works in tandem with these creatures to keep us healthy. Hookworms have had millennia to develop "exquisite strategies" to suppress their host's inflammation, doing as little harm as possible so they can reproduce and infect the next host, says James Cook University biologist Alex Loukas, who is working to develop drugs based on hookworm secretions.

But Scott didn't want to wait for a worm pill. It's illegal to ship the worms to the U.S., but Scott lives in the U.K., and he was able to order 35 live hookworm larvae through a private company. He put the larvae on his arm under a bandage and "got a very bad itch and a rash," as they burrowed in. Then he waited. Although his symptoms improved, he also experienced what some DIY worm therapy devotees describe as "worm flu." In Scott's case, this meant bouts of diarrhea not associated with his Crohn's disease. The side effects subsided after a few months, however.

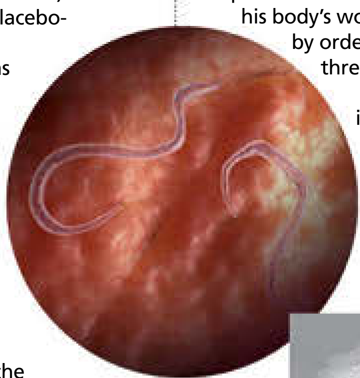
The upside: Scott was eventually able to tolerate foods he hadn't eaten since he was a teenager. He saw other health improvements as well, and he maintains his body's worm population to this day by ordering a fresh supply every three months.

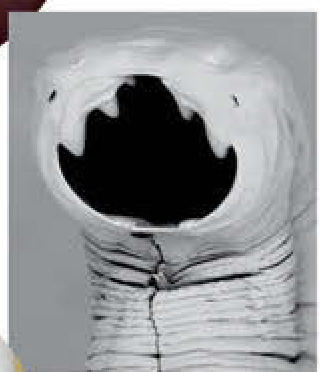
The worms' excretions increase the host's number of regulatory T cells, "the peacekeepers of the immune system" that keep inflammation in check, Loukas says.

But that may not be the only way the worms work. A recent paper in the experimental biology publication *The FASEB Journal* describes how peptides found in hookworms inhibit the proliferation of effector memory T cells, which, unlike regulatory T cells, can actually trigger inflammation.

The bottom line is that scientists haven't dug up all the hookworm's secrets — yet. "I'm viewing the worms more as a veritable pharmacopoeia," says Loukas.

—LEAH SHAFFER





Hookworms, at home in the small intestine (above) and close up (right). Worm therapy fans often experience a rash after infecting themselves with the parasites (below).

FROM TOP: SCIENCE PICTURE CO/SCIENCE SOURCE; ALEX LOUKAS/JAMES COOK UNIVERSITY; JOHN SCOTT

DID YOU KNOW? Got drugs? According to a new study, 63,151 tons of antibiotics and other antimicrobials were used in livestock production worldwide in 2010.

Herd Mentality

By sticking together, sperm can find a more direct path to the egg.

We think of a sperm's mission as a lonely one, each one hoping to find and fertilize the egg before the rest of pack. In some species, however, sperm literally stick together in a grouping that gives them a competitive boost. How does this all-for-one attitude give sperm that edge?

Biologist Heidi Fisher of Harvard University analyzed the behavior of clumping sperm from two different mouse species — one monogamous, one promiscuous — under microscope slides. One contained sperm from multiple promiscuous males; the other had sperm from multiple monogamous males.

Fisher found that sperm from the promiscuous species often recognized and latched on to other gametes from the same male, upping the odds of passing on that mouse's genes. Sperm from the monogamous species still clumped, but not in male-specific groups, suggesting that grouping into a sperm herd has advantages beyond the competitive edge it gave swimmers from the promiscuous species.

"We assumed it was something like the way cyclists all form a group and move with greater speed," Fisher says. But recently, when they tested this idea with a custom-designed mathematical model, they found the groups swam *straighter*, not faster. By flocking together, the sperm group's momentum cancels out any wayward movements of a lone gamete, collectively giving them a more direct path to the egg.

And it turns out the sperm of the promiscuous species were more likely to form optimally sized groups — six or seven swimmers — than the less competitive monogamous species. When evolutionary rivalry heats up, it seems, sperm team up. —MARCUS WOO

SPRINGER MEDIZIN/SCIENCE SOURCE

Still Unplugged

But net-zero communities remain elusive.

April 2003 issue

In 2003, when we wrote about the Los Olivos Pilot Zero Energy House in Livermore, Calif., it stood as a beacon, promising a new age of homes that could produce as much energy as they used. ("Unplugged," April 2003.) Although the house is still up and running more than a decade later, the net-zero energy trend has yet to hit the mainstream.

Centex, the home's builders, stopped their zero-energy efforts a few years later, finding that buyers are more willing to pay for a few energy-efficient features than a full net-zero home, complete with solar panels and a higher price tag.

Yet Davis Energy Group, the consultant behind Los Olivos, still believes in the net-zero dream. The company, which collaborates with utilities and builders to create and monitor net-zero buildings, is working on several projects, says co-founder David Springer. This includes the largest planned net-zero energy community in the U.S., at the University of California, Davis, which will eventually house up to 3,000 people.

California has a more ambitious goal for all new residential construction to be net-zero by 2020. Although the slow process of updating housing standards may make that goal unreachable, says Springer, most of the necessary technology already exists. Energy Star appliances, LED lighting, condensing furnaces and ventilation cooling systems can dramatically lower energy use, while high-performance walls, attics and insulated foundations keep heat loss to a minimum.

To demonstrate the potential of net-zero homes, the National Institute of Standards and Technology created a test house near Washington, D.C., to simulate the energy demands of a family of four for a year. The house ended up last year with enough extra energy to power an electric car for roughly 1,440 miles. Homes like this and Los Olivos (See "Green Buildings Go Beyond Net Zero," page 70) are important places to test and evaluate new tools and techniques, and to increase awareness — the first step toward building a net-zero future. —BRENDA POPPY

QUICK HIT

ASAS-SN Hunts Exploding Stars

Astronomers have a new tool to hunt the brightest and nearest exploding stars: ASAS-SN. The two observatories of the All-Sky Automated Survey for Supernovae scan the Northern and Southern hemispheres every night with six 5.5-inch telescopes (eight total by the end of the summer), taking photos of the sky and comparing successive images to find changes, such as supernovas. At $100,000 per pair of telescopes, a bargain in professional astronomy, ASAS-SN proves that small projects can do big science: Since coming online in 2013, it has already found more than 100 supernovas, almost half of the total number of similar discoveries. —LIZ KRUESI

Off-the-shelf equipment helps keep the price tag low for ASAS-SN's hardware.

Octo Doc

Tentacles inspire the next generation of robotic surgery.

Imagine flexible, robotic arms crawling through the organ-packed spaces of a patient's body. The tools deftly navigate through the intestines to reach a section of colon. The arms then gradually stiffen and, using a gripper tip, perform delicate surgery. That's the vision, complete with prototype, inspired by octopus tentacles and executed by a European group of engineering, neurobiology and robotic experts.

The project, the ponderously titled "STIFFness controllable Flexible and Learn-able Manipulator for surgical OPerations" consortium, is generally known by its more creative acronym STIFF-FLOP. As the long-form name suggests, the consortium is building robotic arms that would work together to perform minimally invasive surgeries by making just one entry incision or approaching organs through natural orifices. The arms would be flexible and long enough to navigate complex anatomy, yet stiff enough to pull off an intricate procedure. But the prototype had an issue: How would the arms avoid tangling or grabbing the wrong organs?

Octopuses, with their eight wavy limbs, had the answer. Unlike human brains, which let us know if we're crossing our arms, octopus brains lack similar motor neuron maps. Yet, amazingly, their flexible, sucker-covered arms hardly ever end up in a tangled mess.

The Octopus Research Group at the Hebrew University in Israel, now one of the STIFF-FLOP partners, had been studying octopus motor skills. They noted that tentacles, even an hour after separation from an octopus's body, wriggled and grabbed at objects in their tanks but never touched their former owner, other octopus limbs or skin samples. They concluded that a chemical on the octopus skin must prevent the tentacles from nabbing each other. They haven't identified the chemical yet, but they're applying a version of that self-avoidance trick to the STIFF-FLOP project, where engineers are re-creating it in computerized form.

Their program will enable the prototype's arms to recognize each other and certain body parts. For example, they could "identify the internal walls of the intestine and avoid grabbing them in the same way that an octopus' arm is 'programmed' to identify its neighboring arms," says Guy Levy, a neuroscientist from the Hebrew University of Jerusalem and one of the researchers. — KAREN EMSLIE

A demonstration of the STIFF-FLOP system shows the tentacle-like arm maneuvering itself into the dummy's body cavity. Inset: An inside view of the robotic arm at work.

FROM TOP: MARK ELPHICK/LOS CUMBRES OBSERVATORY; HELGE WÜRDEMANN/CORE/KING'S COLLEGE LONDON/STIFF-FLOP(2); BENNY HOCHNER/THE HEBREW UNIVERSITY OF JERUSALEM

THE CRUX | TECH

The New Oxygen Channel

Researchers find a salty solution to bulky air tanks.

University of Southern Denmark researchers have discovered a way heavy metal might help patients with lung disease. We're not talking Black Sabbath. The heavy metal is cobalt, in the form of a crystalline salt.

A mere 10 liters — about a bucketful — is enough to suck up a room's worth of oxygen. Oxygen stored in the crystalline salt can then be released as needed. Another bonus? That 10 liters of special salt holds three times the oxygen as a conventional tank of the same size, possibly rendering bulky scuba tanks and portable oxygen therapy equipment obsolete. Using pressurization, it could allow lung disease patients and deep-sea divers to draw oxygen directly from their environment using special masks. Other possibilities include regulated oxygen supply for fuel cells in electric cars.

The oxygen-sucking substance might sound like a perfect weapon for an evil mastermind, but researcher Christine McKenzie, part of the team that created the material, said you can't just toss it into a room to sop up all the air.

"At normal atmospheric pressure and temperature, where air is 21 percent O_2, the material already contains oxygen and cannot absorb more," McKenzie explains.

The crystalline salt can steal oxygen from its environment only after it's been "emptied" of the oxygen already attached to it, which requires specific conditions, such as pressurization. Trying to actually suck up the oxygen in a room would be, as McKenzie puts it, "like trying to squeeze water out of a sponge under water."

Whew. That's got us breathing easier. – JIM SULLIVAN

WEB

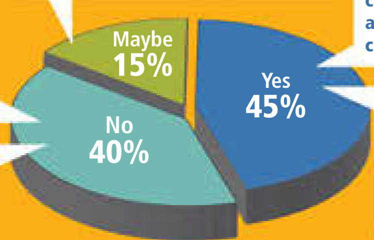
Eyes in the Sky

On our new Drone 360 blog, we asked you: Would you be in favor of your local police department deploying drones? Here's how you responded:

"Local departments don't need this for routine day-to-day operations. A limited number of drones should be available in each state for special purposes."

"Laws and regulations are needed concerning drones first."

"Drones can go where typical police vehicles can't go and can't see: accidents, fires, building collapses, etc."



"It allows for improved recon and improved response time, which, in turn, can improve citizen safety."

"Watching/spying is not 'policing,' it's just intimidation."

What do you think? Weigh in at DiscoverMagazine.com/Policedrones

TOP: KPG_PAYLESS/SHUTTERSTOCK; ALISON MACKEY/DISCOVER

Meet the Beauty in the Beast

Discover this spectacular 6½-carat green treasure from Mount St. Helens!

For almost a hundred years it lay dormant. Silently building strength. At 10,000 feet high, it was truly a sleeping giant. Until May 18, 1980, when the beast awoke with violent force and revealed its greatest secret. Mount St. Helens erupted, sending up a 80,000-foot column of ash and smoke. From that chaos, something beautiful emerged… our spectacular ***Helenite Necklace***.

EXCLUSIVE
FREE
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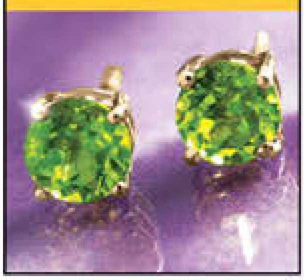

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THE STRANGE CASE OF THE RICKETY COSSACK

By Ian Tattersall

Venerable paleoanthropologist Tattersall opens his latest book recalling the time when, as a young researcher in the '70s, he traveled to the Comoros Islands to study lemurs and instead found himself in the midst of a coup. But *Strange Case* is more than reminiscing. It's an insightful look at how — and why — we *Homo sapiens* so often get human evolution wrong. Tattersall makes it clear that he's arguing his interpretation of the fossil record, but even his opponents will find themselves chuckling at many of his wry, sometimes withering critiques, from the near-comical initial interpretation of the first Neanderthal skeleton to be unearthed (referenced in the book's title) to ongoing debate on whether our family tree is actually a bush. —GEMMA TARLACH

BEYOND WORDS

By Carl Safina

Most of us have been guilty of anthropomorphizing animals at one point or another, and in doing so we often fail to appreciate the rich complexity of other species' emotions and communication skills. MacArthur fellow and noted conservationist Safina aims to broaden our understanding of how the finned, furry and feathered think and feel. He blends current science with his own observations of animals in the wild (and, in the case of his pets, on the couch), making a beautifully written, provocative case for seeing animals through their eyes. —GT

THE WEATHER EXPERIMENT

By Peter Moore

Long before Doppler radar, a small but dedicated group of Englishmen attempted not only to understand weather scientifically, but also to standardize how it was measured and described. With Dickensian detail, Moore brings to life the likes of Francis Beaufort, with "sabre scars on his arms, reminders of his days at sea," and the determined Robert FitzRoy. Years after captaining the HMS *Beagle* with a certain Charles Darwin aboard, FitzRoy promoted the first formal storm-alert system and coined the term *weather forecast*. From ideological scuffles to moments of childlike delight — such as pioneering meteorologist James Glaisher's fascination with snowflake shapes — Moore captures the suspense and wonder of a scientific discipline's birth. —GT

PLANCK: DRIVEN BY VISION, BROKEN BY WAR

By Brandon R. Brown

Max Planck's place in the physics pantheon was secured around 1900 when his thermal radiation equation set the stage for modern quantum theory. More compelling, perhaps, is the tragic arc of his life, from the early work that put him in the forefront of German science to the later years he spent bending and nearly breaking under a Nazi yoke. After losing his first three children to illness and war, Planck, at age 87, endured the execution of his beloved youngest son, Erwin, linked to the 1944 assassination attempt on Hitler. Physicist Brown illuminates all these episodes — as well as Planck's celebrated friendship with Einstein — with heartbreaking empathy. —KEVIN P. KEEFE

EARTH'S WORST DAYS

You may lament your short life span, but cheer up! Your impending death means you won't have to endure billions of horrific years to come. In 2014, scientists found another reason to rejoice in your genes' deterioration: White dwarf stars, like the remnant that will remain at the end of the sun's life, eat rocky planets like Earth for their last meal. Here are a few more milestones to be grateful to miss.

1.1 billion years

The sun is 10 percent brighter. The extra heat hitting Earth's surface causes water to begin to boil off into space. No more yachts, no more Powerade, no more fun.

3.5 billion years

After eons of such heat, the sun has turned our planet into a true twin of Venus: dry, hot and dead. But without beaches, what point was there to staying alive, anyway?

5 billion years

The sun is running out of hydrogen fuel. Its diameter expands, but it loses weight as it gives off a wind of particles. Its ballooning waistline engulfs Earth's current orbit, but its lowered gravitation may send our planet spiraling out and away from destruction. Because putting that charred hunk of lifeless rock out of its misery would be too humane.

5.4 billion years

The sun is a full-on red giant, with hydrogen left only in a shell around its helium core. The star is huge in Earth's sky and would be an amazing sight, assuming Earth's new orbit lies beyond the giant's radiation-laden atmosphere — and if anyone were around to see it.

6.4 billion years

The sun sloughs its outer layers into space, leaving behind a shrunken core of subatomic soup, a white dwarf. It's so dense, a teaspoon of it weighs 15 tons. The system's extreme gravity may cause our molten wasteland of a planet to fall into the remains of its star, finally raining down the ruins of our forgotten civilization. —SARAH SCOLES

LORELYN MEDINA/SHUTTERSTOCK

Vital Signs

A Battle to Breathe

A 6-week-old boy in a small Arctic village struggles to get air to his lungs. Without an X-ray machine or intensive care unit, is a diagnosis futile?

BY JONATHAN REISMAN

Another day of work at a small village clinic in northern Alaska was coming to a close. The final patients filed out the door as I wrapped up my clinic notes. The setting Arctic sun cast an orange glow on the snow dusting the remote village's lead gray beaches. The days were becoming rapidly shorter as winter approached, and I sat back and imagined the Arctic Ocean, just outside the clinic windows, under a sheet of ice in just a few months.

An elderly woman walked in carrying an infant wrapped in blankets.

"He's been breathing funny," she said, her face completely calm.

I lay the tiny 6-week-old Inupiat boy on the exam table and removed his one-piece outfit. Michael was struggling to breathe. His respirations were rapid, and with each inhalation his nostrils flared and the muscles between his ribs strained for air. In my pediatrics training, one of the most important observational skills I learned was to determine a child's "work of breathing" — that is, how hard the muscles of the thorax are working to bring air into the lungs. This infant's "funny" breathing had him working very hard, and something was dangerously wrong.

In my five years as a pediatrician, I had seen many infants struggle in the same way as Michael. But I was used to working in large academic hospitals equipped with full diagnostics and a pediatric intensive care unit never far away. Many of those children ended up needing intubation and a ventilator to breathe for them. But here in a small Arctic village with no road access, the boy's heavy breathing seemed much more urgent.

The nearest pediatric ICU was hundreds of miles away in Anchorage. Even a simple X-ray machine, which could help determine what was going on inside the boy's hidden lungs, was hours away by airplane. I saw darkness coming on quickly out the window, and the cold, choppy sea beside the clinic fed my sense of dread. I realized that if the weather were to turn bad, there was no possibility of evacuation.

His respirations were rapid, and with each inhalation his nostrils flared and the muscles between his ribs strained for air.

I put aside my fears and focused on using what I had on hand to figure out what might be causing this little boy's battle to breathe. His oxygen level was normal, so he did not need emergency evacuation or any immediate intervention.

"How long has he been breathing funny?" I asked his grandmother.

"Since he was born," she said with certainty.

Could he have pneumonia? Pneumonia is a bacterial infection that fills parts of the lungs with pus, thereby preventing oxygen from reaching the blood. The body responds by breathing more deeply and rapidly to take in more oxygen. I had seen many children with pneumonia, and they breathed in the same way as this infant, using all the muscles of the chest wall. Pneumonia is one of the most common infections of childhood and can be deadly.

I placed my stethoscope against the infant's back and heard completely clear breath sounds — no areas of bubbling pus to suggest pneumonia. The village nurse reported that his temperature was normal. The lack of fever and his clear-sounding lungs, and the fact that he'd breathed this way since birth, made pneumonia less likely, but not impossible. The grandmother watched me as I continued with my physical exam, peering into his throat and each ear.

Could Michael have a metabolic condition causing his respiratory distress? If he were born with an absent or dysfunctional enzyme, his aberrant metabolism could be building up dangerous acidic substances. Acids in the blood activate one of the body's primary pH buffer systems — heavy breathing, just as he was doing.

With the possibility of a metabolic disease in mind, my thoughts moved

PANOM PENSAWANG/SHUTTERSTOCK

Cell Phone Inspires Chicago Doctor to Design Affordable Hearing Aid

Outperforms Most Higher Priced Hearing Aids

Reported by J. Page

Chicago: Board-certified physician Dr. S. Cherukuri has done it once again with his medical grade all digital AFFORDABLE hearing aid.

This new digital hearing aid is packed with the features of $3,000 competitors at a mere fraction of the cost. Now, most people with hearing loss are able to enjoy crystal clear, natural sound—in a crowd, on the phone, in the wind — without suffering through "whistling" and annoying background noise.

- **Designed by a Board-Certified Ear, Nose, and Throat (ENT) Doctor**
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- **Thousands of satisfied customers**
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- **Comes ready to use Batteries included!**
- **100% Money-Back Guarantee!**

New Digital Hearing Aid Outperforms Expensive Competitors

This sleek, lightweight, fully programmed hearing aid uses the latest digital technology. While demand for "all things digital" caused most prices to plunge (consider DVD players and computers, which originally sold for thousands of dollars and today can be purchased for less), the cost of a digital, medical grade hearing aid remains out of reach.

Dr. Cherukuri knew that many of his patients would benefit from, but couldn't afford the expense of, these new digital hearing aids. Generally they are *not* covered by Medicare and most private health insurance.

Inspiration From a Surprising Source

Dr. Cherukuri was inspired by his iPhone® — a device that can do all sorts of things. He felt that he could create a technologically advanced hearing aid that was affordable.

The doctor evaluated all the high priced digital hearing aids on the market, broke them down to their base components, and then created his own affordable version the MDHearingAid *AIR* so named for its virtually invisible, lightweight appearance.

Affordable Digital Technology

Using advanced digital technology, the MDHearingAid *AIR* automatically adjusts to your listening environment — prioritizing speech and de-emphasizing background noise. Experience all of the sounds you've been missing at a price you can afford. This doctor designed and approved hearing aid comes with a full year's supply of long-life batteries. It delivers crisp, clear sound all day long and the soft flexible ear domes are so comfortable you won't realize you're wearing them.

Try It At Home 45-Day Risk-Free Trial

Of course, hearing is believing and we invite you to try it for yourself with our RISK-FREE 45-Day home trial. If you are not completely satisfied, simply return it within that time period for a full refund of your purchase price.

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"The pair of AIRs I ordered for my husband is working out wonderful. He had been using a $4000 loaner pair from our local Audiologist, and he had time to compare them. He is a happy camper, as your product proved to be equal to if not better, for the adjustments he could make himself, without the cost going up, up, up." — Patricia F.

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toward what might happen in the coming hours or the following day. Children with metabolic conditions often become progressively and rapidly more ill. Pediatricians use the term *crash* to describe how precipitously the clinical condition of these children can decline, resulting in the need for intensive care. Was his heavy breathing just the first sign of impending doom?

Diagnosing metabolic disease would require extensive testing in a laboratory much better equipped than we had in the village clinic. Putting thoughts of his "crashing" aside, I returned to my physical exam. I put my stethoscope to Michael's heart and, through it, heard a loud and harsh whooshing sound — a heart murmur. This could be a significant clue.

Although soft, melodious murmurs are common in perfectly healthy children, the boy's grating and cacophonous chest suggested heart disease, and a reason for his troubled breathing. That murmur might have been the sound of blood flowing turbulently and reverberating as it passed through malformed structures within his heart. If this boy was born with a heart defect, his abnormally assembled heart could be failing to keep blood flowing forward, thus allowing it to back up into the lungs, flooding them with fluid. His breath sounds were clear and dry to my ears, but to truly assess his heart, Michael would need an ultrasound (an echocardiogram). And the nearest ultrasound machine was far away in Anchorage.

ASSESSING DANGER

I continued my detective work, gathering as much evidence as possible. I felt for the artery in the crux of his elbow and counted a normal pulse rate. Gently turning his head to each side, I looked for bulging veins in his neck but saw none. I pressed my hand deeply into the right side of his dainty abdomen and felt the feathery edge of a normal-size liver. My hands reached down and pressed on both of his shins — they were warm, and my fingers left no impression in his slender legs, showing there was no fluid buildup. All of these findings reassured me that, if Michael's heart was failing, it was not yet at a dangerous stage.

"Has he been eating and growing well?" I asked the grandmother. Poor eating in an infant could be a sign of congenital heart disease. Heavy breathing can interfere with drinking and taking in enough nutrition, and a heart working overtime to compensate for structural inefficiency burns off extra calories — both contributing to slower growth. His grandmother insisted he was emptying many bottles of formula each day and growing well. As if to demonstrate, she put a bottle to Michael's mouth, and he began voraciously feeding.

His weight was increasing, but too slowly. The pieces of the picture were starting to come together.

I asked the nurse to pull up the boy's growth chart — she had recorded his weight every week since birth and plotted it against a curve that showed normal, expected weight gain in babies. It showed Michael steadily gaining weight since birth, but there was a subtle flattening to the rising curve. His weight was increasing, but too slowly. The pieces of the picture were starting to come together.

I crossed the exam room, heading for the telephone on my desk. I had a direct line to specialists in Anchorage with whom I could discuss cases while in isolated towns and villages. Within a few minutes, a pediatric cardiologist got on the phone. I told the boy's story, explained my physical exam findings and attempted to describe the murmur.

"His story is concerning for congenital heart disease," he said. Although we could not know for sure at the time, we agreed that I would treat Michael empirically. I gave him a small dose of a medication to draw fluid out of his lungs. Meanwhile, the nurse made several phone calls to schedule a bush plane to fly him out at first light.

FLIGHT TO RECOVERY

The next morning, a small plane taxied across the snow-covered runway beside the clinic as dawn tinged the eastern sky. I saw Michael's grandmother on the back of a four-wheeler headed out to the waiting plane, a bundle of blankets cradled in her arms. I watched the plane taxi, and then abruptly speed up and take off. As I learned later, the plane brought them to the nearest town with an emergency room, where an X-ray showed an enlarged heart and the markings of fluid in the lungs — both strong signs of congenital heart disease. They flew on to Anchorage the following day, and an echocardiogram showed a hole right through his heart's septum between the left and right ventricles, a ventricular septal defect (VSD).

The pediatric cardiologist caring for him in Anchorage continued to draw out the extra fluid from his heart and lungs, and fortified his formula for better growth. VSDs often close on their own, but if his remained open months later, he would need it sealed shut through surgery.

In the meantime, Michael and his grandmother returned to their Arctic village, far from hospitals and doctors. I had a trip to the region planned for the following year and would check up on his progress during my next stint as a physician north of the Arctic Circle. D

Jonathan Reisman *is a pediatrician and internist at Massachusetts General Hospital and president of the World Health and Education Network. The cases in Vital Signs are real, but names and certain details have been changed.*

A Dream of

Wingsuited BASE jumper Joby Ogwyn glides at about 100 mph over the Lauterbrunnen Valley in Switzerland.

Flying

Whether it's developing self-powered aircraft, wingsuits, jet packs or something even more astounding, for these pioneering daredevils and inventors, the sky is most definitely not the limit.

BY JAMES MCCOMMONS
PHOTOGRAPH BY **JOKKE SOMMER**

How long have humans wished to fly? Likely from the moment hominins first gazed up at a bird and wondered *How? Why?*

Every subsequent civilization created myths, legends, gods and goddesses around flight. Flying dreams are a common part of the human experience. And although there is a universal desire to take wing, some cautionary tales emerged, too. In Western civilization, the Greek myth of Icarus is illuminating. Icarus' father made two sets of wings consisting of feathers and wax so that he and his son could leave the island of Crete. The father warned his son not to fly too close to the ocean or the sun, but Icarus became giddy and carelessly soared too high. The sun melted the wax, and he fell into the sea.

Certainly, the Earth-bound folks who first built wings and strapped them on their arms understood the risks, but some gave it a try. The lucky ones never got off the ground, and those who launched from cliffs and promontories probably crashed and died.

It wasn't until the 1400s that Leonardo da Vinci made serious, intellectual inquiries into flight. After studying the wing movements of birds, he drew machines resembling hang gliders, helicopters and parachutes. He grasped some understanding of aerodynamics, lift and the fluidity of air. However, his ideas remained fanciful and never left the drawing board.

People wouldn't actually take to the skies for another 300 years, when the Montgolfier brothers launched a hot air balloon at Versailles outside Paris. Benjamin Franklin, then serving as the U.S. ambassador to France, witnessed the launch and was stunned by the spectacle. Just two weeks later, an even better hydrogen balloon took to the skies and climbed thousands of feet.

A few decades later, Sir George Cayley, an Englishman who built models and gliders, was considered by many to be the first man to truly understand aeronautics, but the true glide master was Otto Lilienthal, an innovator through the late 19th century. This German pioneer added greatly to the science of flight and gave respectability to the idea of a heavier-than-air machine. He completed about 2,000 glider flights, but he fell from the sky on his last attempt and died. The Wright brothers thought him a genius and a hero.

It was the Wrights, of course, who in 1903 merged glider technology with the internal combustion engine and launched the race to see who could go the highest, fastest and farthest. Over the decades, flying has become normal, even unexciting. But some pioneers today still choose to avoid the routine and the safe. Their dream of flying doesn't include pressurized cabins and first-class seats. It's a dream powered by human effort, by wind or perhaps by a pack strapped to their backs.

Human-Powered Fliers

When it comes to human-powered aircraft, bigger is better because human engines just don't generate much power or speed. That was the challenge faced by AeroVelo, the Human Power Vehicle Team at the University of Toronto, as they attempted to win the famed Sikorsky Prize: a $250,000 award offered by the American Helicopter Society and Sikorsky Aircraft. To win, an individual or team must be the first to build a human-powered helicopter that could hover at least 3 meters off the ground for 60 seconds or longer in a 10-meter square. It sounds like a simple task, but the prize went unclaimed for more than 30 years. It was clear that any serious contender would need a massive helicopter to generate enough lift.

"It's simple analysis and math. Bigger is more efficient, but bigger means more structural weight. There is a break point, or an optimum, past which going any bigger is unnecessary," explains Cameron Robertson, chief structural designer at AeroVelo and co-founder.

The AeroVelo team, consisting largely of graduate students, built Atlas, a helicopter 154 feet across with four rotors, each blade about 33 feet in radius. Constructed of carbon fiber tubes, Mylar, polystyrene foam, balsa wood and synthetic cord, Atlas weighed roughly 122 pounds.

Power came from the legs of Todd Reichert, an elite cyclist and speed skater, engineer and Robertson's AeroVelo partner. Pedaling his modified upright racing bicycle suspended from wires, Reichert generated an average of 550 watts of power.

The AeroVelo team studied previous attempts and incorporated some of the lessons learned through its first human-powered project, the Snowbird, an ornithopter or flapping-wing aircraft. Snowbird was an enormous craft with a wingspan of 105 feet and weight of just 94 pounds. In August 2010, with Reichert again supplying pedaling power, the ornithopter achieved flight — albeit brief, about 19 seconds.

From Snowbird, the team understood the importance of compensating for twist or structural deformation of the craft while under aerodynamic loading. All airplanes flex when flying, but those made of such light, flexible materials especially do. The group spent nearly a third of its development efforts building and testing canards — small lifting wings used for better stability and control — at the end of each rotor blade. The canards were to compensate for the flex and provide the control needed to keep the helicopter from drifting outside the prescribed box.

Top: AeroVelo's Snowbird, the world's first human-powered ornithopter. Above: The Atlas, before its world-record flight in 2013.

"It was a convoluted mess whenever we tried to use these controls, often causing a rotor to tip into the ground," Robertson says. "The canards proved unworkable, and we finally just took them off."

Instead, the team steered the helicopter through thrust vectoring, a method that changed the power between the rotors. Reichert accomplished this simply by leaning the bike.

AeroVelo won the Sikorsky Prize on June 13, 2013, while flying in an indoor soccer stadium. It used the money to provide internships for the graduate students — most were volunteers — and to pay for materials for upcoming projects. The team expects to take to the air again in 2016 when they

REACH FOR THE SKY: History's Highs and Lows of Floating, Gliding and Flying.

1480s Leonardo da Vinci does the first real studies of flight. He produces designs for gliders, parachutes and human-powered helicopters.

1783 The skies around Paris are unexpectedly busy in the waning months of 1783. In September, brothers Joseph and Etienne Montgolfier launch a hot air balloon that reaches an altitude of about 1,700 feet. The first passengers are animals; they survive. Two months later, so do the first men to go aloft in a Montgolfier balloon. (But

CLOCKWISE FROM TOP: MIKE CAMPBELL, CKMMPHOTOGRAPHIC/AEROVELO; ERIC BOYD; MARY EVANS PICTURE LIBRARY; GRANGER, NYC go after the 50,000-pound (sterling) Kremer International Marathon Competition sponsored by the Royal Aeronautical Society in the United Kingdom. To win, an aircraft must start from rest, complete two circuits, including a figure eight, and complete the distance of 42 kilometers — the length of marathon — within one hour.

The students are at work on a novel "clean sheet" design of a human-powered, propeller-driven aircraft. It will have to be highly maneuverable and likely will require more than one human to supply the needed power and speed, says Robertson.

"No matter what we do, we want to blow the public's mind and show that as a society, we can do more with less through great engineering and innovative ways of thinking," he says. "We don't expect human-powered flight to ever become practical, but we're looking for efficiencies everywhere, and the lessons learned here can be applied elsewhere."


Charity Kelly, a wingsuit flier from Dallas, leaps into Switzerland's Lauterbrunnen Valley.

Wingsuit Wonders

Although the public generally understands skydiving, some people see little romance in leaping from an airplane, plunging until achieving terminal velocity and then arresting the drop to Earth by pulling a parachute.

But stepping off into an abyss, unfurling the wings of a specially designed suit and swooping forward in a controlled descent — well, that evokes Peter Pan, Superman or Buzz Lightyear "falling with style." A man in a wingsuit gliding down the contours of a mountain like a great bird of prey strikes most people as sheer madness, but there is something magical about this extreme sport.

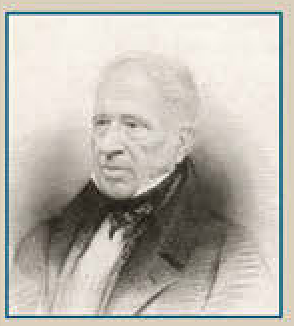
"I got hooked when I saw the ground falling away beneath me," says Tony Uragallo, who makes "TonySuits" at his facility in Zephyrhills, Fla. "Go fast enough, and you can flare the suit up and gain altitude. It really does feel like flying."

Wingsuits are made of tough, high-density nylon used for backpacks and luggage. Webs of fabric run between the jumper's legs, arms and torso. Plastic along the leading edge of the wings creates rigidity. Many airfoil designs include baffles that inflate the fabric to increase the glide ratio — the forward motion relative to the loss in altitude. A modern wingsuit has about a 3-to-1 ratio, or 3 feet forward to every foot down. The world record is a 9-minute 6-second glide from a 37,000-foot drop out of an airplane.

"During a four-minute glide, it's not easy to hold out your arms that long. For nine minutes, you need a chest like a pigeon," quips Uragallo, who tweaks his prototype suits in the lab, using a leaf blower in lieu of a wind tunnel, then flight-tests them while skydiving. During a free fall, he can barrel roll and somersault, slow down to 35 mph or pitch headlong into a dive exceeding 200 mph — faster than terminal velocity. In 2012 at age 58, Uragallo won the World BASE Race in Norway. He also jumped from China's Tianmen Mountain during the World Wingsuit League competition. He came in seventh, one second behind the leader.

His experiences, though exhilarating, have been bittersweet. During the Chinese competition, fellow competitor Victor Kovats of Hungary died when his chute failed. In August 2013

one of them, Jean-Francois Pilatre de Rozier, would have the dubious honor of being one of the first men killed in a balloon crash, two years later). In December, Jacques-Alexandre-Cesar Charles and Marie-Noel Robert take to the skies in a hydrogen balloon, complete with wicker gondola and a valve-and-ballast system to control ascent and descent, systems that will be used by balloonists for the next two centuries.



1849 First manned flight of a heavier-than-air glider, designed by aeronautics pioneer George Cayley.

1891-1896 Otto Lilienthal works to perfect long-distance gliders, making 2,000 flights before his death in a crash.

CLOCKWISE FROM TOP: LUKE HIVELY/DALLAS BASE CREW; MARY EVANS/SZ PHOTO/SCHERL; MARY EVANS PICTURE LIBRARY over the Swiss Alps, Uragallo jumped out of a helicopter at 10,800 feet followed by Mark Sutton, who had just gained fame when he skydived as a James Bond look-alike into London's Olympic Stadium during the opening ceremony of the 2012 Summer Games. While Uragallo filmed with a helmet camera, Sutton was killed after slamming into a rock ridge at 125 mph. Risks can be minimized, but some birdmen fly within an arm's length of rock and canyon walls and just a few feet above the trees in what's known as proximity flying.

"You can touch a cloud, and that doesn't hurt. Touch a rock going down a mountain, and it's unforgiving. There is no margin for error," Uragallo says. "To see friends die, literally die right in front of you, it's horrible. It's funny how such a great sport can be so terrible. That's life, though, isn't it?"

Now retired from wingsuit gliding, Uragallo continues to design flight suits for those who want to push the envelope. When stuntman Gary Connery became the first birdman to land without a parachute, by setting down in a pile of 18,000 cardboard boxes, he did so wearing a TonySuit.

"It's hard to say where this is all going to go. We're just at the beginning," Uragallo says. "Small changes — an inch here or half-inch there — in the airfoil can really make a difference. The glide ratios are just getting amazing."

Jet Pack Perfection

In 1965 when the Astrodome opened in Texas, the theme was all space: the Countdown Cafeteria, the comely "Spacette" hostesses, the team name, of course, and the spacesuited guy blasting off and soaring over the infield in a jet pack.

In the 1950s and '60s, when the American military funded Bell Laboratories to produce the first rocket belt, it envisioned GIs flying over minefields and leapfrogging rivers.

Eric Scott, a pilot for Jet Pack International, goes airborne in Denver.

But we never became a nation of flying soldiers or rocketeers. Low-powered rocket belts remain mostly a gimmick: cool to watch at sporting events or at the state fair, but impractical. The No. 1 reason: Flights are brief — about 30 seconds — really just a high, long hop in the air. And although operators can take off from ground level, they need to get back down quickly before their fuel source (typically hydrogen peroxide) is expended. The apogee of the flight is never high enough for a parachute to act as a safety feature.

1896 Astronomer Samuel Langley realizes power is key for flight. He successfully flies an unmanned steam-powered "aerodrome."

1903 After experimenting with gliders, the Wright brothers add an engine for thrust and complete the first manned, powered flight at Kitty Hawk, N.C.

1912
Franz Reichelt, an inventor and tailor, has been hard at work on a parachute-suit that early aviators could wear as a safety device. Testing the suit with short drops off Paris buildings was met with mixed success. Reichelt concludes that he needs more altitude to truly test his latest design, so he picks the tallest structure around: the Eiffel Tower. And he decides to test the suit himself. On Feb. 4, with early newsreel cameras rolling, Reichelt jumps from the first platform of the tower and plummets 187 feet to his death, his suit folded around him. Though not a thrill-seeker in the strictest sense, Reichelt is later hailed by modern wingsuit fliers and BASE jumpers as one of their own.

Subscribers can see more photos and videos of flight attempts through history at DiscoverMagazine.com/Flight

CLOCKWISE FROM TOP: GO FAST SPORTS AND BEVERAGE CO.; LEEMAGE/GETTY IMAGES; GRANGER, NYC; MARY EVANS/SZ PHOTO/SCHERL

And then there's cost. A jet pack runs between $150,000 and $200,000. And you can't just strap one on and take to the sky. You'll need both computer simulation and hands-on training first. It takes a lot of skill and practice, says Troy Widgery, CEO of Jet Pack International and Go Fast Sports and Beverage in Denver. "It's not for the masses. It's always going to be for someone who can afford the price and who is not averse to risk," he stresses. "This is a flying machine. You can get hurt or killed."

Widgery's company sells two different jet pack models, though he freely admits that this end of his business is not a profit-making venture. "We do it because of our passion," he says. "Seeing someone fly with one of these jet packs is one of the coolest things ever."

Around the world, only a handful of companies and entrepreneurs are working on such products. Martin Jetpack, from Christchurch, New Zealand, markets a turbo fan machine, which technically is not a jet pack, but it has reached 5,000 feet with a test dummy.

Widgery and his team are developing the T73, or Falcon, which will use turbines and jet fuel to fly for about 20 minutes. It will take off and land vertically, he says. "We have a prototype, and when it's revealed and demonstrated to the public, it's going to be worldwide news," he says. "It will be the machine that makes sustained flight possible." D

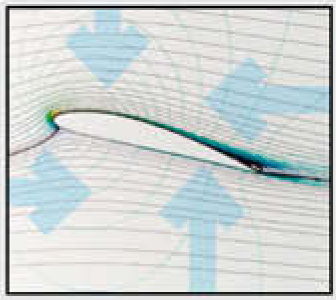
James McCommons *teaches journalism and nature writing at Northern Michigan University. He just completed a biography of George Shiras III, pioneer of 19th-century wildlife photography.*

THE PHYSICS OF FLIGHT

Although the atmosphere seems invisible and gaseous, it's a more apt description to say we're surrounded by an ocean of air that acts more like a fluid. Drag, lift, thrust and gravity — all must be considered when designing an aircraft.

Drag exerts force on an object moving through a fluid. The more sleek the object, the easier it moves through the medium.

Weight represents the downward pull of gravity. Skydivers fall like rocks before pulling parachutes to maximize drag forces and slow their descent.



Lift is exerted on the object as it moves. Generally, lift is directed up, perpendicular to the drag force. Gliding is a modified form of parachuting. The airfoil — that web of fabric between the legs of a wing-suited birdman — sometimes provides lift but mostly delays the fall.

Thrust is the force, the power output that moves an object forward. To really fly — as opposed to falling and gliding — an object must have thrust equal to or exceeding drag. A human can generate about 0.5 horsepower in short bursts and about 0.3 horsepower over a longer period. That's not much. Consequently, a human-powered craft will always be slow. And it requires inordinately long wings and lots of surface area to generate enough lift at low speed. A lack of thrust and slow speed means little force can be applied to steer and make turns. Stalling is a real risk. Some craft have used rudders, others a form of wing warping, favored by the Wright brothers with their first fliers. —JM

1930s "Birdmen" like Harry Ward, Clem Sohn (pictured) and others begin using early wingsuits made of canvas, wood and metal rods.

1959 The first Kremer Prize (50,000 pounds sterling) is established to encourage pioneers in human-powered flight.

1961 First untethered manned flight in a jet pack. (Bell Labs calls it a "rocket belt," but we know what it is.)

1977 With its 96-foot wingspan, the Gossamer Condor, designed by Paul MacCready, wins the Kremer Prize for the first sustained route (a mile-long figure eight) under controlled human power. Made primarily from aluminum tubing, balsa wood and Mylar sheeting, the Condor weighs just 70 pounds, minus its operator. Today, it hangs in the Smithsonian Air and Space Museum in Washington, D.C.

1980 AHS Sikorsky Prize (initially $10,000, later $250,000) is established for the first human-powered helicopter.

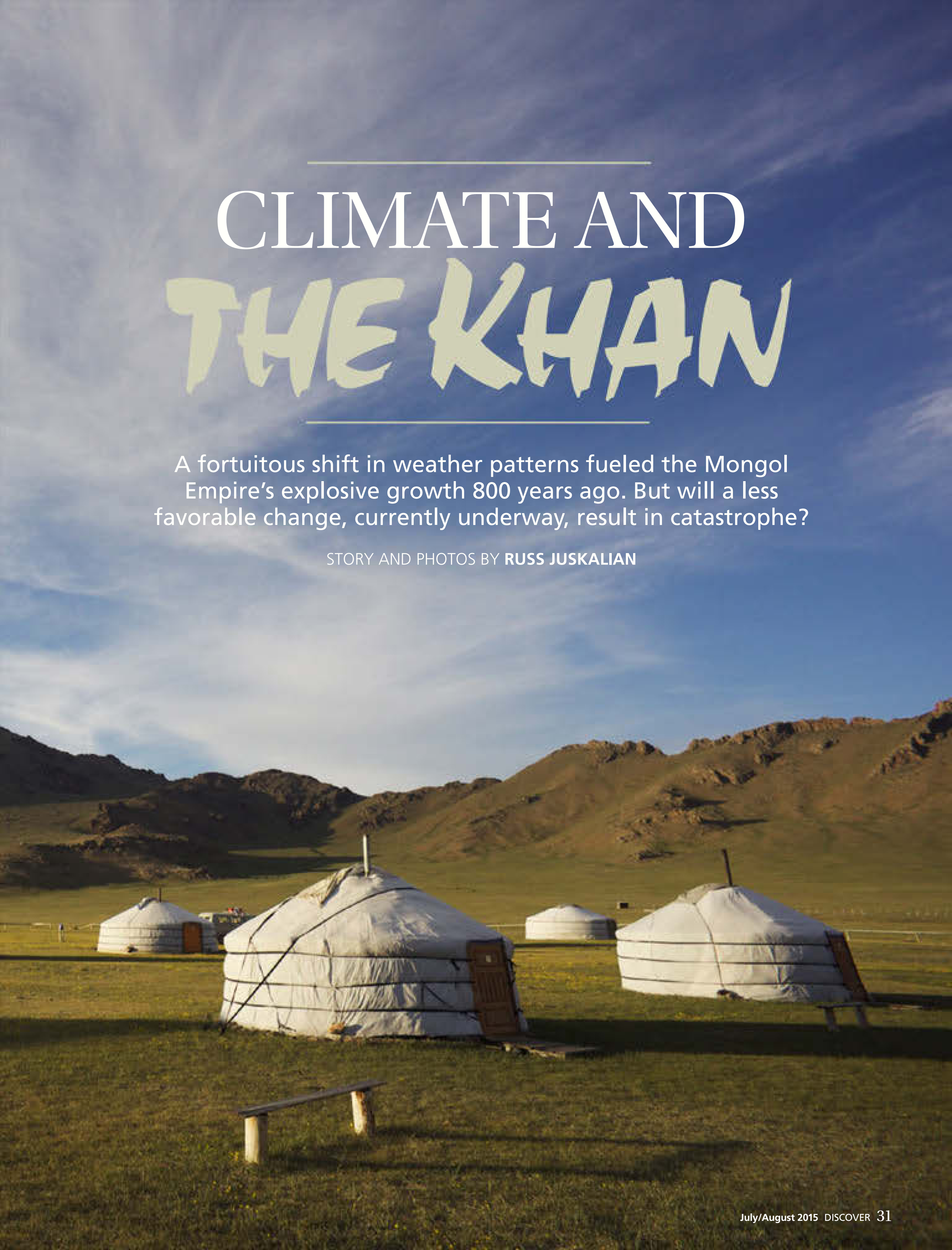
2012 The first Icarus Cup for Human Powered Flight takes place at Lasham Field in England. Sponsored by the Royal Aeronautical Society, it includes a 100-meter sprint, a slalom course and a contest based on takeoff and landing accuracy. No formal competition will be held in 2015, but there are other rallies and several teams getting ready to go after two large Kremer prizes. Industrialist Henry Kremer in 1959 put up 50,000 pounds sterling for a 26-mile marathon flight in under one hour and 100,000 pounds for a human-powered vehicle able to operate under normal conditions. Both prizes remain unclaimed.

2013 AeroVelo claims the Sikorsky Prize.

CLOCKWISE FROM TOP: M.D. SANETRIK/CORBIS; REED YOUNG; DON MONROE; BETTMANN/CORBIS

GENGHIS STATUE: ANDREY BURMAKIN/SHUTTERSTOCK

FORTUNATE SON
The shadow of Genghis Khan still looms large over Mongolia, where even visiting researchers stay in traditional tents called *gers*.



CLIMATE AND THE KHAN

A fortuitous shift in weather patterns fueled the Mongol Empire's explosive growth 800 years ago. But will a less favorable change, currently underway, result in catastrophe?

STORY AND PHOTOS BY **RUSS JUSKALIAN**

A RIDGE TOO FAR
Geographer Amy Hessl (left) stands at a pass in the Khangai Mountains, her eyes on a site she and her team have been preparing to study for a year. Bad weather makes the final stretch of road too dangerous, so Hessl and her team must settle for another location, a mere 10 hours away in a country where distances are vast and horses still roam the steppe (right), much as they did in the days of Genghis Khan, whose horse-powered army carved out the largest contiguous land empire the world has ever known (bottom).

Dense clouds suffocate the sky over Mongolia's Khangai mountain range, and Amy Hessl, by her own admission, is about to cry. She sprawls on the dry, scrubby ground, defeated. As the temperature drops on this early June day and the clouds give way to icy raindrops, all Hessl can mutter is, "I feel sick."

Hessl, a geographer from West Virginia University, studies tree rings for what they can tell us about climate and past environments. She's come to Mongolia to investigate one of history's most enduring puzzles: how Genghis Khan set forth from such an inhospitable place to beget the largest contiguous land empire the world has ever known. Her team, working to unearth this ancient mystery, has found clues of another climate-driven transformation — one that's still underway. It's a tale in which herders and nomads are streaming to urban centers while resources are being exploited without long-term environmental planning, and people, individually and as a society, have no choice but to adapt.

In the past 75 years, Mongolia's temperature has increased more than 2 degrees Celsius, more than twice the global average, and its weather has changed in curious and counterintuitive ways. The country is like a petri dish in which we can see the complex interplay of social, environmental and economic challenges the rest of the world will be dealing with in the coming decades.

On this blustery June day, for Hessl to continue her scientific sleuthing, she needs access to a specific sort of research site, one where trees that died hundreds of years ago have been preserved without rotting or insect infestation. In Mongolia, that means one thing: old lava fields. After two days and about 200 miles of rough travel, the location Hessl chose is tantalizingly close. But there's a problem.

The expedition's drivers say the washed-out track between the team and the site is risky in good weather, and impassable when glazed with ice — a real possibility in the freezing rain. Hessl despairs that a year of planning and a huge outlay of money — $30,000 in travel expenses alone — will have been for nothing if she's forced to turn back now.

Hessl has to make a choice, and fast, to save the expedition. She decides that her target destination, so close, will have to wait another year. Instead, they will travel to Khorgo, a lava field her team has visited in the past. It's on the far side of the mountain range, more than 10 hours away, but it will allow them to make the most of what's left of a two-week research window. Vodka is ceremoniously offered to the elements for protection, and we're on our way again.

NATURE SET THE TABLE

According to legend, Temujin — the man who would become Genghis Khan — was born around 1162, to a woman his nomadic father kidnapped from another tribe. After his father's murder by rivals, and lean years of exile subsisting on scavenged food and steppe rats, Temujin began climbing the tribal ladder with a cunning strategy: He paired pragmatic alliance-making with unbridled use of force. In 1206, he conquered the nomadic tribes of the steppe and became Genghis Khan (or Chinggis Khaan, as Mongolians transliterate the title), great leader of the nascent Mongol Empire. He then led his relatively small force of mounted archers east to China and west to the Caspian Sea in a conquest of unmatched velocity. Before his death in 1227, Genghis had built an empire eclipsing that of Rome — and in a fraction of the time.

Horses were the dynamo of Genghis' army. The animals provided speed and agility in fighting, transportation for people, dried dung for heating fuel and nourishment in the form of milk and meat. But researchers have long sought to understand not only the pace of Genghis' conquest, but that it happened at all. The Mongolia of the late 12th century, when he began his meteoric rise, was engulfed in drought. It was an

See more photos from our writer's trip at
DiscoverMagazine.com/Mongolia

unlikely starting point for a horse-based campaign of world domination.

Genghis, a follower of the shamanistic belief known as Tengrism, credited his success to the Eternal Blue Sky. And as it turns out, he may have been right.

Research by Hessl and others has revealed Genghis happened to be the right man in the right place at the right time. His conquest coincided with the most consistently wet — and likely resource rich — period in Mongolia in more than a thousand years.

"Nature set the table, and Genghis Khan came to eat," says Hessl.

In the summer of 2010, Hessl and her colleague Neil Pederson, a forest ecologist then working at the Lamont-Doherty Earth Observatory of Columbia University, were in Mongolia sampling larch trees. Using dendrochronology — analyzing tree rings to date past events — the team was building a record of regional fires and droughts going back about 650 years.

They spotted some Siberian pines in an area where they'd only ever seen larch. The researchers took more than a dozen samples of the pines, both living and long dead. "We really had no idea what we were doing," Hessl says. Pederson had a similar reaction. "In the back of my mind, it was just like,

MAP: ROEN KELLY AND RICK JOHNSON/DISCOVER

'This is cool. I can't wait to work these up later,'" he says.

Pederson finally got around to taking a closer look at the slices of dead pine months later. He put a cross-section of the sample KLP0010 under a scope and watched as its fine lines came into focus. He saw many more tree rings than expected. KLP0010 was old — really old.

For a place like Mongolia, where historical records are scarce, the significance of the discovery was immense. In a hasty, sloppily enthusiastic email to Hessl, Pederson couldn't contain himself:

> *"yes, i can see the yr Chinggis was born. i can see the yr he died. i can see the yrs Mongolia rose to rule Asia!"*

Pederson knew the team's research was about to change. If they could collect enough samples, they'd be among the first scientists to find local evidence of the climate's ebb and flow during Genghis' time. The tree rings would hold secrets about weather, moisture and productivity in the patterns of their growth. The first trip back to Khorgo, in 2012, found evidence of the wet period, or pluvial, that Genghis rode to fame. The next expedition, in summer 2014, would confirm it.

LOCATION, LOCATION, LOCATION

The team was in better spirits when we finally reached the lava field at Khorgo, the site hastily chosen as a backup after the weather drowned our initial plans. The next morning was cold but cloudless, and as we walked through sparse, boot-high grass, the dried earth crunched with each step. After a few minutes, the terrain gave way to dusty, black, pockmarked volcanic rock. I spotted a sun-bleached skull. "Sometimes, horses wander in and get lost," says one of the Mongolian scientists. "Some die."

Location is the key to using trees to determine an annual record of soil moisture. You want to be at the edge of a species's range where, in Hessl's words, the trees are "very stressed, very unhappy, depressed" and therefore likely to respond to changes in water balance. The concept grew out of Liebig's law, a centuries-old principle in agriculture: Growth is regulated not by total resources, but on the availability of the resource that is the most scarce. Where the limiting resource for growth is moisture, the drier years will produce exceedingly narrow growth rings — less than a tenth of the thickness of a sheet of paper — and the wetter years will produce fatter ones.

Dendrochronologists can construct thousand-year histories using trees that, individually, may have lived only a fraction of that time. As Hessl puts it, it's as if the trees are all listening to the same song of the climate, recording the tune in tiny, concentric rings of cellulose. Where the music overlaps, two trees were alive at the same time. Beginning with cores from live trees, the researchers can reconstruct the climate record in reverse, all the way back to the lifetime of trees now long dead.

At the Khorgo site, Hessl was searching for the oldest possible specimens to strengthen the data from the time of Genghis Khan, and to push the record back even further for a more complete understanding of the area's climate patterns. Her team hunted for the signs of a promising candidate: a gray, weathered trunk, no bark and few remaining branches.

As we walked the lava field over the next few days, Hessl explained that a colleague's computer models showed how a wet period would have resulted in highly productive grasslands and healthy livestock — crucial to Genghis' ability to mount a long-term campaign across the expansive Eurasian steppe. Perhaps he even interpreted a favorable turn in the climate, around the year 1211, as proof that the Eternal Blue Sky chose him to conquer the world. Nicola Di Cosmo, a historian collaborating with Hessl, later told me that wetter, milder

FAR LEFT: NEIL PEDERSON

conditions than the previous decades of drought would have given Genghis and his army significant advantages, including a constant supply of horses, increased agricultural production and other resources needed to support a centralized government and large military.

On my last day with the team, I joined a Mongolian forestry graduate student named Badar-Uugan as he wielded a chain saw to cut samples. A few days earlier, Badar-Uugan's father, who lived 20 minutes down the road in the dusty town of Tariat, told us that small bodies of water, including the one at the bottom of Khorgo's volcanic crater, had been disappearing over the past few decades. I asked Badar-Uugan if he had observed the same things. "The amount of rain is the same," he tells me. "But the biggest difference is the variability. We used to get more consistent precipitation, but now it rains all at once, and then maybe it won't rain for another month or two."

Late that afternoon, as Hessl sat on the black rocks and stretched her bad back, she told me she'd seen something foreboding in the climate record. As Mongolia warmed during the 20th century, it experienced some wet years, similar to those during the early 13th century.

Instead of the rise of a khan, this modern pluvial overlapped with the country's transition from Soviet satellite to market economy. Livestock capacity exploded, and herding shifted from traditional yaks and sheep to more voracious goats, valued for their cashmere.

But in 1999, "the bottom dropped out," Hessl says. The next 10 years were marked by drought, massive herding losses, rapid soil degradation and wave after wave of nomads migrating to the capital of Ulaanbaatar. Here's the scary part: If the late 20th century pluvial turns out to be an anomaly — and it looks like it might — decades of expansion were built on a new normal that was anything but. Mongolia's struggles could be just getting started.

BACK TO THE FUTURE?

The next morning, I caught a 14-hour bus ride to UB, as locals often call Ulaanbaatar, and passed the time watching the parched steppe with new eyes. I saw patches of grassland turned sandy and beachlike, and huge curtains of dust raised by strong winds. In UB's modern core, Chinggis Khaan Square, children zipped around on toy electric cars amid a profusion of hipsters. Depictions of the khan were everywhere, on dozens of bottles of vodka, on the steps of the Government Palace, on signage for banks and the Grand Khaan Irish Pub.

I rushed to the National University to catch the end of a talk by Clyde Goulden on the country's changing climate. Goulden is something of a superstar here. The American scientist, now in his 70s, has conducted climate research in Mongolia for 20 years. He was recently awarded the highest honor the country gives to foreigners, the Order of the Polar Star.

As Goulden parsed meteorological records and the results of more than 100 interviews he and his Mongolian wife, Tuya, had conducted with nomadic herders in the northern provinces of Hovsgol and Khentii, he paused and apologized to the audience: "I'm sorry to bring all this depressing news to you."

The herders, Goulden says, were so distressed by the growing unpredictability of the weather that many had talked about giving up. They spoke of hot days "burning" the grass, winds scouring the soil and rapidly fluctuating temperatures.

Just as Inuit dialects have many ways to describe snow, modern Mongolian puts an emphasis on describing nuances in rainfall. For a herder in a dry country, survival depends on the rains. According to Goulden, nearly 98 percent of the herders said that lighter, longer rains — *shivree*, *namiraa* and *zuser* — were increasingly being replaced by shorter, high-intensity rains called *aadar*.

Instead of a drizzle that would last for days and be slowly

RINGS OF TRUTH
Neil Pederson, one of Hessl's colleagues, dated this sample of a long-dead pine from Mongolia (far left) and discovered the tree lived from the seventh to 14th centuries and was alive when Genghis Khan built his empire. Terkhiin Tsagaan Lake provides a scenic backdrop to Khorgo's lava fields (center top), where Hessl (center bottom) and her team hunt for tree ring patterns that could provide clues to past climate. Team member Bader-Uugan (left), who studies forestry in Ulaanbaatar, hails from Tariat, a small town near the site.

absorbed by the steppe grasses, the same amount of rain was falling in 20 or 30 minutes. *Aadar* was problematic, the herders told Goulden, because its intense precipitation fell on small areas, eroding the soil and spilling off the steppe faster than it could be absorbed.

After the talk, Goulden told me his research had implications far beyond the steppe lands. "I want to know what it's like," he says, "to see what happens in Philadelphia when it warms 2 degrees Celsius, or in Kansas, where I grew up." We might learn from Mongolia's effort to adapt to its environmental challenges, he says.

So far, the lesson is a cautionary one. Since Mongolia's democratic revolution in 1990, the country's livestock numbers have more than doubled, intensifying environmental stress. More than 70 percent of Mongolia's land is already degraded. In a dangerous feedback loop exacerbated by overgrazing and poor resource management, whole regions are losing biodiversity. Soil is releasing stored carbon dioxide and beginning to desertify. Destabilizing forces of poverty and large environmentally aggravated migrations are rising.

According to UNICEF, up to 70,000 herders can flee unproductive lands in particularly difficult years in Mongolia. Almost all head, permanently, to UB's interconnected slums. From the air, the city's so-called ger district looks a lot like

a plant under a microscope. Each small, wooden-walled plot of land, like a cell, butts up against its neighbor, with a white *ger* — the traditional wood and felt tent of nomadic Mongolians — at its nucleus. More than simply a district, its 750,000 residents represent about 60 percent of the capital's population, and more than a quarter of the entire country. The shantytown's concentric bands of humanity can be read in the same way scientists like Hessl read the rings of a pine tree. Instead of moisture, the district's onion-like growth measures the movement of people in response to ecological breakdown.

As one travels away from the city's core, the ratio of gers to more permanent structures increases. About 6 miles northeast of downtown UB, the city runs out, and beyond the last wooden fence there is nothing but steppe and mountains and desert. It was here where I saw 62-year-old Dolgorsuren Chimeddulam stacking dried dung to fuel her stove. Chimeddulam erected her ger the month before in this narrow, treeless valley, framed by a dump on one side and a cemetery one ridge over. She squinted her weathered face and waved me inside.

Chimeddulam had hunched shoulders, and she wore rubber shower sandals, a bright turquoise headscarf decorated with images of flowers and a burgundy *deel* — the traditional neck-to-ankle tunic that Mongolians have donned for centuries

THIS PAGE, BOTTOM LEFT: TUUL AND BRUNO MORANDI/CORBIS

CLIMATE CLASH
Sheep have grazed the Mongolian steppe for centuries (top left), but as more land becomes degraded, shepherds are forced to abandon their traditions and move their gers to an ever-larger slum on Ulaanbaatar's outskirts (top right). Outside Hustai National Park, a woman milks cows in a buffer zone where reduced rainfall and overgrazing have desertifed the land (far left). Inside the park's boundaries, a fence protects a study plot of thriving native grasses (middle left). As skyscrapers loom above the ger slums of Ulaanbaatar (near left) and Genghis Khan's face becomes a marketing gimmick for everything, even vodka (right), Mongolia moves further from its nomadic roots.

RECENT ARRIVAL
On the outskirts of Ulaanbaatar, Dolgorsuren Chimeddulam welcomes a visitor into her ger. Chimeddulam, 62, explains that she lost all of her livestock in the *dzud*, a term Mongolians use to refer to extreme storms, but also to an increasingly volatile environment of drought and desertification. Researchers believe Mongolia's situation may only get worse as the country's temperatures continue to rise.

— embroidered with geometric designs and detailed with gold thread. Inside her ger were a few painted dressers, a frame filled with photos and a small shrine.

Chimeddulam offered me candy from a bowl and apologized for not being able to pour me a cup of salty milk tea, a staple of nearly every guest-host interaction in the country. "I lost my livestock in the *dzud*," she says, by way of explanation. "I lost them all."

If you ask five people to define *dzud*, you're likely to get five answers. Most describe a brutal winter or spring storm in which the temperature plummets as low as minus 40 degrees Fahrenheit, fodder is inaccessible and animals die en masse. Herders will tell you dzud starts earlier, with a summer drought that prevents animals from thriving. Others, like Hessl and researchers at the World Bank, refer to a social component — a sort of collective narrative of hardship and loss that reifies the dzud as a national phenomenon. It's unclear whether dzud can be linked to climate change. What is clear is that overworked grasslands and worsening weather conditions are making dzud harder to mitigate.


Przewalski's horse

For Chimeddulam, the calamity meant the loss of wealth, income and lifestyle. Without animals, she had no milk for her tea, and nothing to sell. So she traveled more than 200 miles to the capital — one of the city's latest arrivals, judging by her spot on its outskirts. As I talked to other residents of the district, I heard Chimeddulam's story repeated with slight variations:

"The grass used to be tall, up to my waist, you could get lost in it."

"The rain used to be regular and predictable, but now it's confused."

"The soil never used to blow away in the wind."

"My animals died, and I have nothing left."

LOSING GROUND

Most people visit Hustai National Park — an expanse of more than 123,000 acres about 90 minutes west of UB — to see the *takhi*, or Przewalski's horse, the last truly wild horse left on the planet. But after hearing about the changes to Mongolia's steppe, I came to stare at the ground with Tserendulam Tseren-ochir, a biologist studying grassland degradation and recovery.

The rolling hills surrounding the park were covered in greenish-gray vegetation. "*Artemisia* and *Carex* dominate this area," Tserendulam says, referring to the plants in a buffer zone between the unprotected steppe and the sanctuary of the park. "That is a sign of degradation," she explains. Overgrazing has led to imbalance: Some native plants thrive while others diminish.

Nearby, a fenced plot of meter-high, flaxen grasses looked like something from the American plains. The fencing, built a decade ago, was a simple experiment to keep out grazing animals and allow biologists to study the undisturbed area. *Carex* and *Artemisia* still grew inside the fence, but the species balance was healthier; native grasses, preferred by livestock, were able to compete when allowed to grow to full height.

Tserendulam led me to the center of the park, where clumps of native grasses, like *Stipa krylovii* and *Achnatherum splendis*, were healthier and more abundant, no fencing required. But even here, the changing climate was having an impact. Over the past 15 years, Tserendulam says, streams that were once consistently wet often flowed only after a storm, erosion was accelerating, and some plants were blossoming at different times than in the past.

On the far side of the park, along a buffer zone near the Tuul River, we stopped at a lone ger. A young couple inside served us milk tea and heaping bowls of homemade noodles with chunks of mutton and fat. Thick vegetation grew next to the riverbank, but the land by the ger was in rough shape. Even species that thrived in areas of moderate degradation were struggling to survive here — a sign of impending desertification.

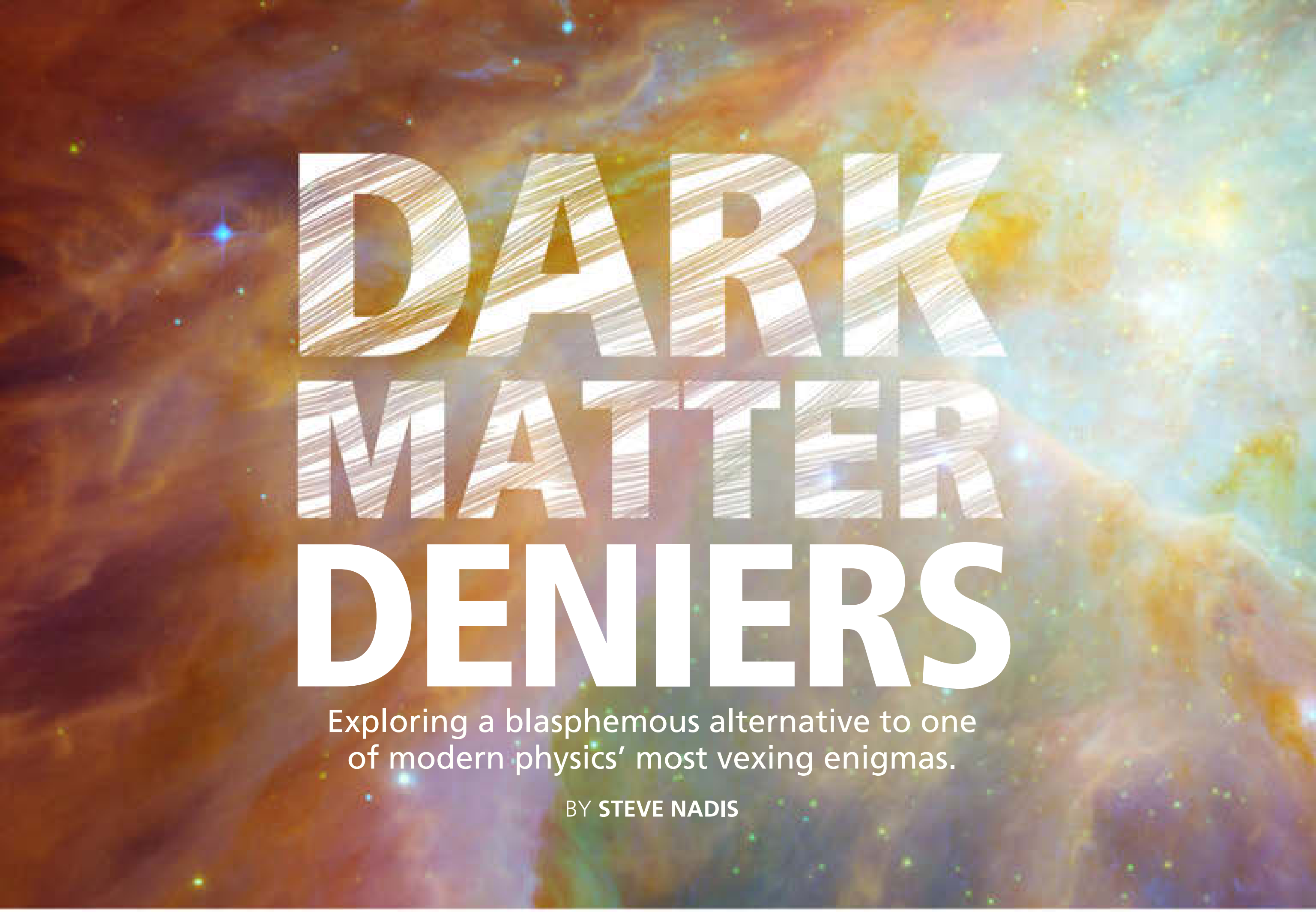
"Look, this is *Carex*," Tserendulam says, crouching to measure a stalk with her finger. "It is normally 8 to 10 centimeters, but here it is only 1 to 2 centimeters. When it is totally degraded, it will be almost all just dust." It was still possible to reverse the damage, she says, but recovery would take decades. Back in the park, a plot of land similarly degraded more than 20 years ago still hadn't returned to full health.

By the time I returned to UB the next morning, Hessl had emerged from the field with about 140 new tree ring samples. We met over a beer to discuss the parallels between Genghis' time and our own. Earlier, Hessl had told me that the two periods were, in broad ways, "mirror images of one another"— each marked by changing climate, urbanization and societal reorganization. Now, sitting among UB's rising middle class, she warned against interpreting her findings in an environmentally deterministic way. The climate did not make the khan; the khan made use of the climate.

Later that evening, I took an elevator to the top of Mongolia's tallest building. Peering out past the glass, I could see the twinkling lights of the new Mongolia in the square below, and further beyond that, the faint outlines of the old Mongolia on the dark hillsides of the ger district. I thought about Chimeddulam without her milk tea, and the trees recording the climate's tune, and Genghis Khan's remarkable insight to break from tradition when it no longer served him and seize a new opportunity served up by nature.

The climate may not pick winners and losers, as Hessl said. But in her tree rings is ample evidence that a changing climate can shift our story, creating a set of conditions that we can adapt to and take advantage of in order to thrive. Or ignore, to our detriment. D

__Russ Juskalian__ is a writer and photographer based in Munich. Since writing this story, he inspects tree stumps for growth rings on a regular basis.



DARK MATTER DENIERS

Exploring a blasphemous alternative to one of modern physics' most vexing enigmas.

BY **STEVE NADIS**

When it comes to the universe, most cosmologists argue, what you see is not what you get. In fact, the latest survey of the Big Bang's residual light suggests that more than 84 percent of the matter in the cosmos is of the "dark" variety: exotic particles unlike the ordinary atoms that make up our everyday world and the objects therein.

Dark matter, according to current orthodoxy, is largely responsible for the formation of galaxies, galaxy clusters and larger entities, and it also provides the gravitational glue needed to keep these structures intact. In countless galaxies observed to date, stars orbit the galactic center so quickly that gravity alone shouldn't be enough to keep galaxies from flying apart. The picture makes more sense when you introduce hidden, invisible matter to hold the galaxies together. Furthermore, computer simulations of the universe have largely reproduced the cosmos we see today by following a recipe of roughly 5 parts dark matter to 1 part regular matter.

Yet there is a rather significant catch. No one has ever detected a single dark matter particle, and no one can say for certain what it would consist of. "Why are all the dark matter searches coming up empty-handed?" asks Stacy McGaugh, an astronomer at Case Western Reserve University in Cleveland. His answer runs contrary to the conventional wisdom: "It's possible it ain't there."

For the past two decades, McGaugh has reluctantly played the role of the doubter. He was a dark matter enthusiast like most of his peers, but he started losing faith in the mid-1990s when he realized that models predicated on the invisible stuff didn't match up with the phenomena he was witnessing in galaxies.

Instead, McGaugh is considering an idea called Modified Newtonian Dynamics, or MOND. Although many astronomers regard it as blasphemous, MOND has consistently outperformed dark matter models in describing the motions of stars and gases in galaxies. Instead of relying on new, hypothetical types of matter, this alternative theory merely tweaks Isaac Newton's laws of gravity to strengthen the gravitational pull as needed. If gravity plays by different rules than we thought, MOND advocates suggest, we might be able to explain galaxy dynamics, and other puzzling aspects of the universe, without having to invoke dark matter at all.

CHANGING THE RULES

Mordehai Milgrom, a theoretical physicist at the Weizmann Institute of Science in Israel, came up with MOND more

NASA/ESA/T. MEGEATH (UNIVERSITY OF TOLEDO) AND M. ROBBERTO (STSCI)

than 30 years ago as an alternative to dark matter. At the time, Milgrom was studying star velocities in other galaxies. Normally, he says, "you expect objects near the center of a galaxy to rotate faster and objects farther from the center to go slower and slower, but this wasn't observed." Instead, velocities flattened out, staying constant as one moved farther from the galactic center.

If dark matter is responsible for such uniform rotation speeds, it would require an extraordinarily precise distribution of the invisible stuff — "fine-tuning in the extreme," as Milgrom calls it. "It's like taking 100 building blocks and throwing them on the floor, and lo and behold, I see a castle." MOND offers an explanation he finds more plausible: "You don't need the hidden mass." The desired effects can be explained by modifying our understanding of gravity.

No one has ever detected a single dark matter particle, and no one can say for certain what it would consist of.

Milgrom's brainchild, MOND, builds on Newton's laws of gravity in a similar way as Einstein's gravitational theory, general relativity. General relativity predicts the same thing as Newton's laws wherever gravity is not overly strong, but it yields different answers in extreme environments, such as in the vicinity of a black hole. MOND does something similar, except that it takes over for Newton somewhere different — in places where gravitational forces are weak.

Newton's laws, for example, work well near Earth's surface and in describing planetary motions in the solar system, where the gravity is moderately strong. Those laws don't work so well, however, in describing the motions of stars in a galaxy where gravitational forces are much weaker because the stars are widely scattered. Milgrom noticed that in diffuse systems like this, Newton's laws begin to falter — and make untrustworthy predictions — whenever gravitational acceleration dips below a specific threshold, 10^{-10} meters per second per second, 100 billion times weaker than the force of gravity felt on Earth.

Milgrom devised a straightforward equation, the so-called MOND formula, to describe how fast objects should move depending on the gravitational forces and accelerations exerted on them. Simply put, above the 10^{-10} threshold, you get Newton's gravity, and below it, you get MOND's modified version. The formula also provides for a smooth transition between these two physical regimes.

A GUARDED RECEPTION

When Milgrom introduced MOND to the world in a 1983 paper, it was greeted with indifference — a reaction that largely persists to this day. "In the beginning, MOND was ignored by almost everyone," Milgrom recalls. "That wasn't unfair. It was the correct attitude. Heretical theories should be given a hard time."

Stacy McGaugh

Mordehai Milgrom

And that's exactly how McGaugh responded. He first heard about MOND while he was a postdoctoral fellow at the University of Cambridge in 1995, when Milgrom came to speak. McGaugh almost skipped the lecture because he didn't want to waste his time on "crazy talk" about overthrowing the known laws of gravity.

But he went anyway, and his interest picked up when Milgrom discussed "low surface brightness" galaxies — ones with much lower concentrations of stars than normal spiral galaxies like the Milky Way. These galaxies are smaller, stretched-out versions of spirals, with stars spread so thin — and gravity, accordingly, so weak — that they pose a good test of MOND. Milgrom used the MOND equation to predict stellar rotation speeds in these galaxies.

McGaugh, who was studying low surface brightness galaxies at the time, already had data in hand that he assumed would "falsify this stupid idea, once and for all." He compared Milgrom's predictions with his data, "and darned if they didn't all come true." That finding stunned McGaugh.

The self-professed "true believer" in dark matter could barely sleep as he tried to figure out how MOND's wacky predictions could have possibly been confirmed when there seemed to be so much evidence for dark matter. It took him nearly a week of soul searching before he overcame his shock and accepted the fact that MOND's success in this instance may not have been a fluke.

Since then, McGaugh has resolved to test MOND under various astronomical and cosmological conditions to find out, as rigorously as possible, how well Milgrom's ideas hold up. "My role has been the objective observer to his theorist," McGaugh says.

NOT THERE YET

Based on the evidence collected so far, "MOND can claim an impressive number of correct predictions regarding the dynamics of galaxies," says Anthony Aguirre, a cosmologist at the University of California, Santa Cruz. But there's a reason it's still not the prevailing theory.

MOND has not fared so well in describing the universe on larger scales, such as galaxy clusters, and particularly "rich clusters" that consist of dozens of bright galaxies and hundreds of fainter ones. The predictions MOND makes for rich clusters are off by a factor of 2, McGaugh concedes, meaning that you need twice as much mass as you see to explain galaxy motions.

To make up the deficit, one idea is that the clusters may harbor unexpectedly large quantities of neutrinos — another type of elusive invisible particle. But unlike dark matter particles, neutrinos are ordinary matter, known to exist in great numbers. The universe has enough concealed, ordinary stuff in it to potentially solve this problem without resorting to unknown dark matter, McGaugh says.

Another shortcoming of MOND is that, unlike general relativity, it offers no compelling physical reason as to why MONDian effects occur. There are theories explaining why MOND works, but no one yet knows which, if any, may be correct. Milgrom, for one, would like to see this deficiency addressed through the development of a broader theory of gravity that incorporates aspects of both general relativity and MOND while eliminating dark matter altogether. He came up with a relativity-friendly version of MOND in 2009, even though another such theory — called TEVIS — was devised five years earlier by Jacob Bekenstein of the Hebrew University in Jerusalem. "TEVIS works pretty well," Bekenstein says, but like MOND, it can't explain the behavior of truly large structures. "Maybe some smart guy will come along who can succeed, but that hasn't happened yet."

It's a "really hard problem," McGaugh acknowledges. "I can at least imagine a more general theory that encompasses general relativity and MOND, with MOND applying in one special case and general relativity applying for the rest." He's tried a hand at this himself but hasn't gotten far, noting that "some people don't think of it as a valid problem to work on." Unfortunately, among cosmologists, that attitude extends to pretty much anything involving modified gravity.

OUTSIDE THE MAINSTREAM

McGaugh's investigations of the countercultural MOND have exposed him to professional hardship and a barrage of criticism. "I've forgotten more slights than most people suffer," he quips. "A new generation of students raised to believe in dark matter often assumes I must be some kind of crackpot."

Still, he and Milgrom are not alone in taking MOND seriously. Other respected physicists have signed on, too, among them contemporary researchers in Belgium, France, the Netherlands, the U.K., the U.S. and elsewhere. All told, more than 100 astronomers have published

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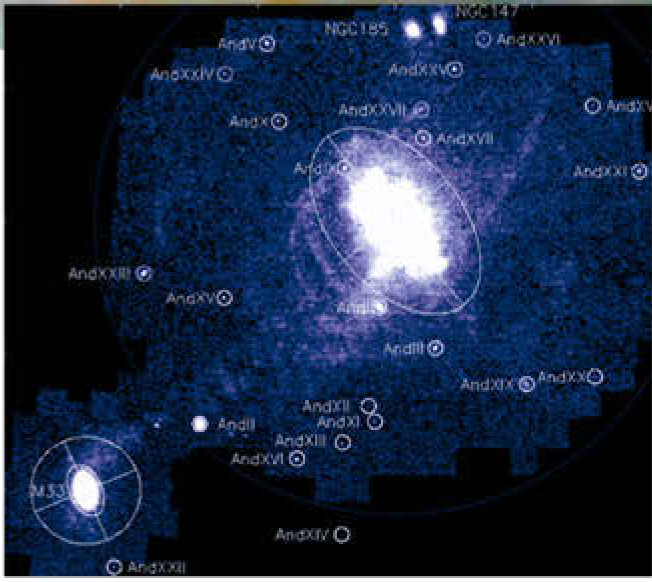

The Pan-Andromeda Archaeological Survey has revealed several new targets for tests of MOND: dwarf galaxies around Andromeda (center). The controversial theory consistently makes accurate predictions.

The dwarf galaxy Andromeda VII (diffuse, centered), also known as PGC 2807155, is an example of a low surface brightness galaxy ideal for assessing MONDian predictions. (The vertical bar is an imaging artifact.)

scientific papers on the subject.

McGaugh is also buoyed by the fact that, unlike other alternative theories that have come and gone, MOND has held up surprisingly well. No one has unequivocally disproven it, despite concerted efforts over the past 30 years to do so. But McGaugh also recognizes that in the end, popular opinion — even among scientists — is largely irrelevant. "Ultimately," he says, "science is not a consensus endeavor. The data rule."

And that is what he has focused on — the data. He goes where it leads him, even though it has carried him on an unexpectedly tortuous journey. The majority of his research pertains to galaxies, which happen to be his specialty. He broadened his studies of low surface brightness galaxies to include "basically all kinds of galaxies," he says, such as denser, high surface brightness galaxies, even more star-rich spirals and irregular galaxies — those that don't come in spiral or ellipsoidal shapes. His conclusion? MOND works well in each of these cases.

McGaugh's investigations of MOND have exposed him to professional hardship and a barrage of criticism.

ON TO ANDROMEDA

McGaugh's most recent research, undertaken with Milgrom and other collaborators, has focused on the undersized ("dwarf") galaxies of Andromeda, the nearest large galaxy to the Milky Way. Astronomers have spotted among the outer fringes of Andromeda a few dozen small and roughly spherical galaxies with stars orbiting in random directions. The dwarfs' low stellar densities (and correspondingly low gravitational forces) make them especially good places to look for MONDian effects.

The Pan-Andromeda Archaeological Survey (PANDAS) is exploring Andromeda in unprecedented detail, using the Canada-France-Hawaii Telescope in Hawaii. Shortly after the survey discovered and analyzed 10 new dwarf galaxies, McGaugh and Milgrom predicted in a 2013 paper how fast the stars should be moving, according to MOND. The stellar velocities were later measured, and their predictions were right on the mark for nine of the 10 (with the last one having too few stars to support a velocity measurement). Predictions for two additional nearby dwarf galaxies made by McGaugh and his postdoc Marcel Pawlowski, published in 2014, were also correct.

"When you make predictions and they come out right, that's about as good as it gets," McGaugh says. "As the Andromeda measurements have shown us, as the data improve, the agreement with MOND seems to keep getting better."

He accepts the fact that MOND still faces many challenges. There is the cluster problem, which has not gone away, and the difficulty of tying in MOND with a broader description of gravity. Dark matter models, on the other hand, have not fared well in explaining star motions in galaxies, either, and in some cases the models are off by a factor of 100. McGaugh agrees with Bekenstein, who maintains that "dark matter models have problems of the same magnitude [as MOND]."

As to exactly where that leaves us, McGaugh is unsure, though he's more convinced than ever that MOND warrants further investigation. "The formula has predictive power," he says, "so it's got to be telling us something." If he's right, other astronomers might find it worth their while to listen. D

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A User's Guide to RATIONAL THINKING

Cut through flawed assumptions and false beliefs — including your own — with these strategies.

BY **CHRISTIE ASCHWANDEN** ILLUSTRATION BY **PAT KINSELLA**

In the digital age, information is more plentiful than ever, but parsing truth from the abundance of competing claims can be daunting. Whether the subject is Ebola, vaccines or climate change, speculation and conspiracy theories compete with science for the public's trust. Our guide to rational thinking is here to help. In the following pages, you'll learn tools to identify the hallmarks of irrational thinking, evaluate evidence, recognize your own biases and develop strategies to transform shouting matches into meaningful discussions.

The Irrationalist in You

We're programmed for irrational thought.

Irrational thinking stems from cognitive biases that strike us all. "People don't think like scientists; they think like lawyers. They hold the belief they want to believe and then they recruit anything they can to support it," says Peter Ditto, a psychologist who studies judgment and decision-making at the University of California, Irvine. Motivated reasoning — our tendency to filter facts to support our pre-existing belief systems — is the standard way we process information, Ditto says. "We almost never think about things without some preference in mind or some emotional inclination to want one thing or another. That's the norm."

If you think you're immune, you're not alone. We're very good at detecting motivated reasoning and biases in other people, Ditto says, but terrible at seeing it in ourselves. Spend a few minutes in honest reflection, and chances are you will find a few examples from your own life. Whether we're telling ourselves that we're better-than-average drivers, despite those traffic tickets, or insisting we'll get through a 40-hour to-do list in a single day, we're all prone to demonstrably false beliefs.

Much of our thinking on contentious issues is influenced by our pre-established social or cultural groups, says Dan Kahan, a law professor and science communication researcher at Yale Law School. Kahan studies cultural cognition — the idea that the way people process information is heavily determined by their deep-seated values and cultural identities. We don't have time to evaluate every piece of evidence on every issue, so we look to people we trust in our in-groups to help us make judgments, Kahan says. Once a certain idea or stance becomes associated with a group we belong to (part of what Kahan calls a cultural identity), we become more inclined to adopt that position; it's a way to show that we belong.

If you consider yourself an environmentalist, for instance, you're primed to adopt the view that hydraulic fracturing, or "fracking" — the controversial method of oil and gas extraction that involves cracking rock with pressurized fluids — poses a threat to the environment and human health. On the other hand, if you're a conservative, you're more apt to believe that fracking is harmless, since this is the stance taken by others in that group.

Being science-literate won't protect you from such biases, Kahan says. His research has found that people who score high on measures of science comprehension tend to be more polarized than others on contentious issues. In one such study, Kahan and his research team surveyed a diverse sample of about 1,500 American adults regarding their political views. The team asked them to do a calculation designed to test their ability to slow down and do the math, rather than taking gut-reaction shortcuts that can lead to the wrong answer. The researchers presented the same math problem framed two different ways: as a nonpolitical question, and as a question looking into a politically charged issue, such as gun control. They found that the people who scored the best on the nonpolitical math problem fared the worst when the same problem was presented as a politically charged issue. The better your knowledge of science and the stronger your ability to understand numbers and make sense of data, the more adept you are at fitting the evidence to the position held by your group identity, Kahan says.

Is it possible to overcome these internal biases that sidetrack our thinking? The Center for Applied Rationality (CFAR) thinks so. This nonprofit group, based in Berkeley, Calif., holds workshops and seminars aimed at helping people develop habits of thought that break through biases.

The first step toward overcoming bias is to recognize and accept your fallibility, says Julia Galef, president and co-founder of CFAR. "We tend to feel bad about ourselves when we notice we've been wrong," she says, but if you punish yourself, you create a disincentive for searching for truth. "We try to encourage people to congratulate themselves when they notice a flaw in their belief or realize that the argument someone else is making has some basis," Galef says.

Another trick Galef recommends is the flip — turn your belief around. Ask yourself, "What are some reasons I might be wrong?" This strategy forces you to turn your attention to contrary evidence, which you might be motivated to overlook if you simply listed reasons for your views. Consider what it would look like for you to be wrong on this issue. Is any of the evidence compatible with this opposite view? Would you be inclined to believe this opposite argument if it were being promoted by someone from your own political party or social group? The answers can help you determine the strength of your position, Galef says, and whether it's time to reconsider it.

A Field Guide to Irrational Arguments

Scientific explanations are based on evidence and subject to change when new facts come to light. Irrational ones rely on assumptions and involve only the facts that support a chosen side. Here are five hallmarks of irrational arguments.

The science is nitpicked to fan doubt.

Rather than considering the totality of the evidence, unscientific arguments cherry-pick data, mischaracterize research methods or results, or even make outright false claims. For instance, people who insist that vaccines cause autism may point to the known dangers of mercury as evidence, even though mercury is no longer a component of most vaccines, and studies have found no link between vaccines and autism. When a proponent's explanation of the research contradicts the scientists, that's a good sign that they're peddling this type of false doubt.

The science is rejected based on implications, not data.

Instead of taking issue with the evidence itself, these types of arguments focus on the perceived implications, says Josh Rosenau, programs and policy director at the National Center for Science Education. "People will say, 'Well, if evolution is true, then we don't have souls, or we should all behave like animals.' " Never mind that the science doesn't actually say anything about how people should behave. If the science can be implied to repudiate beliefs that people hold dear, it creates a huge incentive to engage in motivated reasoning, lest one's world view comes crashing down.

Scientists' motives and reasons are attacked.

Critics often turn to personal attacks on scientists to cast doubt on their findings. Instead of criticizing the science itself, these lines of argument suppose that scientists have rigged their research to support the scientific consensus. Paul Offit, director of the Vaccine Education Center at the Children's Hospital of Philadelphia, co-invented a life-saving rotavirus vaccine. Anti-vaccine crusaders seized on his association with it to imply that his advocacy stems from his financial interest in vaccines and ties to pharmaceutical companies. Offit has concluded that some of these people cannot be convinced. "It doesn't matter how much data you show that person. If in their hearts they're conspiracy theorists, you can't convince them."

Legitimate disagreements among scientists are amplified to dismiss the science.

Evolution is one of the foundations of modern biology, but biologists are still discovering details of how evolution works. When geneticists offer contrary ideas about how speciation occurs, they're debating the nuts and bolts of how evolution works, not arguing over whether it happens. Yet people fighting the teaching of evolution in schools may seize on legitimate scientific disputes as reasons to dismiss the scientific theory altogether, Rosenau says. When they present gadflies or scientists whose views are out of step with the majority of the field as the most trustworthy experts on an issue, that's another red flag.

Appeals are made in the name of "fairness."

People touting this argument say, "We should just teach kids both sides because there are exactly two sides, in equal proportions," even though there aren't, Rosenau says. In most cases, this appeal is invoked to give false equivalence to a concept like intelligent design, which lacks evidence. If not counteracted, this approach can lend legitimacy to debates without scientific merit, Rosenau says.

How to Stop Shouting:
6 Strategies for Conversing With Someone Who Has Irrational Ideas

When you encounter, say, some neighbors who refuse to vaccinate their children because of long-debunked fears of autism and mercury poisoning, it's tempting to throw facts at them. But — as you know if you've ever tried this approach — bombarding people with evidence is doomed to fail. If you want any chance of engaging in a meaningful conversation, you'll need better tactics. Here are six worth trying. We can't promise they'll work, but they'll give you a fighting chance.

Be a good listener and make a connection.

As much as we'd like to think otherwise, most human judgments aren't based on reason, but on emotion, says Ditto, the UC Irvine psychologist. Aim to forge a personal connection that makes the other person inclined to see you as "one of us." Research by Yale's Kahan has shown that people tend to adopt beliefs associated with their cultural groups. So look for common ground.

That means listening with respect, says Randy Olson, a scientist-turned-filmmaker and author of *Don't Be Such a Scientist*. "Do not lecture. Nobody wants to hear that," he says. Instead of throwing out a bunch of facts, ask questions. Show that you're open to what the other person has to say. "Don't rise above them; approach them at their level," Olson says. The moment you create a divide (by implying that you're smart and they're not, for instance) you've lost the debate. Ultimately, it makes no difference how much evidence you've got. If you want your message to register, you have to speak it in a voice that's trusted and likable, Olson says.

Figure out where they're coming from and devise a frame that speaks to that.

When people cling to irrational beliefs, it's often because they're somehow tied to their identity or social group. Whenever possible, present your argument in a way that fits, rather than challenges, the other person's self-identity, says Julia Galef, co-founder of CFAR. For example, imagine you are trying to convince a friend who thinks of herself as bold and decisive that it's OK to change her mind about an issue on which she'd taken a public stand.

One way to do this, Galef says, would be to frame an about-face as a gutsy and strong move.

Usually it's not an aversion to science that motivates people to tout unscientific ideas, but some underlying cultural, social or personal issue, says Rosenau, of the National Center for Science Education. For instance, he says that many evangelicals he's encountered see evolution as a repudiation of their religious beliefs. As long as they view it that way, they can't endorse evolution without giving up their identity — and they're unlikely to do that, no matter how compelling your facts, Rosenau says. The solution? Find a way to talk about evolution that doesn't force them to abandon their group identity or belief system. "I might say, 'Did you know that [National Institutes of Health Director] Francis Collins is an evangelical Christian?' Then we might have a real conversation and talk about what it means to be a Christian who accepts that evolution is true."

BOOK BACKGROUND: DABOOST/SHUTTERSTOCK

Affirm their self-worth before knocking down their erroneous beliefs.

When your facts challenge people's self-identities, their immediate impulse will be to reject them — that's human nature, says Brendan Nyhan, a political scientist at Dartmouth College. When the thought of giving up a tightly held belief feels like a threat to our identity or world view, we're prone to reject it out of hand.

One way to circumvent this problem is to make the person feel positive about themselves before presenting evidence that might topple their self-image. In one study, Nyhan and his colleagues had volunteers participate in an exercise designed to bolster their feelings of self-worth, such as remembering a time they felt good about themselves or recalling a value that was important to them, before presenting them with information that contradicted their beliefs about political events. The results showed that the self-affirming drills increased participants' willingness to accept uncomfortable facts.

In real life, this might look more like an exchange that happened between my husband and me while we were backpacking. Coming to a fork in the trail, I insisted that we needed to go one way, while Dave was sure the other way was correct. It turned out that he was right, and I knew he was right, but I didn't like what that said about me — that I have a poor sense of direction. This notion contradicts the vision I have of myself as a competent person. But when Dave laughed about it, and told me how funny it was that a smart person like me could get lost, I was suddenly able to accept his facts because they no longer challenged my beliefs about myself. By telling me that I can be a smart person and also get lost, he gave me a way to accept his directions and still feel good about myself.

Focus on the facts, not the misconceptions.

When trying to counteract a myth, a natural response is to present and then debunk it. But tread carefully, says Nyhan. Studies show that repeating a misconception in order to disprove it often ends up reinforcing the erroneous idea in people's minds.

In one study, volunteers viewed a pamphlet debunking myths about flu vaccines. Immediately afterward, people correctly sorted myths from facts, but just a half-hour later, they performed worse on this sorting task than they had before reading the flier. Reading the myths connected them to flu shots in participants' minds, Nyhan says. People remembered reading those things about the flu shot, but over time they forgot which were true and which were false.

Instead of reiterating myths, Nyhan advises finding a simple, truthful message to present. If you overwhelm the person with a long list of complex explanations, you could invoke the so-called overkill backfire effect that drives your target to an explanation that's more appealing.

"A simple myth is more cognitively attractive than an overcomplicated correction," write researchers John Cook and Stephan Lewandowsky in *The Debunking Handbook*.

Ask the person to explain what they know.

People who feel sure of their position set a high bar for contrary evidence, Ditto says, but often such confidence stems from a misperception that they know more than they actually do, a phenomenon researchers call the illusion of explanatory depth. Break this illusion, and the person may become more open to your position, Ditto says.

A study published in the journal *Psychological Science* in 2013 found that when people were asked to explain the details of how a political policy they supported would work, their beliefs on the issue became more moderate. Asking people to explain what's behind their beliefs seems to make them scrutinize what they know, which in turn can force them to recognize the gaps in their knowledge. As a result, they become less sure of their position and possibly more open to what you have to say.

I recently tried this approach with an acquaintance who expressed concern that vaccines would harm her baby. What, exactly, was she worried might happen? Halfway through her attempt at an explanation, she admitted that she wasn't really sure how immunizations would hurt him, but it scared her to give such a young child so many shots at once. She didn't change her mind then and there, but she did agree to read some information I gave her to ease her fears.

Engage in person, not in writing.

It's no secret that people can behave poorly online. When you're having a discussion in the abstract, it's easy to set people off without being conscious of it, since you miss the body language and other social cues that would normally inform your behavior, says Chris Mooney, co-author of *Unscientific America*. "Once the emotions are working, responses are hot rather than cold, and pretty soon everybody's circling wagons," Mooney says. It's more difficult to spiral into mindless rants and name-calling when you're engaging someone face-to-face than when you're arguing with their avatar. If you want to have a real debate, Mooney says, "go have a beer. Don't argue on Facebook." D

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POWERING

Innovative technologies and forward-thinking policies can

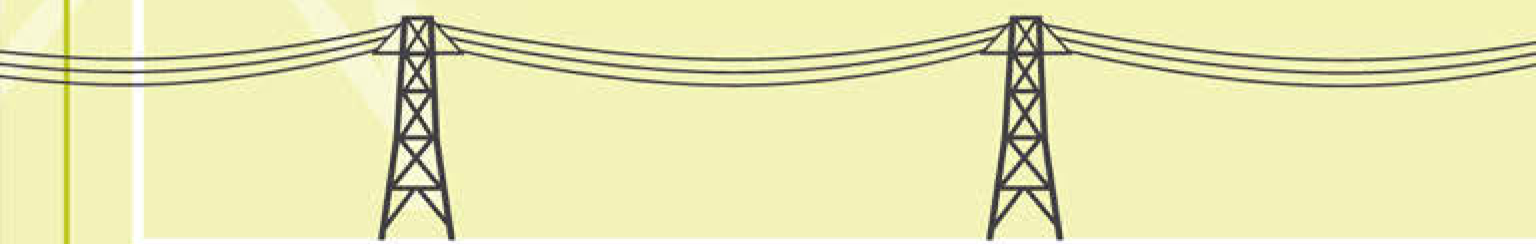
Chances are you're reading these words by the light of fossil fuels. Coal, oil and natural gas still account for 67 percent of energy use in the United States, a figure that sums up the nation's conflicted stance on renewable energy.

Those carbon sources — the decomposed remains of prehistoric plants and animals — fueled an economic, industrial and social renaissance. But powering up came with a steep cost. Since the Industrial Revolution, atmospheric carbon dioxide levels have risen 42 percent. Greenhouse gases have cloaked Earth in an invisible blanket, raising global temperatures. On average, the world is 1.4 degrees Fahrenheit (0.8 degrees Celsius) warmer today than it was in 1880, and climatologists say temperatures could increase by 5.6 to 7.2 F (3 to 4 C) by 2100.

That may not sound like much, but climate scientists warn if we don't snuff the smokestacks and tailpipes, our world will be transformed in ways humanity has never witnessed. Rising sea levels will swamp coastal cities. Forests will die. Hurricanes will intensify. Droughts and floods will become the norm. Some of these changes are already evident, from the rising tides in Micronesia to the shrinking glaciers of Glacier National Park.

But there is some good news. If we can rein in emissions enough to keep global average temperatures from rising 2 C (3.6 F), we can avert the biggest shocks to Earth's system, scientists say. We still have time, but not much. Carbon emissions around the world will need to

ARMA BANCHANG/SHUTTERSTOCK



THE FUTURE

help light the way to a low-carbon world.

plummet over the coming decades, and sputter out completely by the end of the century.

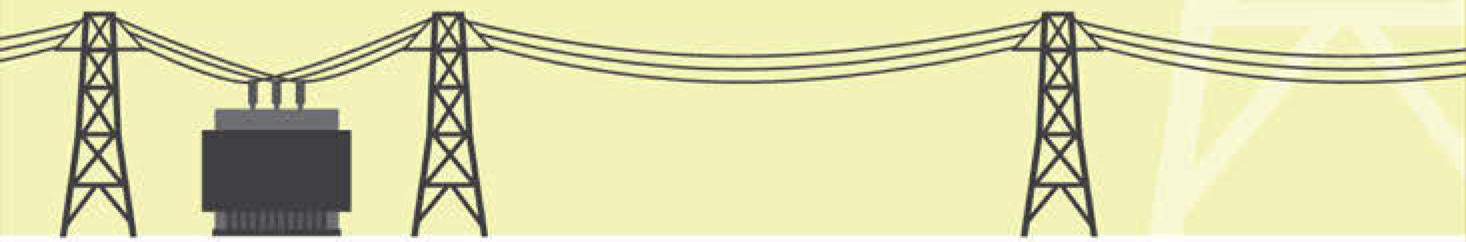
"If you want a stable climate, you have to bring emissions to zero," says David Keith, a physicist and public policy expert at Harvard University.

A major test of the world's willingness to phase out greenhouse gases will arrive in December, when nations gather in Paris to try to agree on what to do about climate change. The aim is for countries to commit to meaningful emission cuts and kick off a global deployment of low-carbon technologies.

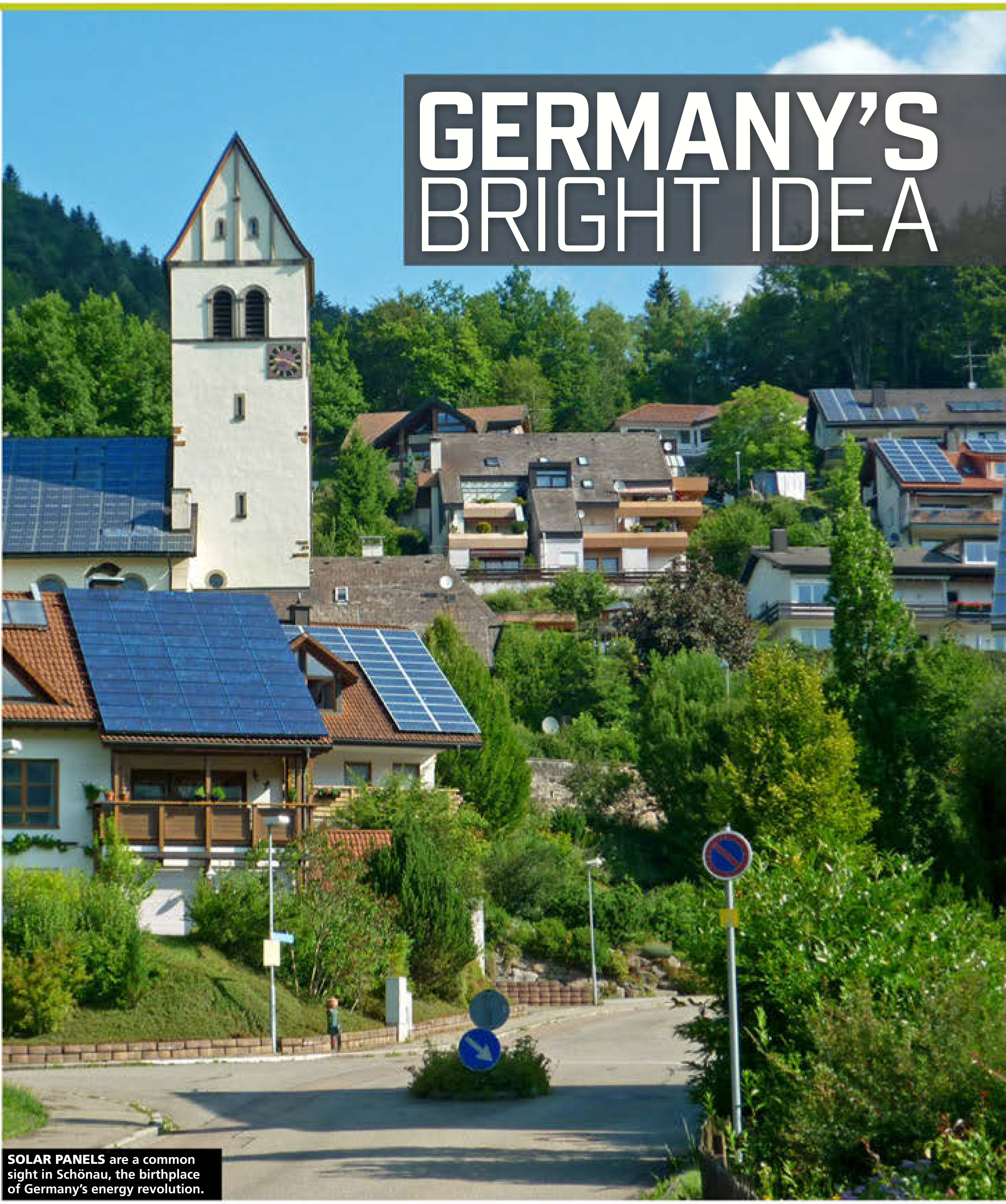
Technology is no silver bullet, yet it's an essential part of the decarbonization equation. Technological innovation allowed us to tap carbon fuels deep underground hundreds of years ago; now we need it to reinvent the energy system those fuels created.

In this special section, you'll discover some of the more promising ways to keep the climate cauldron from boiling over. You'll see how two different countries are transitioning to clean energy, and you'll get a peek at some innovative and practical energy technologies, from low tech (gravity) to high tech (space solar). Together, these innovations can help illuminate a path to a low-carbon future. — APRIL REESE

How much do you know about energy? Test your energy IQ and weigh in on how to power the future at **DiscoverMagazine.com/Energy**



GERMANY'S BRIGHT IDEA



SOLAR PANELS are a common sight in Schönau, the birthplace of Germany's energy revolution.

Thirty years ago, a mountain village sparked a national energy revolution. Now, the political and technological movement may face its greatest challenge yet.

BY **OSHA GRAY DAVIDSON**

Schönau im Schwarzwald, Germany — Coming off the twisting mountain road that cuts through the heart of the Black Forest, the village of Schönau looks like something out of Grimm's fairy tales. Small shops and rustic beer gardens line narrow streets built for horses and foot traffic. Dairy cattle, a rare variety bred here centuries ago to be as sure-footed as mountain goats, graze on steep-pitched pastures high above the village. From the highway north of town, Schönau appears much as it did in the 12th century.

Viewed from the south, however, Schönau looks quite different. The sun glints blue off thousands of rooftop photovoltaic (PV) panels — small, grid-connected power plants owned by residents. The panels generate more electricity on sunny days than the village of 2,500 people consumes. If the bucolic view from the north is a reminder of the past, the second one, says Schönau resident Ursula Sladek, is a hopeful vision of the future, of a society transformed.

"With something new, a few people must always go first," Sladek says through an interpreter. "The others come afterward." She leans forward and stage-whispers in English: "But only if it works."

If you ran into Sladek at the local Aldi grocery store, the word *revolutionary* would probably not come to mind. In her late 60s, with piercing blue eyes and straight gray hair, Sladek looks like the grandmother and former schoolteacher she is. But in the mid-1980s, in the wake of the Chernobyl nuclear power-plant disaster, she spearheaded a local movement to achieve what she considered a reasonable, even modest, goal: that Schönau residents should decide how their electricity is generated.

Sladek and her neighbors didn't know it at the time, but their battle with the local utility — and their challenge of the conventional wisdom about how an energy system should run — would become part of a nationwide technological and political movement called the *Energiewende*, or Energy Revolution. The Energiewende aims to abandon nuclear power and nearly eliminate fossil fuels as an energy source in Germany, the world's fourth-largest industrial economy, with a population of 80 million. Nearly three decades after Schönau's energy upset, about a quarter of the country's power comes from renewable sources like wind, solar and biomass, the highest percentage of any large industrialized nation. By comparison, the United States gets just 13 percent of its electricity from renewables. Almost 25,000 wind turbines dot the German countryside, producing 52 terawatt-hours (TWh) of electricity in 2014, enough to power the entire country of Colombia. (A terawatt-hour equals 1 million megawatt-hours.) More than a million rooftop solar systems, including those in Schönau, add another 30 TWh to the German grid.

The ENERGIEWENDE, or Energy Revolution, aims to nearly eliminate fossil fuels and nuclear power as energy sources in Germany.

The Energiewende also has sparked enough technological innovations to fill a patent office. Thanks to hundreds of improvements in fields from mechanical design to material sciences to electrical engineering, the average wind turbine installed in Germany in 2014 generates six times as much electricity as those from 1990. Building facades made of solar panels are popping up across the country. In many basements, combined heat and power units burn biofuels or natural gas to generate electricity and capture what was once considered waste heat to keep homes warm through the long German winter.

But for all its achievements, the Energiewende is in danger of losing its way, critics say. They point to a slowdown in the reduction of greenhouse gases, a potential decline in industries that still rely on nuclear power and fears about the grid's ability to handle ever higher levels of power from small, decentralized renewable sources. Even some supporters are concerned. Andrea Lindlohr, a rising star in the Green Party, puts the problem this way: "Germany *can* do it. The technological hurdles can be overcome. But I'm not sure if Germany *will* do it because that depends on politics."

SVEN EBERLEIN

THE ELECTRICITY REBELS

To understand the Energiewende's future prospects, it helps to know a bit about its past.

In late April 1986, Sladek was hobbling around her home with a broken leg, the result of a skiing accident, when she heard a news report about an explosion at a Soviet nuclear power plant. German officials assured the public there was nothing to worry about. "Chernobyl is 2,000 kilometers away," Germany's interior minister told the nation. "There is no danger."

He was wrong. The next day, radioactive particles from the catastrophic explosion at Chernobyl began falling on Schönau. Sladek and the other residents were warned to stay indoors.

In the months after the disaster, Sladek and her neighbors decided that it made no sense to continue relying on power generated by nuclear plants. They asked the regional power company to divest from nuclear. It refused.

"At first we just wanted to make sure this never happened again," Sladek says. "Then we realized that the only way to be sure was to take things into our own hands."

At the time, what Sladek knew about electricity didn't go much beyond changing a light bulb. Over the next several years, Sladek and her allies learned about power generators and the grid — that mind-numbingly complex web of wires, power substations and transformers.

The German grid, like the one in the U.S., was designed more than a century ago around a simple organizing principle: Electricity generated by a few massive power plants needs to be delivered to millions of users, large and small, across an entire region. That centralized system, with power moving in one direction from plant to user, worked well enough as long as there was a dependable amount of electricity to meet demand at any given moment (called baseload). Sladek's proposal would flip this model on its head. Renewable sources — such as rooftop solar panels, which sometimes generate more power than a household uses — required a decentralized system in which electricity flows in *both* directions, from many small generators into the grid, and from the grid to consumers. And the system had to be flexible enough to handle wildly varying power loads.

Renewable sources require a DECENTRALIZED system in which electricity flows in *both* directions: from many small generators into the grid, and from the grid to consumers.

THE CHERNOBYL NUCLEAR PLANT explosion in 1986 sparked a backlash against nuclear power in Germany.

Solar and wind power generate electricity only when the sun shines or the wind blows — a characteristic that's called "undependable" if you're an opponent of renewables, or "variable" if you're a supporter. Before real change could come, researchers would need to develop new technologies to improve renewable energy's integration into the electricity mix.

URSULA SLADEK

The Schönau group also would have to navigate an even more complex web: the countless regulations that would need to be revised to allow the shift from a centralized system to a decentralized one. Schönau's push for what's called *BürgerEnergie* — energy produced by citizens — meant challenging the interests of the powerful electrical utilities that were content with the monopolistic and highly lucrative status quo.

"Perhaps it was good we didn't know what we were getting into back then," Sladek admits with a smile.

The Schönau residents came up with an ambitious plan: to buy their local grid and run it themselves. They began with a campaign to raise $2.4 million, the amount they believed was required to purchase the system. The owners responded by claiming the grid was worth at least $5.2 million. (A judge later put the fair market value at $2.2 million.) By the early 1990s, the David-and-Goliath battle was on and soon drew the attention of the national media. A reporter dubbed the Schönau group the *Stromrebellen*, the electricity rebels. The name stuck.

At the end of it all, the rebels prevailed, and they had a new name: Elektrizitätswerke Schönau (EWS), the Schönau Electric Power Co., with Sladek as its president. By 1996, through a local network of solar panels and small hydroelectric dams, EWS supplied "green" power to

HANS-JOSEF FELL

the entire village.

The Stromrebellen was a major victory, but it was an isolated one. Not every town could afford to buy its grid even if it wanted to. And generating electricity from solar panels remained wildly expensive, with the solar modules priced at nearly $7 a watt in 1996 — a victim of what Germans call the "devil's circle." Without economies of scale, in which mass production drives down cost, few could afford solar panels. But lacking sufficient demand, no solar manufacturer would ramp up production enough to lower prices. Without a new approach, the Energiewende would remain a green fairy tale set deep in the Black Forest.

BAVARIA'S BIG IDEA

In 1993, while Sladek was still battling for control of the local grid, some 200 miles to the northeast in Bavaria, Hans-Josef Fell was orchestrating a different kind of energy overhaul as a member of the town council of Hammelburg (population 12,000), his hometown. A physicist by training, a science teacher by vocation and an environmental and peace activist, Fell was intrigued by all facets of renewable power. He was convinced early on that solar and wind power presented an alternative — not just to fossil fuels and nuclear power, but to wars over oil and to the potential for nuclear conflict.

As a local politician, Fell drafted legislation to encourage the use of renewables in Hammelburg using a feed-in tariff, or FiT. Under the system, residents who installed solar panels received an above-market price for each kilowatt-hour of electricity they supplied to the grid. The amount of the incentive was designed to fully compensate the owners for the cost of their solar installation and, crucially, a little bit more.

Fell may have been a bearded, longhaired *Ökofreak* (ecofreak), but he understood that most Germans weren't — especially in deeply conservative Bavaria, where the right-wing Christian Social Union (CSU) had governed almost continuously since 1946. Fell knew he couldn't sell an energy revolution to his fellow Bavarians by quoting Gandhi, so he channeled Adam Smith instead.

"You must make the FiT high enough so that the profit is possible," Fell says, explaining his thinking at the time. "And you must guarantee the FiT for 20 years so that it will be a secure investment."

Bavaria and BürgerEnergie went together like sauerbraten und Pilsner. That's partly because Bavarians are equally opposed to market-skewing big government and monopolistic businesses, on the grounds that both stifle competition. Take Josef Göppel. He's a leader of the conservative CSU, but when he talks about the Energiewende, he sounds more like Michael Moore.

"The reason that so many Germans are interested in pursuing renewable energy is a simple one," Göppel once told a reporter. "It is the desire for independence from big companies."

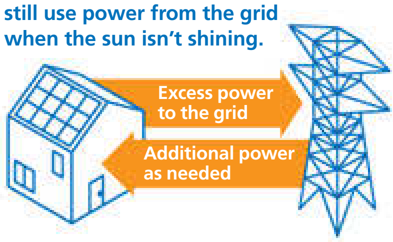
Hammelburg's FiT applied only to the first 15 kilowatts of solar panels installed on local roofs, a size that Fell today calls "ridiculously small." But Fell's law was a test run, the first of its kind in the world. And it succeeded: The 15-kilowatt cap was quickly reached, and residents who didn't act fast enough were left clamoring to get in on the action.

Other towns followed suit, but like Schönau's Stromrebellen, the impact of the Hammelburg experiment was primarily local. It was time to up the ante. The movement got its chance to go national in 1998, when Bavarians sent Fell to Berlin to represent them in the German national parliament. The very next year, party leaders tapped Fell, a member of the Green Party, to draft a new German energy policy that put renewables front and center. He had his work cut out for him: For years, opponents had questioned the grid's ability to handle large amounts of electricity generated by renewable sources. Above 4 percent of total generation, experts cautioned, the grid would disintegrate, plunging cities into freezing darkness and destroying the bulwark of the German economy — its energy-intensive manufacturing sector.

Fell was eager to prove the naysayers wrong. He knew his first task was breaking the devil's circle. Fell's solution was the Renewable Energy Sources Act

Feed-in Tariff (FiT)

Under a FiT system, homeowners with solar panels are paid for the extra power they generate. They can still use power from the grid when the sun isn't shining.



STEFAN KIEFER/IMAGEBROKER/CORBIS

(EEG), adopted in 2000. The new law created a national FiT (paid for by a monthly surcharge added to utility bills) to encourage mass deployment of renewables. It also aimed to cut emissions of greenhouse gases. The next year, lawmakers mandated a nuclear phaseout.

The EEG was a major victory, but many supporters wondered if its goals — particularly its renewables target — might be unrealistic. Before the EEG, just 2.6 percent of the country's electricity was generated by renewables — virtually the same meager amount as in the United States. As a top utility executive later put it, "[The Energiewende] is a political wish that is without a realistic view of what is achievable."

To everyone's surprise, however, the Energiewende proceeded according to Fell's plan. Germans jumped at the opportunity to fight climate change, phase out nuclear power, make a profit and free themselves from the "Big Four" utilities. In 2002, after just two years of the EEG law, the share of renewable power on the German grid doubled to 5 percent, far ahead of schedule and without any cities going dark. By 2007, renewables claimed 10 percent of the grid — more than twice the amount predicted to crash it. And even without goals for citizen power, 50 percent of all renewable generation came from ordinary citizens. The Big Four's share was just 6.5 percent.

While the utilities ignored the Energiewende, the FiT was transforming the devil's circle into a virtuous one. To keep up with German demand, manufacturers around the globe ramped up production of solar panels, causing the price of going solar to plummet worldwide. Solar modules that cost $3 per watt in 2000 sold for half the price in 2010. The price of a rooftop system in Germany that went for $23,000 in 1990 had plummeted to $2,200 by 2013.

To keep up with German demand, manufacturers around the globe ramped up production of solar panels, causing the PRICE of GOING SOLAR to PLUMMET worldwide.

Market competition spurred researchers to squeeze every last electron they could from the 1,000 watts of solar energy falling on each square meter of the planet's surface. When the EEG was passed in 2000, the most efficient PV cells converted about 30 percent of solar radiation to electricity. Today, PV cells can achieve efficiency rates over 44 percent by combining layers of different elements (gallium, germanium and indium, among others) that together generate electricity from across the spectrum, from ultraviolet to infrared radiation.

As renewable generation increased, supporters amended the EEG to increase its renewables targets: up to 12 percent by 2010 and 80 percent by 2050. Skeptics merely upped their estimate for when the sky would fall. German Chancellor Angela Merkel cautioned that "the share of renewable energies in electricity consumption to a 20 percent increase is not very realistic."

BAVARIAN ROOFTOPS collect the sun's energy with solar panels. Germany leads the world in installed solar capacity (see graph).

Merkel's 20 percent threshold was reached and then surpassed, however, and new BMWs and little bottles of Bayer aspirin continued rolling off German assembly lines, *eins* ... *zwei* ... *drei*, without interruption.

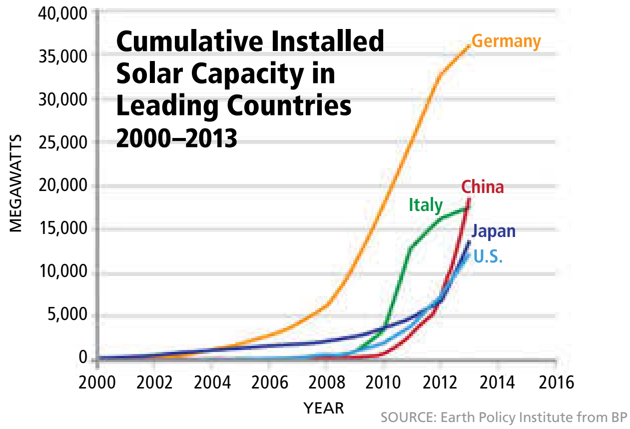
But the critics aren't entirely wrong. The Energiewende does face some hard choices — and they're coming up fast.

TECH CITY

Stuttgart, in southwestern Germany, has long been synonymous with industry. Sometimes called the Original Motor City, Stuttgart is the birthplace of the automobile. Many of the area's 1 million workers are employed by the giant automakers headquartered here, including Mercedes-Benz and Porsche. Despite its deep fossil-fuel roots, Stuttgart is speeding into the energy future. The center of engineering innovation in Europe, the Stuttgart area spends a greater percentage of its gross domestic product on research and development than anywhere in Germany. It leads the nation in patent applications because of the high concentration of high-tech research institutes, including the Center for Solar Energy and Hydrogen Research (ZSW).

ZSW's managing director, Frithjof Staiss, has spent his adult life studying the promise — and challenges — of a renewable energy economy. For Staiss, the Energiewende marks a historical and technological divide.

"In the old world, you delivered power from a big utility to the small user," Staiss says, sitting in his utilitarian but comfortable third-floor office on Stuttgart's *Industriestrasse* (Industry Street). "Now the consumer at

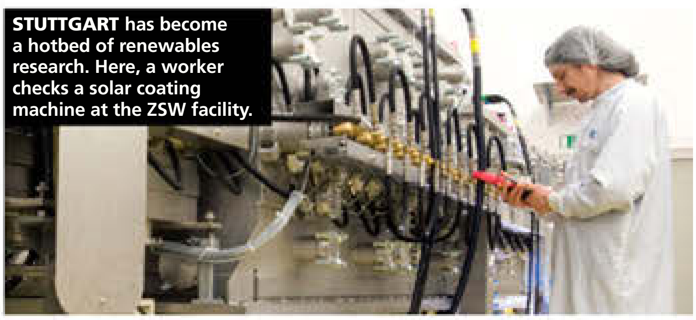


the end of the line adds PV. That changes things." Power that flows both to and from homes with solar panels, and that dips and surges depending on cloud cover and wind speed, requires a more flexible system.

One of the most important changes needed, Staiss says, is an overhaul of the German grid. Its 557,000 small transformers were intended for power that flowed in only one direction. As part of the Energiewende, German engineers have developed bidirectional transformers to replace the existing ones, as well as a host of other technological innovations to meet the new demands of an influx of renewable energy, says Maike Schmidt, head of ZSW's Department of Systems Analysis. Superconducting cables minimize energy loss, and power-to-gas systems store excess electrical generation as hydrogen or methane.

"In a country like Germany, we need these innovative developments to sell to other countries," she says. "That is our core business. The Energiewende is an opportunity to have more innovation and sell it to the world." German businesses are making the most of that opportunity, with exports of renewable energy technologies totaling $30 billion in 2013.

Even industrial giant Siemens, which built Germany's first nuclear power plant, has been transformed by the Energiewende. In September 2011, the company that helped build all 19 of Germany's nuclear power plants announced it was exiting the business completely.

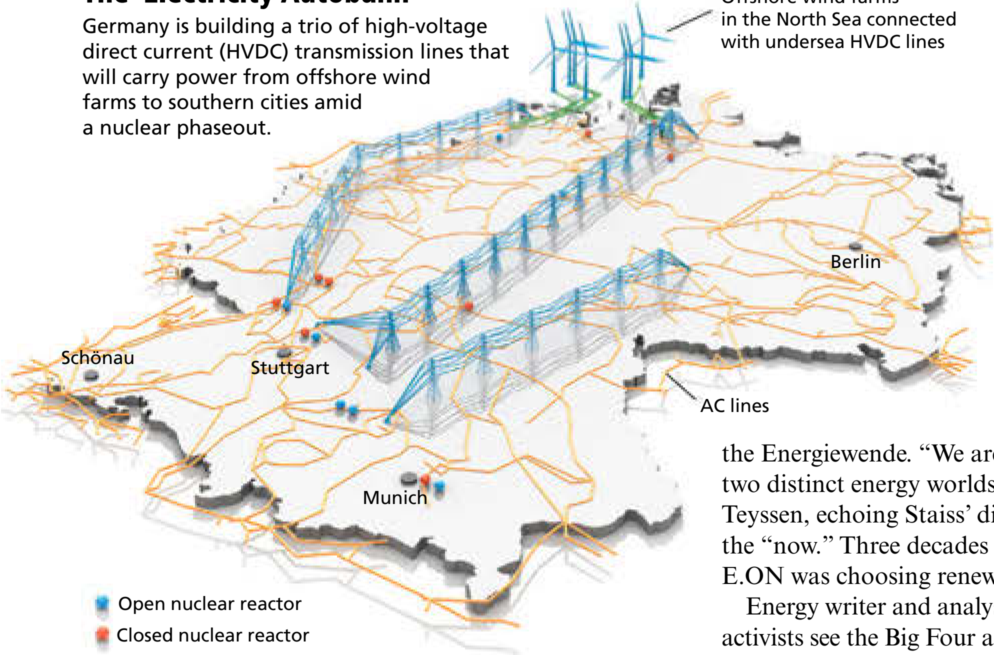


STUTTGART has become a hotbed of renewables research. Here, a worker checks a solar coating machine at the ZSW facility.

TOP: ALISON MACKEY/DISCOVER AFTER EARTH POLICY INSTITUTE FROM BP. BOTTOM: ZSW

The 'Electricity Autobahn'

Germany is building a trio of high-voltage direct current (HVDC) transmission lines that will carry power from offshore wind farms to southern cities amid a nuclear phaseout.



Siemens turned its attention to the lucrative global offshore wind-power market, predicted to reach $142 billion a year by 2020. Three months after its nuclear exit, the company announced plans to install 80 giant wind turbines in the North Sea, enough to power 300,000 households and cut carbon emissions by 815,000 tons a year.

With the last German reactor scheduled to close down in 2022, the south, which has depended on nuclear reactors for nearly half its electricity, desperately needs that power. It stands to benefit greatly from the next phase in the Energiewende, which involves building an "Electricity Autobahn" — a trio of high-voltage direct current transmission lines (HVDC) spanning 2,000 miles to carry huge amounts of electricity from offshore wind farms in the North Sea down to the heart of Germany's manufacturing region.

As the Energiewende has gained momentum, it has become a MODEL for OTHER COUNTRIES.

The undertaking, estimated to cost $22 billion, is controversial. Economist Claudia Kemfert points out there's plenty of sun and enough wind to greatly expand renewable generation in the south. And two of the three HVDC lines, she adds, will carry electricity from polluting coal-burning plants, which is at odds with the objectives of the Energiewende.

Some also see the Electricity Autobahn as a threat to community energy and democratization. A government-created FiT will pay for power from offshore wind at rates more than double that paid for onshore projects.

Faced with a shrinking market share and dwindling profits, the Big Four utilities are waking up from their fossil fuel-induced slumber. Last November, one of Germany's largest utilities, E.ON, stunned energy watchers by announcing a shift toward clean energy and acknowledging that its old business model "can no longer properly address these new challenges" brought on by the Energiewende. "We are seeing the emergence of two distinct energy worlds," says E.ON CEO Johannes Teyssen, echoing Staiss' division of the "old world" and the "now." Three decades after Schönau's Stromrebellen, E.ON was choosing renewables.

Energy writer and analyst Craig Morris says many activists see the Big Four as interlopers trying to hijack a revolution they first ignored and then opposed. "The grass-roots movements see the corporations as saying, 'Excuse me, but I'll have that energy sector back,'" now that proponents have made the Energiewende work, he says.

That success is especially evident in Schönau, where Sladek's EWS is now the primary power provider for 170,000 households in every German state. Customers anywhere in Germany can choose EWS as their utility and pay for power EWS purchases from green energy generators throughout the country. That model could be challenged, however, if the energy landscape is once again dominated by powerful utilities.

A U.S. ENERGIEWENDE?

As the Energiewende has gained momentum, it has become a model for other countries; more than 50 have copied the FiT alone. But as energy expert John Farrell notes, neither the FiT nor any of the Energiewende's other elements has been widely adopted in the U.S. Farrell, with the Minnesota-based Institute for Local Self-Reliance, has spent years designing and promoting an Energiewende for the United States, earning him a reputation as the "guru of distributed generation" in the U.S.

A host of differences between Germany and the U.S. makes an energy revolution more challenging here, he says. With a population density one-sixth that of Germany, the U.S. grid must traverse tremendous distances to bring electricity to its people and industries.

BRYAN CHRISTIE DESIGN

OFFSHORE WIND FARMS, like this new Siemens project, are expanding in the North Sea, off Germany's northwest coast. But the large pulses of intermittent power they generate are not easy to integrate into the grid.

Most Americans can't pick power suppliers based on their use of green energy, or anything else for that matter — with a handful of exceptions, utilities operate as legal monopolies. And while Germany is phasing out nuclear power, five new reactors are under construction in the U.S., adding to its existing fleet of 99 commercial reactors. Unlike Germany, the U.S. has vast deposits of fossil fuels owned by powerful corporations. Partly because of that drive to keep drawing greenhouse gas-producing fuels from the ground, the U.S. lags far behind Germany in the share of electricity generated from renewable sources.

That's especially unfortunate, Farrell says, because the U.S. has everything it needs for an energy transformation, including a surfeit of untapped solar, wind and other renewable resources that far outstrip Germany's. A study by the National Renewable Energy Laboratory concluded that fully 80 percent of electricity could come from renewables by 2050.

The U.S. is ahead of Germany in another crucial area: developing low-cost, efficient energy storage. Researchers at Harvard, for example, are perfecting an organic flow battery that can store a full day's production of electricity from solar or wind farms, a development that could play a key role in integrating variable electrical generating sources into the grid.

NUCLEAR POWER has attracted new interest in the U.S. Two reactors under construction near Waynesboro, Ga., will be the first built here in 30 years.

TOP: SIEMENS AG/TENNET. BOTTOM: GEORGIA POWER

Given these advantages in resources and technology, Farrell says there's only one thing holding the U.S. back: political will. "We need to design a system for the 21st century," he says. "Germany has given us a great example of what's possible when people have a vision."

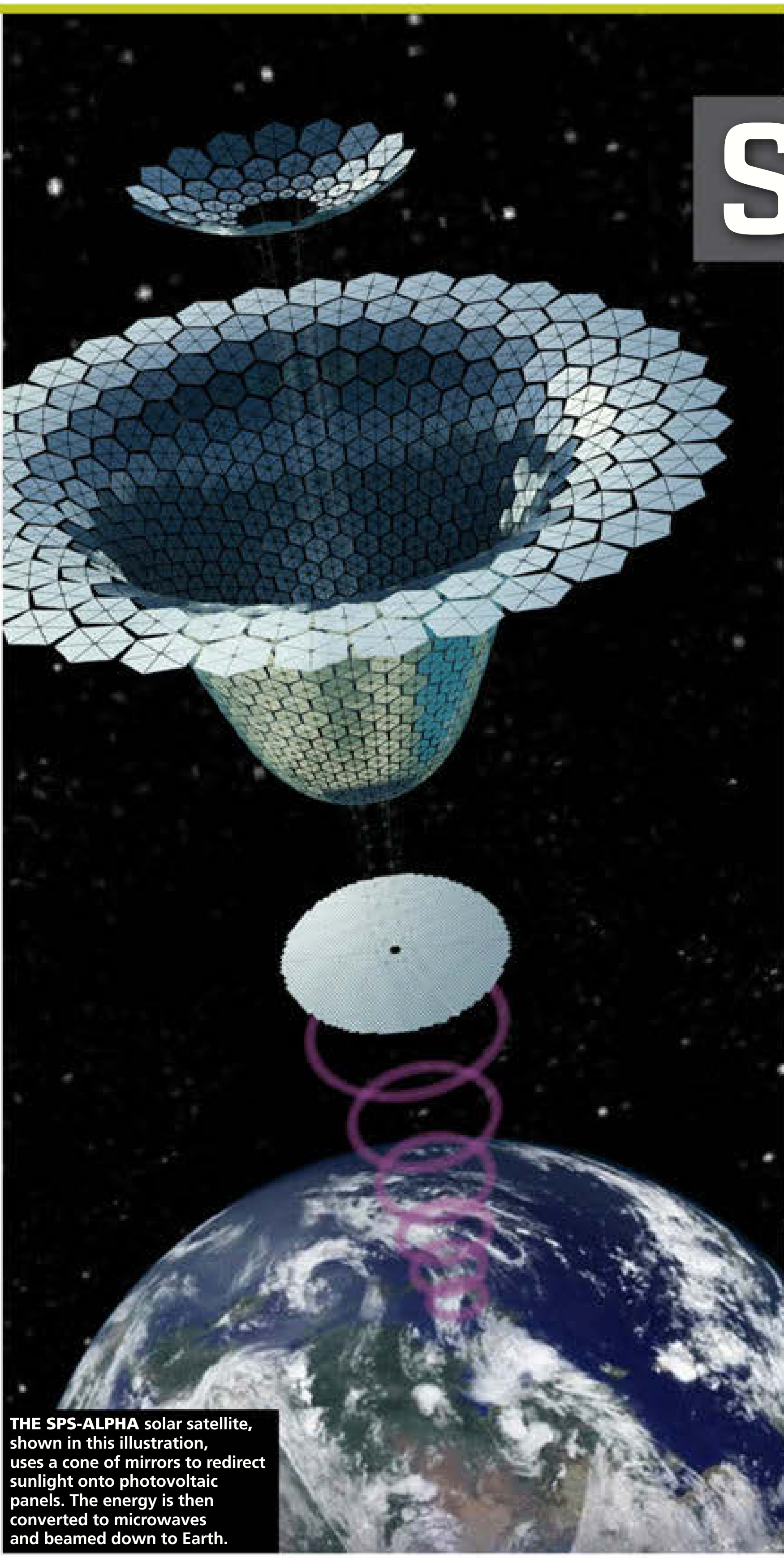
More specifically, Germany is an example of what's possible when people stick with a vision. The Energiewende has its roots in an American energy revolution that began under President Jimmy Carter. In February 1977, two weeks after taking office, Carter urged Americans to turn down their thermostats and announced a plan to move the U.S. away from fossil fuels and toward a system based on solar and other renewable energy sources. Carter installed solar thermal panels on the White House roof and pumped millions in R&D into alternative energy development.

For a few years, the U.S. led the world in developing renewable energy. But after Ronald Reagan defeated Carter in 1979, America made an abrupt U-turn. In the next few years, the White House's solar panels were removed, fossil fuel prices dropped, and federal support for renewable energy dried up.

The U.S. may have lost its vision of a renewable energy future, but an ocean away, Hans-Josef Fell and others were inspired by America's flirtation with renewable energy.

"There was wind power in California and solar power on the White House," Fell recalls. "I thought, 'Oh, this is wonderful! Why can't we have this in Germany?' " He smiles and adds, "And, of course, now we do." D

***Osha Gray Davidson** is a freelance writer based in Phoenix.*



THE SPS-ALPHA solar satellite, shown in this illustration, uses a cone of mirrors to redirect sunlight onto photovoltaic panels. The energy is then converted to microwaves and beamed down to Earth.

SPS-ALPHA CONCEPT/JOHN C. MANKINS

STELLAR

BY **W. WAYT GIBBS**

Nowhere on Earth does the sun shine as brightly as it does in geosynchronous orbit, that parking space 22,236 miles up where a satellite can keep a spot on Earth in steady view all day, every day.

Placed high above the gauzy atmosphere, solar panels can intercept rays 35 to 70 percent more intense than midday sunlight on the ground. In high orbit, there is no cloud cover, no twilight, no wan winter sun. And a cleverly designed and positioned solar satellite can avoid the shadow of night for all but 44 hours a year, so there is no need to store energy to keep the electrons flowing almost continuously.

All told, an advanced photovoltaic cell in space can deliver up to 40 times the annual amount of reliable 24/7 energy that the same cell would generate on the ground. It's not solar power so much as it is stellar power.

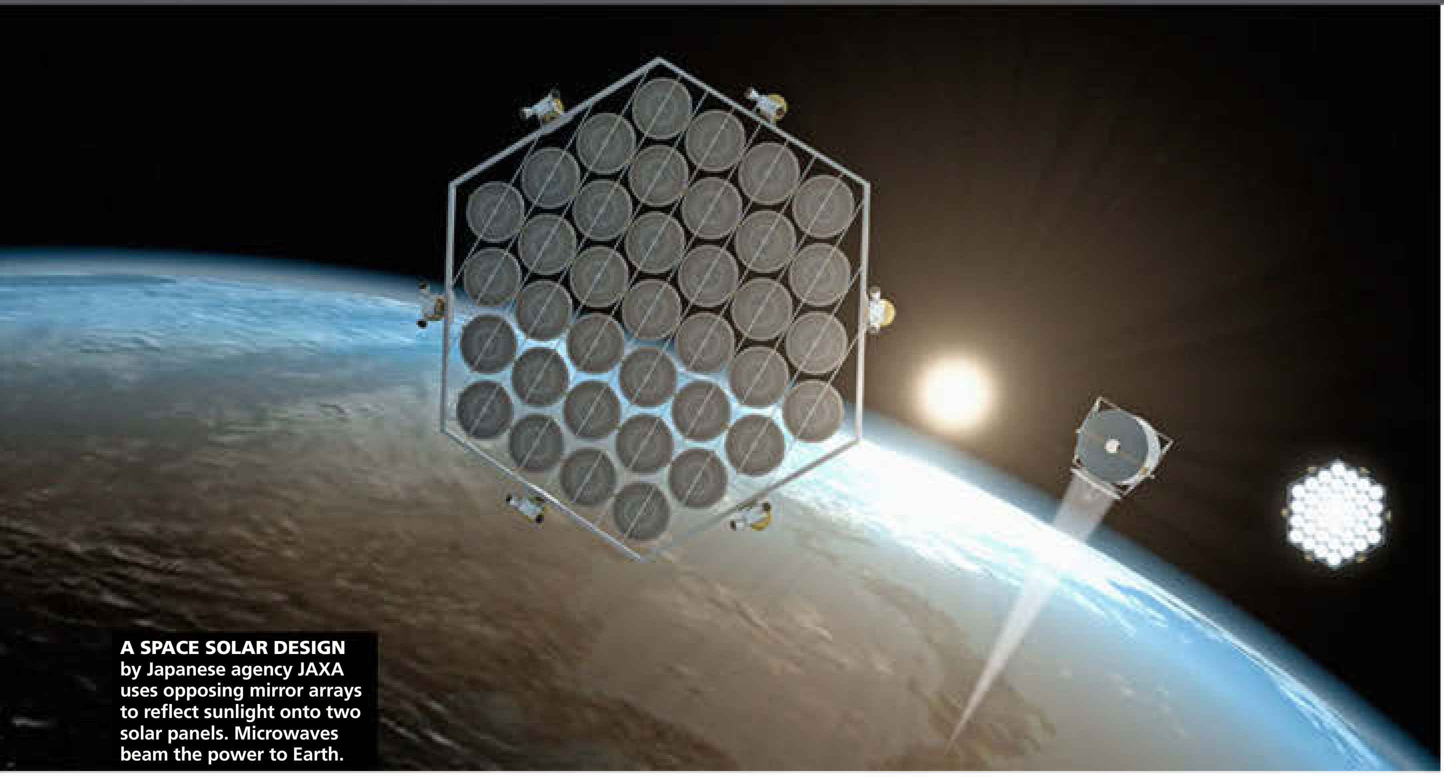
Dreamy-eyed physicists have effused about the potential of stellar power, also known by the more prosaic name of space-based solar power, or SBSP, since the 1960s. They have sketched out preliminary designs that would bring that power from orbit to the grid — a giant engineering challenge, to be sure, but one that now has plausible solutions. What they haven't been able to do is make it affordable.

Now that stumbling block may be cleared as well. Stellar power entrepreneurs are reporting flickers of interest among private investors and potential customers.

Space scientists have roughed out designs for several different kinds of

ENERGY

Solar satellites could deliver clean, abundant power — if they get off the ground.



A SPACE SOLAR DESIGN by Japanese agency JAXA uses opposing mirror arrays to reflect sunlight onto two solar panels. Microwaves beam the power to Earth.

JOHN MACNEILL

stellar power plants. Some look like an orbiting version of a terrestrial solar farm, with flat photovoltaic arrays stretching for miles. A design for NASA called SPS-Alpha, by former NASA physicist John Mankins, instead arranges thin-film mirrors into a bell shape that can redirect sunlight from almost any angle onto a smaller photovoltaic array.

The electrical current generated by an orbiting array can be sent to Earth in one of two forms. It could be converted into a broad infrared laser beam, or it could come down as a wider cone of microwaves, which, as Mankins notes, pass through clouds unimpeded. In either case, the satellite would focus its transmitter on a large receiving station on the ground. (See next page.) To ensure safety, the beam would be no more intense than the noonday sun, and a feedback signal would keep it from straying from its target.

As Mankins points out in his 2014 book *The Case for Space Solar Power*, the orbiting plants would tap an essentially limitless supply of free fuel. After they are launched, their only waste stream would be heat, which poses tricky technical issues but not environmental ones. And a solar plant in space would need far less routine maintenance than one on the ground. Although commercial-scale power satellites would be huge and hard to build in orbit — with assembly done mainly by robots — they would have hardly any moving parts and could last for generations.

Placed high above the gauzy atmosphere, solar panels can intercept rays 35% to 70% MORE INTENSE than midday sunlight on the ground.

NASA, the U.S. departments of Energy and Defense, the European Space Agency, the Japanese Aerospace Exploration Agency (JAXA), a handful of companies and a gaggle of academic scientists all have taken hard looks at stellar power technology, and they concluded that, from a technical point of view, it is feasible.

Yet one obstacle has seemed insurmountable: the cost to get up to

10,000 tons of components all the way to geosynchronous orbit. Rockets today are not reusable, and that makes them so expensive — currently around $4,600 for each kilogram of payload lofted into low orbits — that the economics of putting solar modules in space just don't pencil out, even if the modules use solar-electric propulsion to lift themselves into their final orbit. For stellar power to compete with other kinds of renewable energy, those costs need to drop to around $400 a kilogram, Mankins estimates. Rocket launches would have to become a lot more frequent as well. Building a large plant would require hundreds of launches a year.

ROCKET LAUNCH COSTS need to fall for space solar to get off the ground.

A tenfold drop in price and a manyfold increase in launch frequency might seem like wishful thinking. But SpaceX, a private company whose Falcon rockets now resupply the International Space Station, recently announced ambitious plans to make that happen. The company has designed a reusable booster that it believes can return to Earth, land gently on its feet and take off again within weeks. Elon Musk, the company's audacious billionaire founder, has said that when rockets can be reused like airplanes, launch costs will fall by up to 99 percent.

The first attempt to land a Falcon after it delivered its payload to orbit, in January, ended in a near miss and an explosion. But in a more recent test in April, the rocket returned upright to the correct coordinates. (It landed, but then toppled over in high winds.) Musk has vowed to perfect the process.

He apparently has set his sights on near-daily launches, too. That is key to his plan, announced in January, to enrobe the planet with 4,000 communications satellites — more than triple the number of satellites now in orbit — starting around 2020. Musk has shown little interest in space-based solar power; his goal is to rebuild the backbone of the Internet in space. But if SpaceX succeeds with its reusable rockets and ramps up its launch rate as planned, it "could reduce launch costs enough to make SBSP cost-competitive," says Susumu Sasaki, a veteran of JAXA's stellar power program.

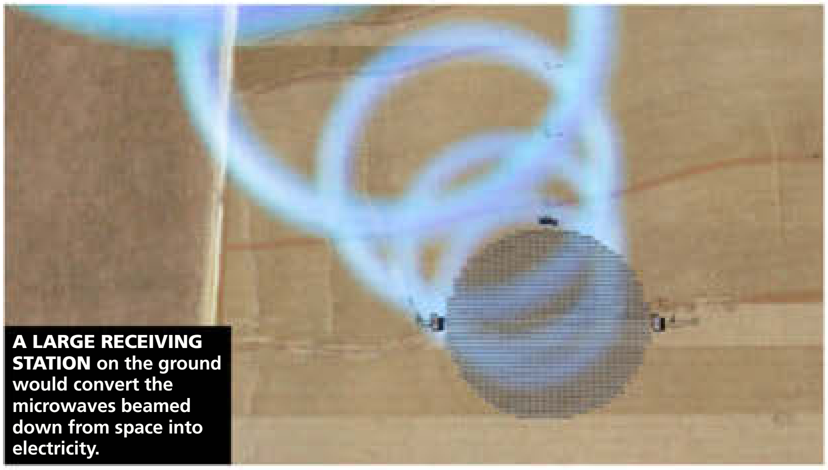
Lower launch costs are one necessary step, but investors will not place big bets on an unproven technology unless it can deliver quick profits, contends Marty Hoffert, an emeritus professor of physics at New York University who has long championed stellar power. "You still need an evolutionary path, with upfront costs that seem manageable, and where you can see a business plan emerging," Hoffert says.

Recent history gives investors reason to be cautious. In 2009, a startup called Solaren won a much-publicized contract to supply the biggest utility in California with 200 megawatts of power from space starting in 2016. Space Energy, another startup, also generated a lot of buzz around that time. But both firms failed to meet their ambitious timelines and have fallen silent.

Mankins, the SPS-Alpha designer, is optimistic, however. He believes he has a business plan that can fly: integrating space-based solar and communications capabilities. These would not be the low-flying satellites that Musk plans to field, but geosynchronous ones that get launched every year to relay TV, radio and telephone signals.

"We could make a very small version of SPS-Alpha and slightly modify the transmitter before launch to send radio signals rather than a microwave beam. Then the power station becomes a high-power communications satellite" with potentially megawatts at its disposal, he says. It could offer 10 to 50 times more bandwidth, thereby generating more revenue, yet cost little more than a standard satellite, he says. Mankins has lined up investors and recently launched a startup that will to try to sell the idea to customers like DirecTV or Verizon.

Such next-gen satellites would provide both funding and real engineering experience to develop space-based solar energy further. That might seem like a small step for global energy production, but it would be a giant leap for stellar power. **D**



A LARGE RECEIVING STATION on the ground would convert the microwaves beamed down from space into electricity.

__W. Wayt Gibbs__ is a freelance science writer based in Seattle.

TOP: SPACEX. BOTTOM: MAFIC STUDIOS INC.

GEOTHERMAL'S CO_2 BOOST

BY **XIAOZHI LIM**

In the war against climate change, carbon dioxide is the enemy. But when used to boost geothermal energy, it can be an ally.

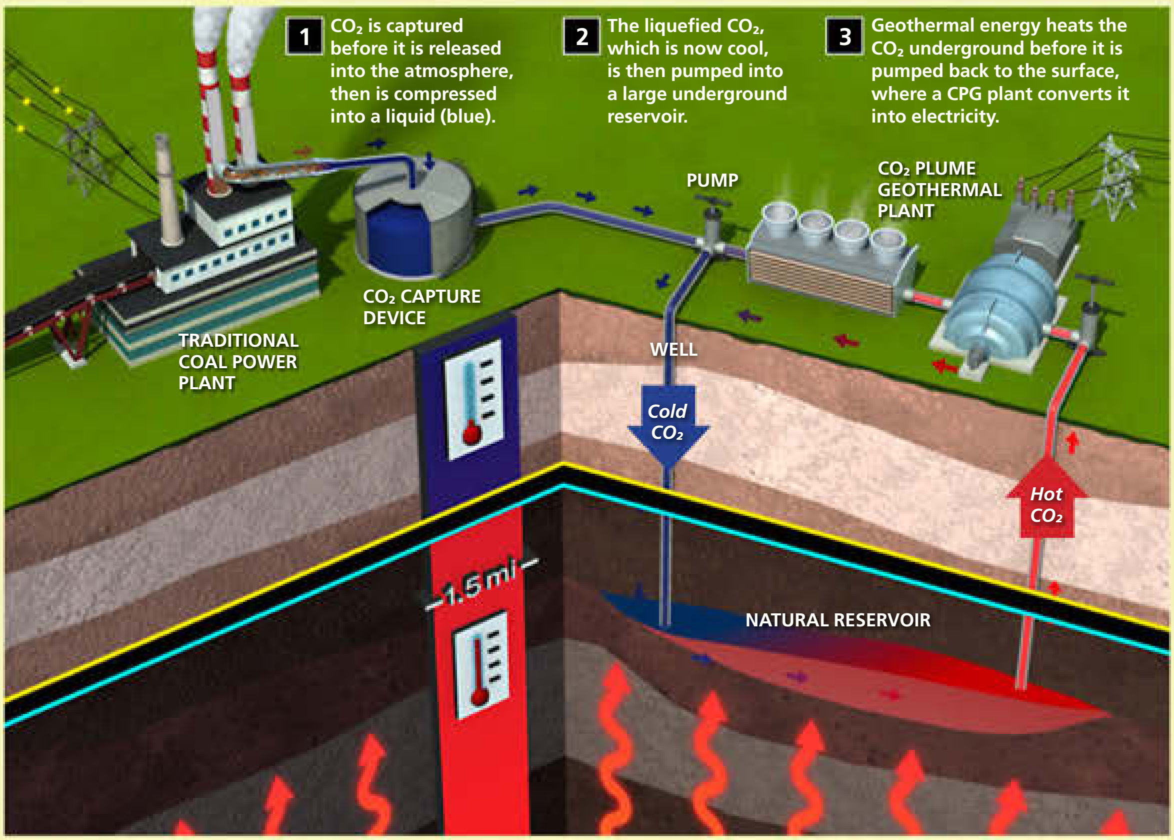
Scientists have known for years that carbon dioxide can be captured from power plants and stored underground to reduce emissions, but the practice is cost-prohibitive without federal incentives. Researchers have now found a way to use carbon dioxide to enhance and expand geothermal energy, which can offset the costs of capturing and storing the gas.

"The goal is to simultaneously sequester carbon dioxide and use it to generate electricity," says Jeffrey Bielicki, an energy and sustainability researcher at Ohio State University who is part of a team exploring the unusual combo's power potential.

Underground heat is typically mined by pumping water into the earth, then bringing it back up hot to power turbines that generate electricity. But carbon dioxide can outperform water: The greenhouse gas extracts heat about two to four times more efficiently. In a computer simulation, researchers found that compared with an average geothermal plant, a carbon dioxide-fed geothermal plant could produce 10 times more power while also locking away the annual carbon dioxide emissions from as many as three midsize coal-fired power plants.

Preliminary tests of the technology, called carbon dioxide plume geothermal (CPG), are underway. Meanwhile, researchers are also looking for other ways to use carbon dioxide in tandem with renewable energy. "We need to reduce carbon dioxide emissions, and expand and develop renewable energy technology," says Bielicki. "What I really like about my research is it combines the two." D

CARBON DIOXIDE PLUME GEOTHERMAL: HOW IT WORKS



SHANNON GILLEY WITH JEFF BIELICKI/OHIO STATE UNIVERSITY

ENGINEERING ALGAE TO MAKE BETTER — AND CHEAPER — BIOFUEL

BY **KARI LYDERSEN**

In 2009, a Boeing 737 powered partly by algae took off from Houston and circled over the Gulf of Mexico. The 90-minute test flight was a success, bolstering hopes that algae biofuels, which emit much less carbon than standard gasoline and diesel, could soon power everything from jets to cars. But scientists have struggled to find a way to produce and process algae cheaply enough to compete with petroleum fuel. Now, thanks to advances in genetic engineering, filling up your car with algae-derived biofuel is a step closer to reality.

The simplest way to make biofuel from algae is to essentially wring out the natural oils and refine them, much like petroleum. Genetic engineering can make this process more efficient. For example, scientists with the Scripps Institution of Oceanography figured out how to curb an enzyme that breaks down the lipids in algae that are crucial for making biofuel. Typically, algae growers "starve" the algae to boost lipid production, but that inhibits growth. The genetically engineered algae can grow quickly while still accumulating lots of lipids.

Algae can also be used for biomanufacturing: Microscopic algae are turned into a living machine that can be genetically programmed to produce molecules like lipids and hydrocarbons ideally suited for biofuels.

STEPHEN MAYFIELD of the University of California, San Diego has genetically engineered algae to make biofuels.

"If you just squeeze the oil out of algae, what you basically get is vegetable oil, which you can convert to diesel," says Stephen Mayfield, a molecular biologist at the University of California, San Diego. "But because we have complete control of genetics now, we have all the technology to make [algae into] some kind of fancy photosynthetic machine."

For now, Mayfield is using genetically engineered algae only to make drugs and nutritional supplements. But if oil prices rise enough for algae fuels to be cost effective, scientists hope to use what they've learned from that process to make biofuels that are both clean and profitable. D

FUSION COMES DOWN TO EARTH

BY **W. WAYT GIBBS**

Deep inside the massive Z machine at Sandia National Laboratories in Albuquerque, N.M., a tiny cylinder of beryllium, no bigger than a pencil eraser, awaits its big moment. The capsule holds a smidgen of neutron-rich hydrogen gas, hardly enough to make a small pop if you burned it.

But the physicists at Sandia have in mind a grander plan than combustion, one that will release kilowatts of power from this tiny capsule: thermonuclear fusion. It's the same process that heats the sun, and the Z machine team is testing a promising new way to transform it into a clean and plentiful source of electricity on Earth.

Red lights flash, and a loud horn sounds. Rivers of electrical current fill banks of capacitors. Nineteen-million amps of current zap through the machine with a violent crack, creating a "Z pinch" force that crushes the capsule while an ultrastrong magnetic field keeps its contents in place. Adding to the searing heat of compression, a trillion-watt blast of green laser light sends the temperature of the hydrogen nuclei soaring to 30 million degrees Celsius — hot and fast enough to fuse hydrogen

ERIK JEPSEN/UC SAN DIEGO PUBLICATIONS

HYDROPOWER IN A PIPE

BY **PETER FAIRLEY**

Beneath Powell Boulevard in Portland, Ore., a newly laid 60-foot section of main carries water downhill from a nearby reservoir. But this is no ordinary water pipe: A series of four turbines spin within the 42-inch main, generating power as the water flows.

Drinking water and sewage systems account for between 3 and 4 percent of total U.S. energy consumption and absorb up to 40 percent of municipal energy budgets, according to the EPA. The LucidPipes, created by Portland-based startup Lucid Energy, help address both of those challenges. The $1.3 million Portland system, which came online in March, produces enough renewable energy to power about 150 homes, and the resulting power revenues can help pay for much-needed infrastructure upgrades.

The LucidPipes work by taking advantage of gravity-driven flow. The turbines' svelte aerodynamic blades skim off surplus pressure from the moving water rather than impede it the way a conventional hydropower turbine would.

"Our system is based more on the science of a wind turbine or an airplane wing," says Lucid Energy CEO Gregg Semler. And it brings none of the environmental impacts that come with hydropower from dammed rivers.

Gravity-based water systems can meet 10 to 15 percent of their power needs with LucidPipes, and at an attractive price. LucidPipes generate power at 5.6 cents per kilowatt-hour in Portland, less than half the average U.S. residential power rate.

TURBINES installed in water and sewage pipes can generate power — and revenue — for cities. The LucidPipes system in Portland, Ore., shown here, will produce enough energy to power about 150 homes and help pay for infrastructure upgrades.

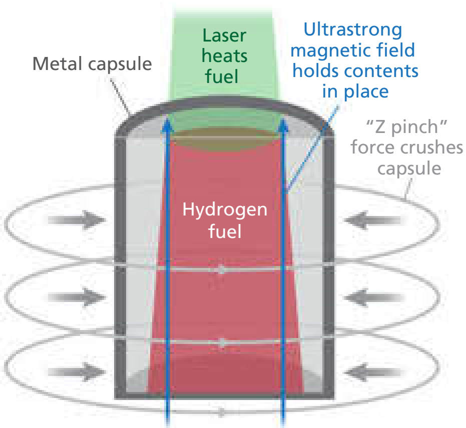
Semler estimates there is enough spare pressure in U.S. and Canadian water systems to support several thousand installations like Portland's. D

atoms together into helium nuclei. The whole event is over in less than a millionth of a second, but it ejects energetic neutrons by the trillions.

MagLIF fusion, as this approach is known, is relatively new, but its rapid progress since initial tests in late 2013 has excited fusion enthusiasts. They envision zero-carbon power plants that run on fuel made from hydrogen isotopes in seawater and produce less waste than today's nuclear power plants.

Sandia's dark-horse entry in the fusion race still consumes far more energy than it releases, but that is also true of the more conventional — and more expensive — approaches to fusion, such as bombarding encapsulated fuel with laser light from every direction (as the National Ignition Facility in Livermore, Calif., does) or using giant superconducting magnets to heat levitating plasma for minutes at a time inside a doughnut-shaped chamber (as the International Thermonuclear Experimental Reactor in France may do when it's completed around 2027).

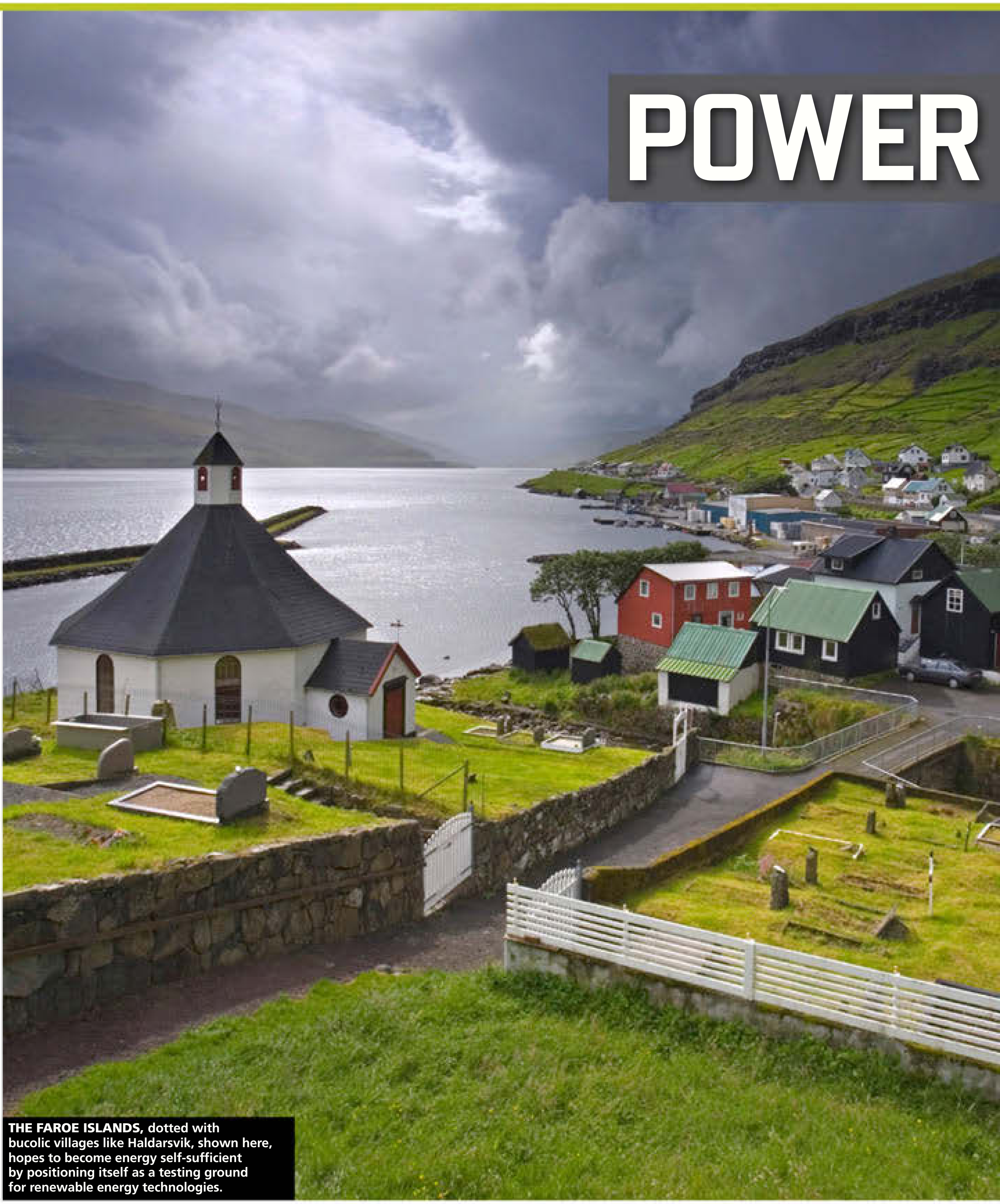
Taking MagLIF technology to commercial feasibility means increasing output a thousandfold — and persuading a skeptical Congress to bankroll the effort. D



MAGNETIZED LINEAR INERTIAL FUSION (MagLIF) combines powerful laser light with strong magnetic fields to fuse hydrogen atoms into helium nuclei.

FROM TOP: CATHY CHENEY; SHERRI KAVEN/LUCID ENERGY; ALISON MACKEY/DISCOVER AFTER MATTHEW GOMEZ, ET AL./SANDIA NATIONAL LABORATORIES

POWER



THE FAROE ISLANDS, dotted with bucolic villages like Haldarsvik, shown here, hopes to become energy self-sufficient by positioning itself as a testing ground for renewable energy technologies.

ISLAND

An isolated North Atlantic archipelago courts a renewable energy boom.

LEFT: DIETER MENDZIGALL/SODAPIX/CORBIS. FAROE ISLANDS: PETER HERMES FURIAN. GLOBE: ALISON MACKEY/DISCOVER

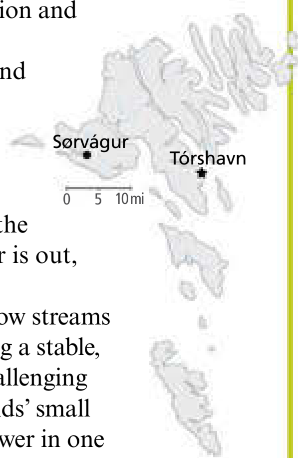
BY **SARAH KOLLMORGEN**

On the edge of a hill sprinkled with sheep, above a quiet two-lane highway, sits the smolt site for HiddenFjord fish farm. The group of small warehouses overlooks a picturesque inlet, bordered by hills, waterfalls and rolling clouds. A nice view, but nothing unusual for the Faroe Islands.

Inside one warehouse are three water-filled concrete tanks, each about 15 feet in diameter. It's quiet, save for the muffled hum of engines pumping oxygen into the water. The millions of salmon that pass through these tanks each year, swimming and eating at all hours, leave the air with a distinctly earthy smell.

Fish-farming companies such as HiddenFjord, in the town of Sørvágur, are the lifeblood of the Faroe Islands, a small nation in the North Atlantic Ocean halfway between Iceland and Norway. In a given year, fish may make up to 96 percent of the country's exports. Many Faroese salmon are destined for fine restaurants in the United States, the United Kingdom, Germany and Russia.

But the fishing industry in the Faroe Islands faces a serious threat — one that, in just 30 minutes, could cost a fish-farming business about $3 million and years of production: power blackouts.



"If the main [electricity] net is down and the generator system is not working, we are in big trouble," says Roi Joensen, a technical manager at HiddenFjord. Without electricity to power the pumps that feed oxygen into the salmon tanks, the fish start to die off. The longer the power is out, the more fish die.

In a country where brutal winds can blow streams up cliffs and topple wind turbines, creating a stable, independent power system has proven challenging and expensive. Because of the Faroe Islands' small size, when volatile weather knocks out power in one spot, it often affects the power supply elsewhere as well. And since it is isolated from mainland Europe's energy sources, the Faroe Islands historically has relied on imported oil to generate electricity and keep the lights on. In 2011, about 60 percent of the region's power came from imported oil — a practice that will only become more costly if oil prices rise.

THE FAROE ISLANDS is composed of 18 islands covering 545 square miles in the North Atlantic.

To circumvent the volatility of the oil market and preserve their slice of Eden, Faroe Islands residents are developing a power system based on renewable energy. At the heart of their plan is an unusually ambitious goal: to produce 75 percent of the nation's electricity from renewable resources by 2020. By comparison, the European Union's 2020 target is 20 percent.

So how does this little-known fishing nation, with a population of just 49,000, plan to achieve this? By marketing itself as the perfect playground for experimental green energy technology.

If the Faroe Islands succeeds in developing a stable energy system that integrates large amounts of renewable energy, not only will the country secure its own economy, it also could light the way toward low-carbon energy solutions around the world.

WIND TURBINES TWIRL at utility SEV's new Húsahagi site.

AN IDEAL TESTING GROUND

The islands are ripe with fuel for wind, hydro and tidal power. (Although they've dabbled in solar, the region's few winter daylight hours make it less viable.) In this remote archipelago, harnessing the elements to supply its power makes perfect sense.

"We are living from what you get from the sea and from the land," says Svend Aage Ellfsen, a local hotel owner who served as the islands' minister of energy in the 1990s. "I think every man and woman on the Faroe Islands is extremely aware that we have to take care of nature. So renewable energy has a first priority."

And the Faroe Islands' size makes it ideal for testing new technologies because their effects on the country's tiny grid are easier to measure, says Terji Nielsen, a project manager at SEV, the main utility company.

At the site of SEV's first major foray into wind power — a blustery spot overlooking the sea near the little town of Toftir — traditional wind turbines have been replaced with newer models more suitable for the islands' small grid. Now, looking to capitalize further on the islands' high winds — which can reach more than 100 mph during storms — SEV has established a new wind park named Húsahagi, right outside the capital of Tórshavn. Completion of the project last December expanded SEV's fleet of turbines from five to 18; about 23 percent of the country's energy production now comes from wind.

SALMON is processed at the HiddenFjord facility in Sørvágur.

Private energy company RØKT — SEV's sole competitor in the Faroese market — is exploring ways to take advantage not just of the island's strong winds, but also its lakes and mountainous terrain.

RØKT founder Jóhan í Niðristovu is testing a hybrid wind and hydroelectric pump system that will use RØKT's three wind turbines and two nearby reservoirs in the town of Vestmanna. One reservoir sits next to the turbines, at the top of a hill. The other reservoir lies partway down the hill. Niðristovu's plan is to connect the two by expanding an existing tunnel between them. During the day, when demand for electricity is higher, power will be generated by both the wind turbines and water flowing from the upper reservoir to the lower. When demand for electricity dies down at night, power generated by the wind turbines will be used to pump water from the lower reservoir back to the upper reservoir, replenishing it.

The idea, says Niðristovu, is to combine wind and hydropower into a single system. "We are only looking at where you can use known technologies, but in a different way," he says.

Most foreign energy investment in the islands is in cutting-edge new technology, rather than traditional wind and solar. For example, SEV is seeking corporate partners for a new tidal power project.

SUPPLY VS. DEMAND

Similar to larger countries attempting to expand renewables, the Faroe Islands' biggest problem lies in storage and integration into the grid. One downside of wind power is that it's often windier at night, but electricity demand is highest during the day. That variability raises a question scientists around the world have grappled with for years: What is the most efficient way to ensure renewable energy is available when demand is greatest?

FROM LEFT: GARETH PHILLIPS; SEV; SAM EDMONDS/CORBIS

STRONG WINDS blowing in from the ocean make the Faroe Islands an ideal spot for wind power.

SEV plans to install a new battery system at its Húsahagi wind farm in October that will store energy to make up for the turbines' unpredictable output. And through a bundle of projects with DONG Energy, Denmark's largest power company, SEV is testing new grid technologies designed to deliver renewable power where it's needed, when it's needed.

In 2012, the utility installed a type of "smart grid" technology called Power Hub, a digitized system that can automatically determine how to allocate resources and power throughout a large system composed of microgrids — town or neighborhood-size operations that connect to a larger grid. At its headquarters in Copenhagen, Denmark, Power Hub monitors the ebb and flow of electricity around the Faroe Islands. If there's a change in electricity production or a drop in power, Power Hub will reroute electricity throughout the system to keep it stable. The idea is that a large, interconnected system composed of smart microgrids will be more resilient, helping to eventually eradicate — or at least greatly minimize — blackouts.

The Faroe Islands' small size makes it ideal for TESTING NEW TECHNOLOGIES because their effects on the islands' tiny grid are easier to measure.

To put Power Hub to the test, SEV and DONG Energy identified three industrial sites on the Faroe Islands that are major power consumers: HiddenFjord fish farm; a cold storage site called Bergfrost; and Kollafjord Pelagic, a fish processing facility. Anders Birke, the lead IT architect at DONG Energy, says the peak consumption of these three sites totals up to 10 percent of the peak energy consumption on the islands.

The test showed that the facilities especially benefited from a Power Hub feature called virtual inertia, which allows part of each factory to be shut off for a short amount of time without any adverse effects. By switching off power at the industrial facilities, Power Hub creates enough time to address whatever problem caused a drop in power elsewhere on the grid. (Each facility reserves the right to turn off Power Hub if it looks like the power dip will take too long to fix and affect operations.)

"It's the combination of all the different capabilities that Power Hub has that makes it one of the world's most advanced systems," Birke says.

So far, the smart microgrid technology has performed well. Although Power Hub has not completely eliminated blackouts on the Faroe Islands, the lights go out less often now. SEV's Nielsen estimates that Power Hub has prevented three full blackouts on the islands so far and has reacted to about 50 minor power fluxes. HiddenFjord is now incorporating Power Hub into a new warehouse at its smolt site.

For a long time, the Faroe Islands has languished in quiet obscurity. But perhaps the tides are about to turn. Successful projects on the Faroe Islands can inform how other small island nations, and even mainland countries, approach reliable, renewable energy. Recently DONG partnered with Schneider Electric, a French energy management company, to build on Power Hub's success in the Faroe Islands and bring it to other remote islands around the world.

The Faroese hope this is just the beginning: They invite foreign innovation with open arms. "We are moving quite fast in the right way," Niðristovu says. "We have the area, so just come." D

Sarah Kollmorgen *is a freelance journalist.*

GREEN BUILDINGS GO BEYOND NET ZERO

BY **BRENDA POPPY**

Buildings consume 73 percent of the United States' electricity and produce 38 percent of its carbon dioxide emissions. "We need a change," says Eric Corey Freed, vice president of global outreach for the International Living Future Institute. The gold standard in energy efficiency, known as net zero, calls for every building to generate 100 percent of the energy it consumes, but Freed believes builders can go further.

Enter the institute's Living Building Challenge (LBC), a certification program for buildings that aren't just energy efficient but also regenerative — they produce more power than they use and promote well-being.

LBC projects use smart technology, including thermostats that learn when to turn off the heat and "daylighting," which allows natural light to permeate the space. The Bullitt Center in Seattle uses both, along with a large solar array extending across an oversized roof, to achieve net-positive results despite the city's cloudy climate.

LBC also emphasizes cutting carbon emissions across the supply chain. Builders of the Brock Environmental Center in Virginia Beach, Va., used locally sourced materials, as well as salvaged wood and granite, instead of new products that had to be mined and transported long distances. They also purchased carbon offsets to compensate for the carbon pollution they did emit; the funds supported a project that converts landfill gases into electricity.

The LBC green-building model costs slightly more than others; a new LBC office in Washington, D.C., for instance, can run about $202 per square foot compared with $192 for a net zero building. But LBC offers more than just energy conservation, Freed notes. Each building must also be beautiful and promote good health. "It's not just a rating system," he says. "It's a philosophy." D

THE BULLITT CENTER in Seattle

THE BULLITT CENTER is one of the greenest buildings in the world. The office building, which opened on Earth Day, April 22, 2013, generates 60 percent more power than it uses and harvests rainwater to feed bathroom taps. Its parking garage houses only bikes.

SOLAR PANELS cover the roof, providing ample power despite the city's famously overcast skies.

RADIANT HEAT is supplied to each floor by circulating warm water through pipes connected to 26 geothermal wells.

NATURAL LIGHT floods offices, reducing the need for electricity. The floor-to-ceiling windows open to let in fresh air.

COMPOSTING UNITS in the basement recycle toilet waste into usable fertilizer using little water.

CLOCKWISE FROM BOTTOM LEFT: JOHN STAMETS; BENJAMIN BENSCHNEIDER; NIC LEHOUX; STAMETS; BENSCHNEIDER, COURTESY OF THE BULLITT CENTER

POWER STASH

9 INNOVATIVE WAYS TO STORE ENERGY ON THE GRID.

BY **KARI LYDERSEN**
ILLUSTRATIONS BY **JAY SMITH**

We take it for granted that electricity will flow to our light bulbs, computers and microwaves at exactly the moment we need it. We owe that reliability to the electric grid, a vast and complicated machine that constantly adjusts to balance the supply of electricity coming in from power plants, wind turbines and solar panels with the demand from customers.

To keep the grid humming, electricity has to be tucked away for times when demand exceeds supply. That's especially true for renewable power — demand is sometimes greatest when the wind isn't blowing or the sun isn't shining. Right now, only about 2 percent of the electricity that can be generated can be stored on the grid. With more renewables coming online, more storage is needed, and soon. California has even mandated that 1,325 megawatts of energy storage be added to the grid by 2020.

The race is on to find new and better ways to stash power. Scientists and entrepreneurs are already testing new technologies and improving old ones to expand capacity and bring down costs.

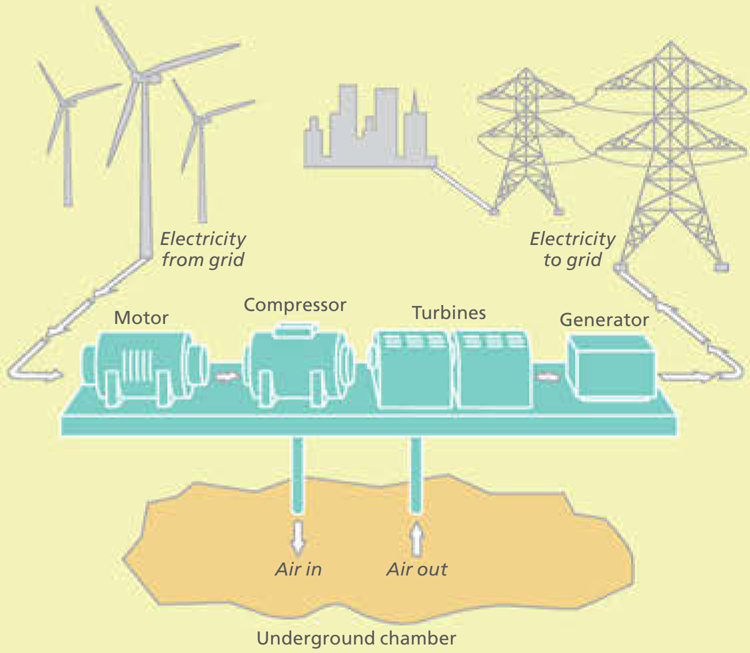
"There's going to be a shakeout, as to which technologies are truly ready," says Jeff Chamberlain, executive director of the Joint Center for Energy Storage Research based at Argonne National Laboratory. "It's going to be a blood bath for the technologists." D

1 COMPRESSED AIR ENERGY STORAGE (CAES)

How it works: At times of low energy demand, motors powered by electricity or natural gas compress air and pump it into an underground cavern, abandoned mine or other large confined space. Later the air is released and heated. As it expands, it drives a turbine to make electricity.

Pros: *Proven. Cities and mining operations have been using CAES for decades. It's relatively cheap, and it involves no toxic materials.*

Cons: *Requires a cavern or other suitable space.*

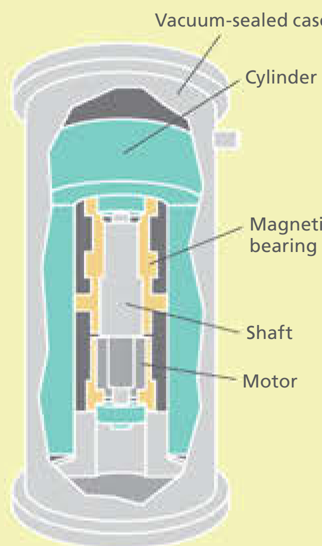


2 HIGH-SPEED FLYWHEELS

How it works: When demand is low, electricity is sent to a motor that accelerates a cylinder spinning in a case, which is vacuum-sealed to reduce friction. When electricity demand is high, the resulting kinetic energy is converted back to electricity.

Pros: *Responds almost instantly to changing energy needs.*

Cons: *Stored energy lasts only about 15 minutes, good just for short bursts.*



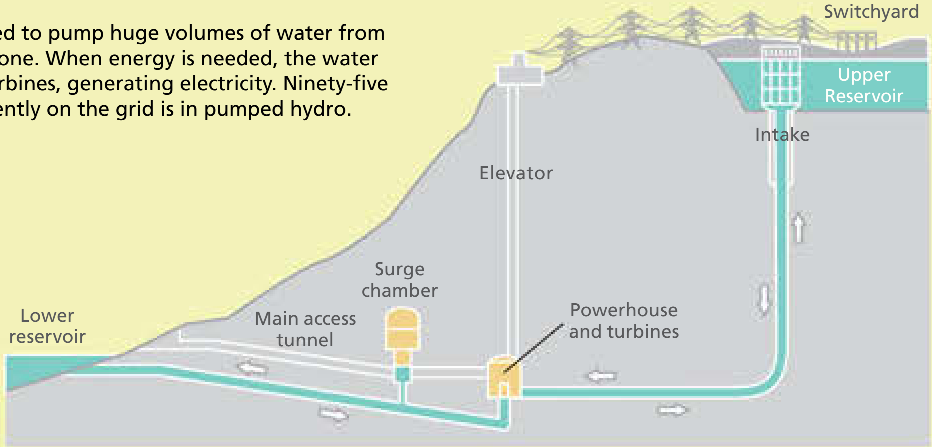
3

PUMPED HYDRO

How it works: Electricity is used to pump huge volumes of water from a lower reservoir to an upper one. When energy is needed, the water is released to flow through turbines, generating electricity. Ninety-five percent of stored energy currently on the grid is in pumped hydro.

Pros: *Can store large amounts of energy — 10,000 MWh in a reservoir a kilometer in diameter and 25 meters deep. Storage installations last a half-century or more.*

Cons: *Requires space for a deep reservoir, and water to fill it. Low storage capacity despite the large volume of water involved.*



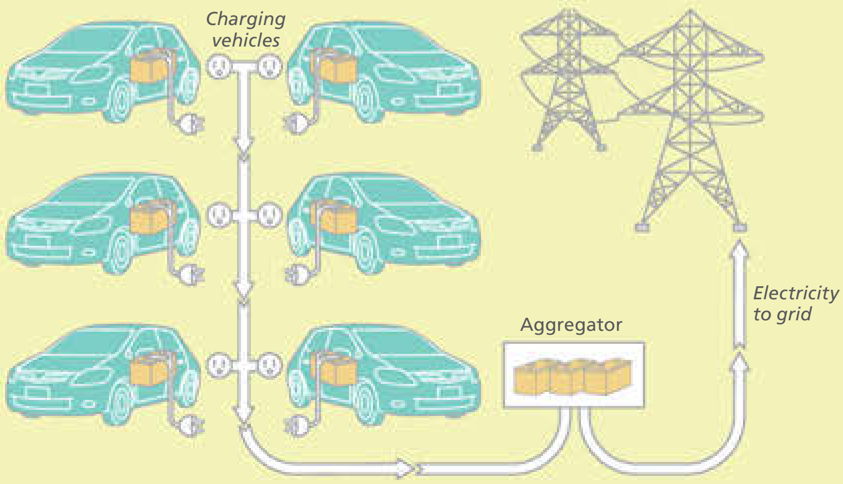
4

VEHICLE-TO-GRID

How it works: Electric vehicles can double as batteries plugged into the grid, saving up power at night when electricity demand is low. Then they can send electricity back to the grid at peak times. An aggregator pools the power into one large source.

Pros: *Can be used anywhere there is a parking spot and a plug. Owners can receive compensation for energy sent back to the grid under utility companies' net metering policies.*

Cons: *Extra charging and discharging can wear out the battery sooner. Feeding the grid could drain the battery, requiring it to be recharged before driving.*



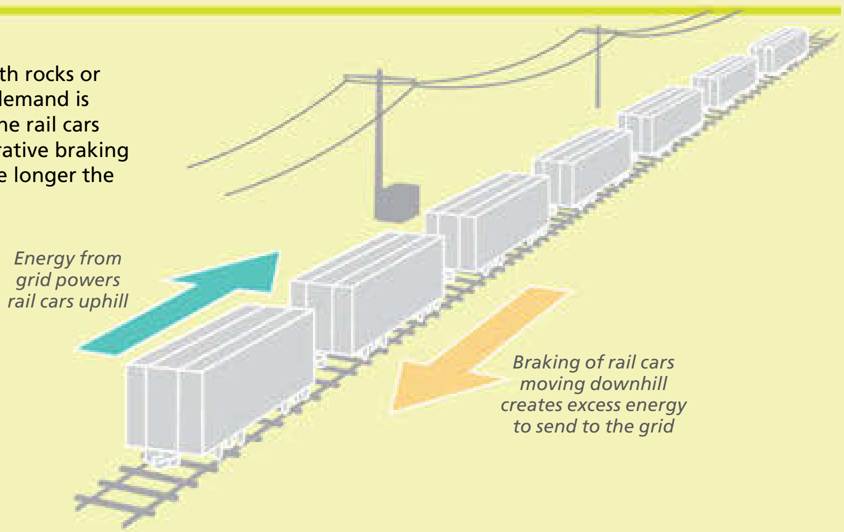
5

RAIL ENERGY STORAGE

How it works: Electric trains loaded with rocks or dirt travel up a slope when electricity demand is low. Then when electricity is needed, the rail cars slide back down the hill, and a regenerative braking system makes electricity as they go. The longer the slope, the better.

Pros: *Can release large amounts of power quickly. Technology is proven, and plans are in the works for a 50-MW rail energy storage system in Nevada attached to California's grid.*

Cons: *Lots of space and a hill are needed, and it works only in certain remote locations.*

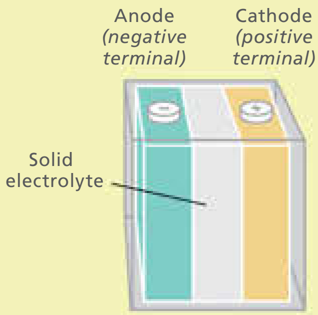


6 SOLID ELECTROCHEMICAL BATTERIES

How it works: Batteries basically store and then release energy by sending ions through chemical compounds between negative (anode) and positive (cathode) terminals.

Pros: *Proven. Solid batteries have been around for more than 200 years, but advances in the materials and chemistry of lithium ion and other batteries have made them much more efficient and effective. They can be used anywhere.*

Cons: *Expensive and store relatively small amounts of energy. Safety risks, including fires.*

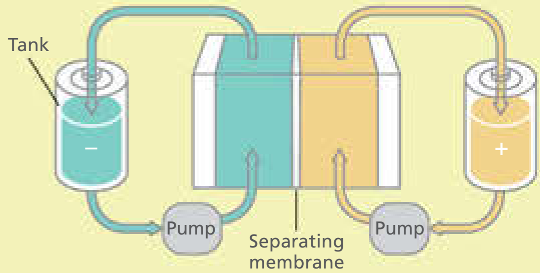


7 FLOW BATTERIES

How it works: Flow batteries work in a similar way to typical solid batteries, but they can store exponentially greater amounts of energy since the chamber where the electrochemical reaction occurs is attached to large tanks that hold electrically charged liquid. The fluid in one tank has a positive charge, and the fluid in the other tank is negatively charged.

Pros: *Large amounts of electricity can be released quickly.*

Cons: *Space is needed to store the large tanks of liquid. Risk of pollution from leaking and sometimes unreliable.*

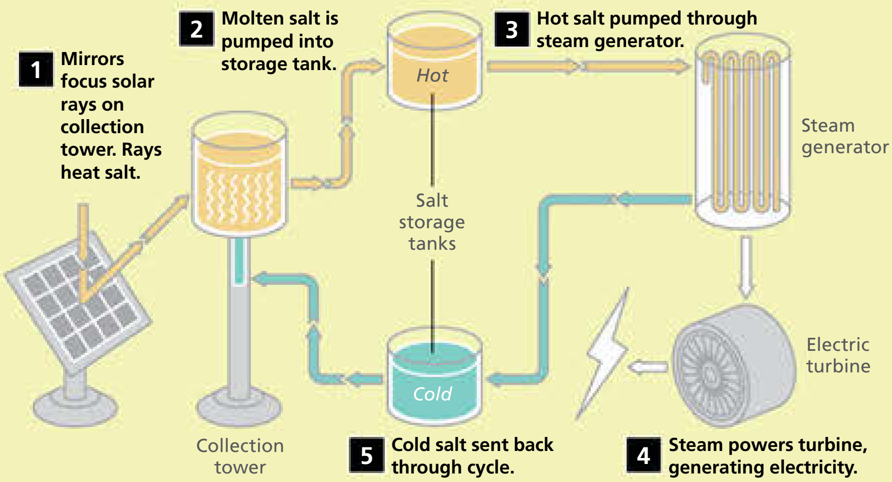


8 MOLTEN SALT STORAGE

How it works: When demand is low, mirrors reflect sunlight onto tanks of molten salt, heating them almost to 1,000 F. When demand is high, the salt's heat turns water into steam to drive a turbine, making electricity.

Pros: *Proven. Molten salt thermal storage is used at large-scale solar installations attached to the grid.*

Cons: *Need lots of space for tanks.*

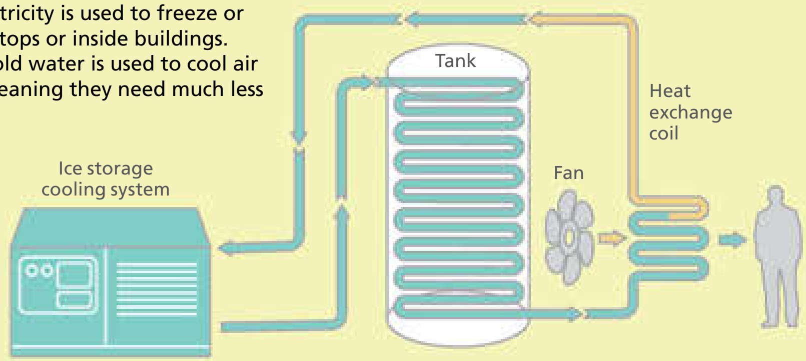


9 THERMAL ENERGY STORAGE

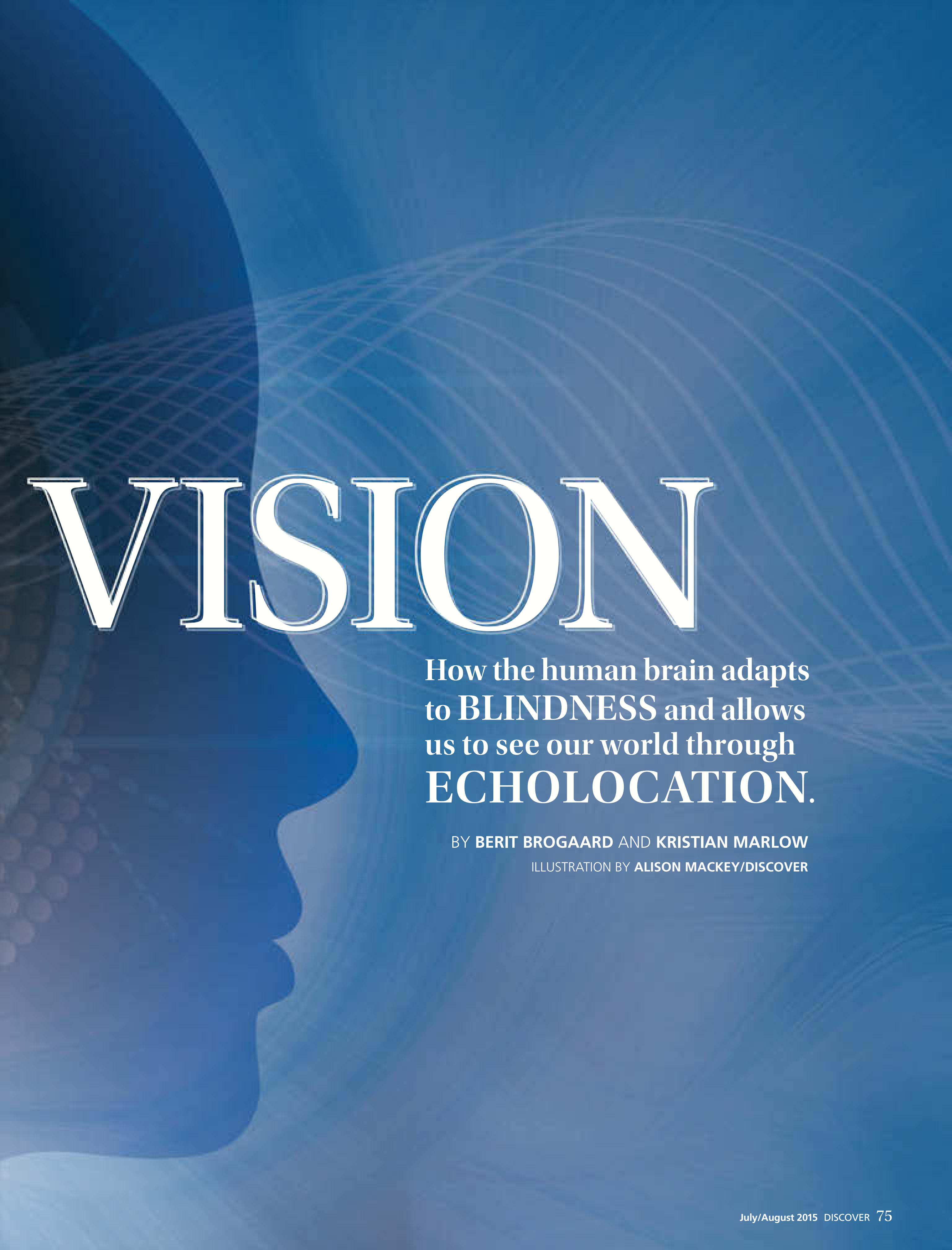
How it works: When demand is low, electricity is used to freeze or chill water that is stored in tanks on rooftops or inside buildings. Then at peak demand times, the ice or cold water is used to cool air for large office or industrial buildings, meaning they need much less power from the grid.

Pros: *Simple thermal energy storage — hauling ice into the city to cool buildings — has been used for centuries. Thermal is among the cheapest types of energy storage.*

Cons: *Cooling buildings is only helpful in the summer.*



SONIC



VISION

How the human brain adapts to BLINDNESS and allows us to see our world through ECHOLOCATION.

BY **BERIT BROGAARD** AND **KRISTIAN MARLOW**

ILLUSTRATION BY **ALISON MACKEY/DISCOVER**

DANIEL KISH HAS BEEN BLIND since he was 13 months old, but you wouldn't be able to tell. He navigates crowded streets on his bike, camps out in the wilderness, swims, dances and does other activities many would think impossible for a blind person. How does he do it? Kish is a human echolocator, a real life Daredevil.

Using a technique similar to what bats and dolphins use, human echolocators navigate using audio cues given off by reflective surfaces in the environment. Few people know that this same technique can work for human beings. But as a matter of fact, echolocation comes quite naturally to people like Kish, who are deprived of visual information. "I don't remember learning this," he says. "My earliest memories were of detecting things and noting what they might have reminded me of and then going to investigate."

VOLKER CORELL

Daniel Kish takes the lead on a tandem bike ride through California's San Gabriel Mountains, even though he is blind. By clicking his tongue and listening for the echo, Kish uses echolocation to navigate.

Kish was born with bilateral retinoblastomas, tiny cancers of the retina, which is part of the eye responsible for sensing visual information. Tumors form early in this type of cancer, so aggressive treatment is necessary to ensure they don't metastasize to the rest of the body.

Unfortunately, the tumors cannot be separated from the retina. Laser treatments are performed to kill them off, followed by chemotherapy. The result is that the retina is destroyed along with the cancer, meaning patients often are left completely blind. Kish lost his first eye at 7 months and the other at 13 months. He has no memory of having eyesight. His earliest vivid memory is from when he was very young, maybe 2½. He climbed out his bedroom window and walked over to a chain-link fence in his backyard. He stood over it, angled his head upward and clicked over it with his tongue, listening for the echo. He could tell there were things on the other side. Curious as to what they were, he climbed over the fence and spent much of his night investigating.

Like Kish, Ben Underwood was a self-taught echolocator and was also diagnosed with bilateral retinoblastomas, in his case at the age of 2. After many failed attempts to save his vision by treating the tumors with radiation and chemotherapy, his mother made the difficult decision to remove her son's right eye and left retina. This left Ben completely blind.

A couple of years later, when Ben was in the back seat of the car with the window down, he suddenly said, "Mom, do you see that tall building there?" Shocked by his statement, his mother responded, "I see the building, but do *you* see it?"

It turned out Ben had picked up on the differences in sounds coming from empty space versus a tall building. When Ben was in school, he started clicking with his tongue. At first it was an idle habit, but then he realized he could use the skill to detect the approximate shape, location and size of objects. Soon, Ben was riding a bicycle, skateboarding, playing video games, walking to school and doing virtually anything else an ordinary boy his age could do. He never used a guide dog, a white cane or his hands. Very sadly, Ben passed away in 2009 after the cancer that claimed his eyes returned.

Subscribers can see Daniel Kish's echolocation in action at **DiscoverMagazine.com/Echolocation**

EXPERIENCING ECHOLOCATION

For centuries, researchers have been trying to find out how blind people compensate for their loss of vision. It was clear that some blind people occasionally were able to "hear" objects that were apparently making no sounds. But no one knew exactly how blind people did this. And although

Like Kish, Ben Underwood was a blind echolocator. In this 2006 photo, Ben uses his skills to navigate the court while playing basketball at home with a friend.

THEO RIGBY

bat echolocation was documented in 1938, scientists didn't become seriously interested in the phenomenon until the early years of the Cold War, when military funding made the research feasible. It turns out human echolocation is akin to active sonar and the kind of echolocation used by dolphins and bats, but less fine-grained. While bats can locate objects as small as flies, human echolocators report that objects must be much larger — about the size of a water glass — for them to be locatable.

Philosophers and neuroscientists often talk about phenomenology, or what it's like to have an experience. If we show you a red ball and ask you about its color, assuming you're not colorblind, it should be easy for you to answer "red." However, if we ask you to describe *what it's like* to see the color red, you'd have a much harder time answering. By their very nature, questions about phenomenology can be nearly impossible to answer, making it hard to discover exactly what it's like to experience echolocation.

Indeed, Kish says that, because he has been blind for as long as he can remember, he has nothing to compare his experience to. He can't really say whether his experience is like seeing. However, he says he definitely has spatial imagery, which has the properties of depth and dimension. Research indicates that the imagery of echolocation is constructed by the same neurology that processes visual data in sighted people. The information isn't traveling down the optic pathway — the connection from the eyes to the brain — but it ends up in the same place. And some individuals who have gone blind later in life describe the experience as visual, in terms of flashes, shadows or bright experiences. It seems possible that echolocators have visual imagery that is similar to that of sighted people.

Ben's case provides some evidence of this, as he consistently reported seeing the objects he could detect, not just hearing them. And while self-reports are notoriously unreliable, there is other evidence that Ben really could see with his ears.

Ben had prosthetic eyes that replaced his real ones, but since his eye muscles were still intact, the prosthesis moved in different directions, much like real eyes. In the documentary *Extraordinary People: The Boy Who Sees Without Eyes*, it's clear Ben's prosthetic eyes were making saccades in several situations that require focusing quickly on different objects in the peripheral field. Saccades are the quick, coordinated movements of both eyes to a focal point. The documentary never discussed Ben's saccadic eye movements, but there's no doubt they occurred and that they matched the auditory stimuli he received. For example, in one scene, he was playing a video game that required destroying objects entering the scene. Although echolocation didn't give him the ability to "see" the images on a flat screen, Ben could play games based on the sound effects played through the television's speakers. Like many blind people, Ben used the sound cues to figure out where objects were on the screen. His saccadic eye movements corresponded to the changes in location of the virtual objects.

IT SEEMS POSSIBLE THAT ECHOLOCATORS HAVE **VISUAL IMAGERY** THAT IS SIMILAR TO THAT OF SIGHTED PEOPLE.

The primary role of saccadic eye movements is to guarantee high resolution in vision. We can see with high resolution only when images from the visual field fall on the retina's central region, called the fovea. When images fall on the more peripheral areas of the retina, we don't see them very clearly. Only a small fraction of an entire scene falls on the fovea at any given time. But rapid eye movements can ensure that you look at many parts of an entire scene in high resolution. Although it's not immediately apparent, the brain creates a persisting picture based on many individual snapshots.

Many other factors govern eye movements, including changes in and beliefs about the environment, and intended action. For example, your eyes move in the direction of a sudden noise. A belief that someone is hiding in the tree in front of you makes your eyes seek out the tree. And intending to climb a tree triggers your eyes to switch from the ground to the tree so you can inspect it properly.

Even when recalling visual imagery and there is no sensory input or external environment to process, saccadic eye movements still occur. This happens because when the brain stores information about the environment, it stores information about eye movements along with it. When your brain generates a visual image, it's likely a composite of different snapshots of reality, and rapid eye movements help keep the visual image organized and in focus. This dual storage mechanism explains Ben's saccadic eye movements: The sound stimuli from Ben's environment triggered his brain to generate spatial imagery matching the sound stimuli, and his saccadic eye movements helped keep the image organized and in focus.

SEEING WITH YOUR EARS

Sighted people often use a simple form of echolocation, too, perhaps without even realizing it. When you're hanging a picture on a wall, one way to locate a stud within it is to knock around and listen for changes in pitch. But when you tap on a hollow space in the wall, you usually don't hear an actual echo — yet you can tell somehow that the space sounds hollow.

Research shows we can perceive these types of stimuli subconsciously. When we do hear echoes, it's from sound bouncing back off distant objects. When you click your tongue or whistle toward a nearby object, though, the echo returns so fast that it overlaps the original sounds, making it hard to hear an echo. But the brain unconsciously interprets the combination of the sound thrown in one direction and the returning sound as an alteration in pitch. What makes Ben and Kish so remarkable is that they can use what everyone's brain unconsciously detects in an active way to navigate the world. And although Ben and Kish may seem superhuman because of their perceptual abilities, research confirms that sighted humans can acquire echolocation, too. After all, the visual cortex does process some sounds, particularly when the brain seeks to match auditory and visual sensory inputs.

OUR BRAIN IS PRIMED TO ACCOMPLISH THE SEEMINGLY SUPERHUMAN, EVEN AT THE BASIC LEVEL OF PERCEPTION.

American psychologist Winthrop Niles Kellogg began his human-echolocation research program around the time of the Cuban Missile Crisis. His research showed that both blind and sighted subjects wearing blindfolds could learn to detect objects in the environment through sound, and a study by another researcher showed that, with some training, both blind and sighted individuals can precisely determine certain properties of objects, such as distance, size, shape, substance and relative motion from sound alone. While sighted individuals show some ability to echolocate, Kellogg showed that blind echolocators seem to operate a bit differently when collecting sensory data. They move their heads in different directions when spatially mapping an environment, while sighted subjects don't move their heads when given the same types of tasks.

Interestingly, when sighted individuals are deprived of visual sensory information for an extended period of time, they naturally start echolocating, possibly after only a few hours of being blindfolded. What's more, with their newfound echolocation skills comes some visual imagery. After a week of being blindfolded, the imagery becomes more vivid. One of Kellogg's research participants said he experienced "ornate buildings of whitish green marble and cartoon-like figures."

Is sound alone responsible for echolocators' ability to navigate the environment? Researchers wonder whether touch cues, such as the way air moves around objects, can offer information about the surroundings. Philip Worchel and Karl Dallenbach from the University of Texas at Austin sought to answer these questions in the 1940s. Their experiments involved asking both blind and blindfolded sighted participants to walk toward a board placed at varying distances. Participants were rewarded for learning to detect the board by not walking into it face-first. After multiple trials, both the blindfolded and blind subjects became better able to detect the obstacle. After about 30 trials, blindfolded subjects were as successful at stopping in front of the boards as blind subjects when they were wearing hard-soled shoes. But this ability disappeared when subjects performed the same experiments on carpet or while wearing socks, which muffled the sound their footsteps created. The researchers concluded that the subjects relied on sound emanating from their shoes, implying sound is responsible for navigational ability.

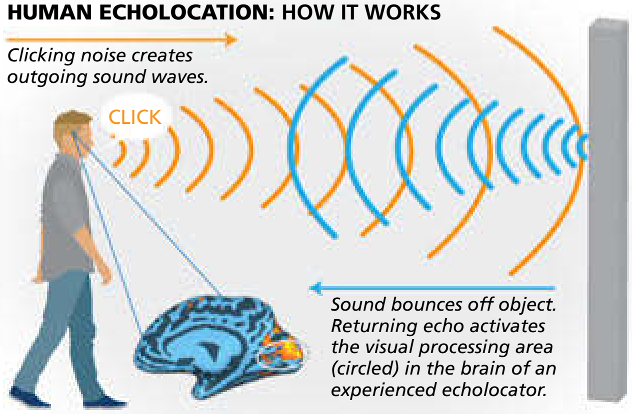
The increased ability to navigate via sound appears to be the result of sound processing in the brain, not merely increased acuity of hearing. One study showed that the blind and the sighted scored similarly on normal hearing tests. But when a recording had echoes, parts of the brain associated with visual perception in sighted people activated in echolocators but not in sighted people. These results showed how echolocators extracted information from sound that wasn't available to the sighted controls.

Some reports seem to indicate that humans can't perceive objects that are very close — within 2 meters of them — through echolocation. But a 1962 study by Kellogg at Florida State University showed that blind people can detect obstacles at much shorter distances — 30 to 120 centimeters. Some participants were accurate even within 10 centimeters, suggesting that although subjects aren't consciously aware of the echo, they still can respond appropriately to echo stimuli.

The above cases show that our perceptual experiences involve a lot more than just what we're consciously aware of. Our brain is primed to accomplish the seemingly superhuman, even at the basic level of perception. It's an extraordinary organ that creates our rich experiences by turning waves that merely strike the eardrum into complicated, phenomenal representations of our surroundings.

Ben navigated with echolocation similar to that of the dolphin he's with in this 2006 photo taken during a special session of SeaWorld's Dolphin Interaction Program.

THEO RIGBY



Kish teaches a young girl how to echolocate with a process he calls systematic stimulus differentiation. By listening to clicks bouncing off the object's surface (illustrated at left), students learn how to discern an object — a Plexiglas panel, in this case — from its background.

TEACHING THE BLIND TO SEE

Perhaps what is most amazing about echolocation is that it can be taught. Kish wrote his developmental psychology master's thesis on the subject, developing the first systematic approach to teaching the skill. Now, through his organization, World Access for the Blind, he strives to give the blind nearly the same freedom as sighted people by teaching blind people to navigate with their ears.

So why don't all blind people echolocate? The problem, says Kish, is that our society has fostered restricting training regimens. One example of this restriction is the traditional cane training method.

The military developed the cane techniques more than 60 years ago for blind veterans, people used to living in restricted circumstances. For them, it was easy to adapt to the regimented system. But now, the majority of blind people, including children and the elderly, learn this system.

Kish's training curriculum differs from tradition by taking an immersive approach intended to activate environmental awareness. It's a tough-love approach with very little hand-holding. He encourages children to explore their home environment for themselves and discourages family members from interfering unless the child otherwise could be harmed.

Kish then changes the cane his students use during walking. The student holds the cane out in front, elbow slightly bent, so the hand is roughly at waist height. With every step, the cane tip lands about where the student's foot will land so the cane clears the area of where the child is about to step. The student repeatedly taps the cane from left to right, called "two-point touch." Although computer models support this method, Kish thinks the movement is unnatural. "We are not robots," he says. "The reality is that the biomechanics do not sustain the kind of regimented movement you have to have in order for that to work — you lose fluidity of motion. You don't have to be a physical therapist to know that's a recipe for a wrist problem."

Then the real fun begins: The students learn to echolocate by systematic stimulus differentiation. Notice the term *detection* isn't included. No stimulus really occurs in a vacuum, so the process is not so much detection as it is distinguishing one stimulus from another and its background. The process follows a standard learning structure: Students first learn to differentiate among strong, obvious stimuli and then advance to weaker, less obvious stimuli. Kish establishes a "hook" stimulus by using a plain panel he moves around in the student's environment. Students don't need to know what they're listening for, since the stimulus is selected to be strong enough that it captures the brain's attention. But the panel doesn't work for everyone at first. In those cases, he uses a 5-gallon bucket or something else that produces a very distinct sound quality. Once the brain is hooked on the characteristic stimulus, he starts manipulating its features to make the effect subtler.

The next set of exercises helps students learn how to determine what the objects actually are. This essentially involves three characteristics: where things are, how large they are and depth of structure, which refers to the geometric nature of the object or surface. Students answer questions such as, "Is the object coarse or smooth?" "Is it highly solid or sparse?" and "Is it highly reflective or absorbent?" Kish says all those patterns come back as acoustic imprints. The key is to notice the changes in the sound when it comes back from when it went out. With determined practice, students eventually learn how to differentiate among general environmental stimuli.

Although the organization's instructors are currently all blind echolocators, Kish anticipates that sighted instructors could teach the skill as well. Several sighted instructors are in training, showing promise of using echolocation themselves. His goal is to have sighted instructors performing just as well as blind echolocators, though he emphasizes that although both sighted and blind individuals can echolocate, they may have profoundly different phenomenological experiences. In the meantime, Kish is hard at work, teaching the blind how to use their ears to see. **D**

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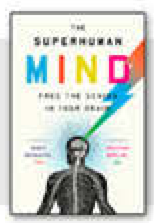
Excerpted from The Superhuman Mind: Free the Genius in Your Brain *by Berit Brogaard, Ph.D. and Kristian Marlow, M.A., to be published Aug. 25, 2015, by Hudson Street Press, an imprint of Penguin Publishing Group, a division of Penguin Random House LLC. Copyright © 2015 by Berit Brogaard and Kristian Marlow.*



Escape Hatch

Even frog eggs can flee from hungry predators. But how do they sense danger?

BY **KATE WHEELING**

A male red-eyed tree frog. The range of the species extends from Colombia to Mexico.

Biologist Karen Warkentin collects red-eyed tree frog eggs from a pond at the Smithsonian Tropical Research Institute in Gamboa, Panama.

→ Karen Warkentin escapes from the sticky tropical heat into one of the few air-conditioned rooms in Gamboa, a quiet town on the banks of the Panama Canal. The biologist shares the first floor of a schoolhouse-turned-laboratory with other visiting scientists, students and an unwelcome orange tabby cat.

"My lab extends from the canoe to the wall of boxes full of egg cups," Warkentin says.

In the middle of the room, part of the Smithsonian Tropical Research Institute, biology student Sonia Pérez Arias sits before a clear plastic box filled with colorful wires. A hollow plastic tube juts toward her from one end. Warkentin hovers behind her as she presses a black button, and with a faint whir, the tube begins to rotate like a spit over a fire. Pérez peers through the lens of a camera, magnifying the mouth of the plastic tube. Inside the slowly spinning tube, the big eyes of a red-eyed tree frog tadpole stare back.

A close-up of red-eyed tree frog eggs at 3 days old. Warkentin discovered that the embryos can hatch early to escape predators.

Warkentin, of Boston University, built the "rollie widget," as she calls it, not to make tadpoles dizzy, but to help answer one of biology's most mystifying questions. Most animals begin life as eggs, yet little is known about the lives of embryos. How does the environment influence behavior during the most vulnerable stage of life?

Warkentin has found the eggs of the red-eyed tree frog (*Agalychnis callidryas*) to be the ideal study subject; they transform from sacs of dividing cells into fully developed tadpoles in just seven days. But it's not an easy week for the embryos. Red-eyed tree frog eggs, which cling to vegetation overhanging ponds and swamps throughout Central America, often succumb to hungry predators, dehydration or drowning. But, as Warkentin was surprised to learn, the eggs aren't completely defenseless: They can hatch early to escape these dangers. Still, it's a

FROM TOP: KAREN WARKENTIN; SEAN MATTSON/SRTI; WARKENTIN

dangerous trade-off: New threats wait in the water below.

The spinning tadpole Warkentin is watching is one of those escape artists; it hatched three days early. How did it weigh the risks of early emergence? She suspects the secret may lie in how the egg senses vibrations, and she built the rollie widget to find out. Warkentin watches the eyes of spinning tadpoles for signs that they can sense their world turning upside down. As it turns out, they can.

How did the embryo weigh the risks of early emergence? Warkentin suspects the secret to this defense mechanism may lie in how the egg senses vibrations.

A BRUSH WITH FATE

Warkentin's fascination with frog eggs began with a chance encounter in Costa Rica in the summer of 1991. Warkentin, then a Ph.D. student at the University of Texas at Austin, was trudging through the dense tropical vegetation of Corcovado National Park in search of a thesis. "I bumped into a clutch [of eggs], and tadpoles were all over me," she recalls. Upon her touch, tadpoles exploded from the tiny gelatinous water balloons and squirmed across her skin. Warkentin had stumbled upon a clutch of red-eyed tree frog eggs — and her future life's work.

At the time, most biologists believed that hatching timing was pre-programmed. "We thought it was like clockwork," says Mike Ryan, a biologist with the University of Texas at Austin. But Warkentin wondered: Could the eggs hatch prematurely to escape danger?

If a brush with a human could make the eggs hatch, how would they react to an egg-eating snake?

A lone tree frog tadpole has hatched early to escape a snake attack in this photo captured in Warkentin's Costa Rica lab in the early 1990s.

KAREN WARKENTIN

In tropical rainforests, tree frogs must outwit many predators to reach adulthood. At the Costa Rica site, Warkentin found that an embryo has a 50 percent chance of meeting a snake or a wasp during the week it spends encapsulated. She figured it was unlikely that frog eggs would remain defenseless against such a common threat. For her thesis, Warkentin caged cat-eyed snakes (*Leptodeira annulata*) with clutches of 5-day-old frog eggs and found that the embryos could hatch to escape. Further experiments with eggs from Panama showed that embryos as young as 4 days old could accomplish the same feat.

The work launched an entire field of study into variation in hatching timing. Since Warkentin's early discovery, other scientists have documented variation in hatching across the animal kingdom. Among amphibians, at least 38 species can manipulate hatching timing. Predators, pathogens, oxygen availability, even bad parenting can trigger early hatching. But preemies have higher rates of mortality than their full-term peers. Warkentin is finding that the decision to stay put or hatch early is often based on environmental cues — including vibrations.

To find out how eggs can tell the difference between vibrations produced by, say, a harmless rainstorm and those produced by predators, Warkentin teamed up with Greg McDaniel, a mechanical engineer at Boston University, in the early 2000s. The duo attached accelerometers to egg clutches and recorded

Student Sonia Pérez Arias aims a camera at the "rollie widget" as Warkentin looks on. Warkentin built the machine to study tadpoles.

As the rollie widget spins a tadpole, Pérez snaps photos, which she'll study for signs that it has developed a key visual reflex.

Taken together, the tadpole close-ups reveal clues about how the amphibians know when to hatch prematurely to escape predators.

the vibrations when the eggs were attacked by snakes or pounded by rainstorms. In the lab, they played those vibrations back to other clutches to find out what kinds of vibrations caused the eggs to hatch. They discovered that the frog eggs were picking up on the pattern of vibrations over time; rain and wind batter the egg clutches more or less continuously, but snakes have to take a break to chew.

But, Warkentin wondered, how did the embryos sense vibrations in the first place?

In the fall of 2013, she found some clues in, of all things, a space experiment. A colleague suggested she look at the work of Eberhard Horn, a neurobiologist at the Karlsruhe Institute of Technology in Germany, who described how the sensory systems of the African clawed frog fared in outer space. Specifically, he studied how spaceflight influenced the vestibulo-ocular reflex in tadpoles. The reflex is eye movement that keeps a tadpole's gaze fixed on an object while its head moves, keeping its field of vision in focus. The mechanism stems from the vestibular system — structures in the inner ear that help vertebrates balance, sense movement and determine their position in space.

Eye movements are the first clue that the vestibular system, which helps sense movement, is beginning to function.

These eye movements are the first clue that the vestibular system is beginning to function.

"This is kind of wild because you've got a whole new stream of information coming online" at that stage of development, says Warkentin. "It's like getting all your news from the radio, and then suddenly you have a TV."

In the Gamboa lab, to pinpoint at what age the visual reflex appears, Pérez, the student researcher, breaks open eggs from a single clutch one at a time using forceps. She then loads each hatchling into the rollie widget, repeating the process every six hours for a week straight. (When the eggs are about 4 days old, she abandons the forceps — she can shake the embryos out instead.)

As the tadpoles spin, she snaps pictures and uses them to measure minute eye movements. "At 3 days old, nothing," says Warkentin. "But at 4 days old, [the reflex] starts showing up." Warkentin's suspicions were right: The vestibular system comes online at the very same age when the eggs can hatch to escape peril.

Back in Boston, Warkentin's team will look at the inner ear of each tadpole to confirm that the structures were fully developed when they hatched. But tonight, as the sun settles down over the canal, she showers the eggs with water from a spray bottle, and puts the tabby cat out one last time, protecting them from at least one potential predator for the night. D

***Kate Wheeling** is a California-based writer.*

FROM TOP: SEAN MATTSON; KAREN WARKENTIN (2)

The Hunt for the Unknown Volcano

A massive eruption set the stage for the coldest decade in centuries. But where — or precisely when — it happened remains a mystery.

BY **JEFF WHEELWRIGHT**

In February 1809, Francisco José de Caldas, director of the Astronomical Observatory in Bogotá in present-day Colombia, addressed an issue that everyone was talking about — namely, the weird sky and crazy weather.

Caldas published a weekly newsletter about science called *Semanario del Nuevo Reyno de Granada*. Under the headline "Meteorological News," he described how the sun had changed its appearance since the previous Dec. 11. Choked by a high, thin cloud, the sun had lost its brightness, "so much so that many have mistaken it for the moon." The sky was milky, not at all blue, and at night the lesser stars seemed to have disappeared. Plus, the weather had been unnaturally cold, the fields covered with ice and crops damaged.

Francisco José de Caldas graces a Colombian stamp in 1958.

"So many have consulted me, and so many have I had to reassure!" wrote Caldas, conscious of his authority. He declared that the cloud causing these things wasn't to be feared, no more than an eclipse should be feared, and that someday science would offer an explanation.

Yet to explain what happened would take nearly 200 years, and *where* it happened remains unclear. As time passed, Caldas' observations sank from sight, pushed ever lower in the archives by the annual layering of history.

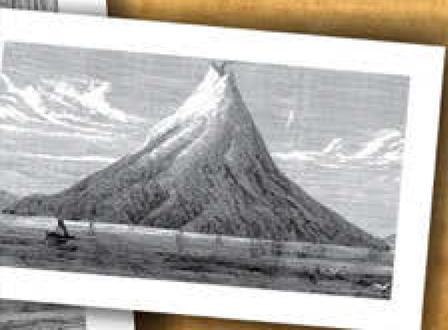
In April 1815, halfway around the globe from Bogotá, Mount Tambora in Indonesia violently erupted. Some 88,000 people perished, making Tambora the deadliest volcano in recorded history. In the aftermath, the atmospheric phenomena that Caldas had described were seen in many parts of the Northern Hemisphere. A sharp cooling of the climate followed, such that across Europe and North America, 1816 became known as the Year Without a Summer. Tambora brought far-reaching social consequences (famine and upheaval due to crop losses) and literary consequences. (Driven indoors by the bad weather, Mary Shelley wrote her novel *Frankenstein* and Byron his gloomy poem "Darkness.")

ERUPTIONS UNNOTICED

The connection between volcanism and climate change was slow to be realized in science. The first mention in English was by Benjamin Franklin. Wondering about the diminished sun and "universal fog" over Europe and parts of America in 1783, Franklin proposed a comet, or a meteor, or an active Icelandic volcano as possible causes. The last one was correct: It was Laki, the most powerful high-latitude

Top: An artist's depiction shows Indonesian villagers fleeing Mount Tambora's 1815 eruption. Above: A depiction of the effect that the eruption had on crops during the resultant Year Without a Summer.

Above: Mount Agung looms over Bali rice fields. The volcano last erupted in 1963-64, killing about 1,700 people after lying dormant for 120 years.



Below: Krakatau, in the Sunda Strait between Sumatra and Java, as it appeared shortly before it erupted Aug. 27, 1883. Left: The volcano's appearance afterward, having blown away about two-thirds of the island.

FAR LEFT: SOLODOV ALEXEY/SHUTTERSTOCK. FROM TOP: ILLUSTRATIONS BY GREG HARLIN/WOOD RONSAVILLE HARLIN (2); MICHELE FALZONE/JAI/CORBIS; ULLSTEIN BILD/GRANGER, NYC; GRANGER, NYC. BACKGROUND: ILOLAB/SHUTTERSTOCK

volcano of the past 1,000 years. Still, climate-impacting eruptions like Laki and Tambora were rare. And, more importantly, the scientists of the time didn't have the technology to monitor them. The 1883 eruption of Krakatau in Indonesia was studied closely by the British (who called it Krakatoa). But the 1888 report by the Royal Society, while noting lurid red sunsets around the world, didn't comment on the temporarily cooler weather.

If it's a powerful eruption, the sulfurous gases will be propelled into the stratosphere, where they will be converted to tiny droplets of sulfuric acid about a thousandth of a millimeter in diameter.

"There were no [major] eruptions between 1912 and 1963, and few researchers were interested or working on it," according to Alan Robock, a Rutgers climatologist and expert on how volcanoes impact the atmosphere. "The science connecting volcanic eruptions and climate change was not really explored until the 1970s and 1980s, following the 1963 Agung [Indonesia], 1980 Mount St. Helens [U.S.] and 1982 El Chichón [Mexico] eruptions." Besides knowing a lot more about the transport of volcanic aerosols in the atmosphere, modern researchers had communications lines and satellites so that news of an eruption could be relayed quickly and the effects noted as they unfolded.

The gases released by an explosive eruption are primarily water vapor, carbon dioxide and sulfur dioxide, not to mention rock and ash, which fall out quickly. If it's a powerful eruption, the sulfurous gases will be propelled into the stratosphere, where they will be converted to tiny droplets of sulfuric acid, aka sulfates, about a thousandth of a millimeter in diameter. An aerosol layer forms; the original scientific term was *dust veil*.

A veil or aerosol layer that stems from an eruption in the tropics spreads first around Earth's equatorial belt, the so-called tropical pipe, and then flows north and south toward the poles. Because the sulfate haze reflects a portion of the sun's energy back into space, the average temperature on Earth's surface drops by as much as 0.5 or even 1 degree Celsius. The aerosols settle out after one or two years, and the climate goes back to what it was doing before the eruption.

RECORDED IN ICE

In the 1970s, researchers discovered volcanic sulfates in a most unlikely location: below the icecaps of Greenland and Antarctica. Snow falls lightly at the poles, but as each year's accumulation is compressed into ice, it encases chemical hallmarks of the atmosphere and climate, including traces of major eruptions.

To extract the information from the ice, cylindrical cores are drilled, dated and examined layer by layer. In the stratum that formed in 1816, about 110 meters down from the surface, scientists found the acidic mark of Tambora. Indeed, all the major eruptions of recent centuries were represented in a frozen column at one or both poles. Each volcano's magnitude and its impact on climate can be estimated from the amount of sulfate deposited in the ice.

Now we get to 1991, which is important to the story for two reasons. First, Mount Pinatubo in the Philippines exploded. Volcanologists and atmospheric scientists were all over Pinatubo, figuratively speaking, tracking it on the ground and in the skies. The best documented, most data-rich volcano in history, Pinatubo became a “calibration point” for the behavior of earlier volcanoes, says Jihong Cole-Dai, a professor at South Dakota State University. Their aerosol paths and effects on surface temperatures could be modeled using Pinatubo guidelines.

The second event was a paper published by Cole-Dai and two colleagues titled “Ice Core Evidence for an Explosive Tropical Volcanic Eruption 6 Years Preceding Tambora.” Although other researchers had noticed a sulfuric signal in the ice layer below Tambora’s, Cole-Dai was the first to announce that it belonged to an 1809 volcano, and what’s more, to a massive volcano that nobody at the time had reported. The Unknown, as it was dubbed, was nearly three times bigger than Krakatau, almost twice as big as Pinatubo, and half as big as the monstrous Tambora. Why did history not remember it? Were there no eyewitnesses?

Environmental scientists who studied the Unknown’s impacts did not pursue the mystery. “Why does it matter what volcano it was?” says Robock. “We knew about it. We know the impact it had on climate. Science isn’t waiting to know the location.”

But when Cole-Dai published another paper about the Unknown in 2009 — in which he made the case that it and Tambora, like a one-two punch, caused the coldest decade for the past 500 years — curiosity about the Unknown flared anew. At the University of Bristol in the U.K., a team of researchers, whose specialty is tying up loose ends in volcanology and climate science, decided to try to find word of the Unknown in the archives of Spain and Latin America. Several months of digging led them to Caldas’ report and a confirming report by a physician in Lima, Peru, who noticed vivid glows at sunset at the same time that Caldas was describing the atmospheric veil. Studying the ice cores, Cole-Dai figured that the eruption happened in February 1809, plus or minus four months. The veil over Bogotá began in mid-December 1808, which meant the eruption occurred a few days or a week earlier.

But where? The now-silent volcano may lie anywhere within the tectonically active tropics. The Bristol group, led by Caroline Williams, a historian of Latin American studies, published its findings last fall, and she and her colleagues continue to ponder the question. They feel fairly certain that nobody from this hemisphere saw the Unknown explode. They promise to keep looking for someone who did. D

Jeff Wheelwright *has a long history with* Discover, *having contributed articles to the magazine since June 1985.*

Left: After 123 years of quiet, Mount St. Helens in Washington state erupted May 18, 1980, blowing its north face and reducing its height more than 1,300 feet.

Below: The June 1991 eruption of Mount Pinatubo, on the Philippine island of Luzon, blasted away nearly 500 feet of the volcano.

FROM LEFT: GRANGER NYC; ALBERTO GARCIA/CORBIS

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Born to Be Mild

Are human beings evolution's most successful story of self-domestication?

BY **ZACH ZORICH**

Forget, for a moment, about the ease with which human beings use tools and the inventive ways we express ourselves through art and language. The behavior that really distinguishes humans from other primates is that we can sit quietly in a theater full of strangers — dozens or even hundreds of us — and not fight or impregnate anybody by the end of the show.

"If you put a hundred strange chimpanzees in a room, there would be bloodshed," says Steven Churchill, a paleoanthropologist at Duke University.

The ability to put up with each other and even cooperate when necessary was a key development in the evolution of our species. It helped our ancestors share knowledge, which allowed them to make ever more elaborate tools and eventually build entire civilizations. Evolutionary anthropologist Brian Hare, also at Duke, is part of a small group of scientists who think they might know how humans evolved this ability, sometime during the 5 million to 7 million years since we shared a common ancestor with other primates.

In the late 1990s as an undergraduate, Hare documented the ability of dogs to follow the gestures and gaze of humans to find hidden food. As a graduate student, he confirmed that this talent also existed in a population of foxes that, through artificial selection over generations, had been domesticated by Russian

Selecting for tamer animals carries with it a suite of unintended evolutionary consequences — ranging from changes in appearance to new behavior traits — known as domestication syndrome.

scientist Dmitry Belyaev. With other researchers, he discovered that selecting for tamer animals carries with it a suite of unintended evolutionary consequences — ranging from changes in appearance to new behavior traits

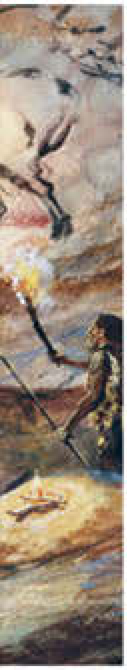
Bred for tameness, foxes in a famous Russian experiment developed other unintended traits.

— known as domestication syndrome. "The foxes were never selected to be good at interpreting human gestures," says Hare. "It must be a byproduct of something else." But that wasn't the only byproduct.

MAKE LOVE, NOT WAR

Physically, dogs and foxes look like juvenile versions of their undomesticated counterparts. Behaviorally, they are not only less aggressive and more playful as adults, but also friendly in situations whereas wild foxes were fearful and violent. Hare saw a parallel in the apes he was studying. He noticed that adult bonobos — the closest relative of chimpanzees — look like juvenile chimpanzees in many ways. They also share the behavioral traits

TOP: DEA PICTURE LIBRARY/GRANGER, NYC. BOTTOM: VINCENT J. MUSI/NATIONAL GEOGRAPHIC CREATIVE



The development of social cooperation was a crucial step in our species's evolution (left). It's a trait we share with bonobos, says researcher Brian Hare (above), shown chillaxing near a young bonobo named Lomela. She arrived at the Lola Ya Bonobo sanctuary with virtually no hair due to malnutrition but eventually recovered and was released into the wild.

of domesticated animals, such as reduced aggression, despite never having undergone selective breeding. Hare and his colleagues call this phenomenon of natural selection for more cooperative behavior "self-domestication." The researchers believe that humans underwent a similar process early in the evolution of our species.

Over the past 10 years, Hare has been observing apes at the Lola Ya Bonobo sanctuary in the Democratic Republic of Congo. He believes that bonobos have self-domesticated over the past million years or so, after their lineage separated from chimpanzees. The social differences between these two groups are striking despite being genetically very similar. Chimpanzees, like most apes, live in male-dominated societies and use violence to maintain their social status and coerce females into mating. Chimpanzees frequently attack and kill other chimpanzees that are strangers. Bonobos, on the other hand, live in societies dominated by coalitions of females and use sex to diffuse tension. Bonobos, however, are not entirely peaceful, and any male that attempts violence against a female is quickly ostracized. Bonobos also seem to enjoy, even prefer, the company of other bonobos that they have never met. Strangers are often greeted with play and sex.

How bonobos developed this kind of social tolerance without being bred for it may provide an interesting parallel to what happened early in human evolution. Owen Lovejoy, a paleoanthropologist at Kent State University, has spent his career studying the fossils of early hominids. He sees evidence in their bones that human ancestors were becoming less aggressive. In virtually all higher primates, males have large, sharp canine teeth that they often use to threaten and attack other males during competition for mates, says Lovejoy. According to Hare, a reduction in canine size is something that universally happens in domesticated mammals. Humans have evolved to have small, dull canines, meaning that, over time, they no longer needed to fight with other males to attract mates.

"In this case, it would have to be that females are choosing males with smaller canines, which means that they are choosing non-aggressive males," Lovejoy says. He believes that our early ancestors attracted mates by providing them with food. According to Lovejoy, this reduction in canine teeth is first seen in the fossils of *Ardipithecus ramidus*, which were found in Ethiopia and dated to 4.4 million years ago. Lovejoy believes that these hominids probably had a more bonobo-like social structure where males were more likely to cooperate than fight. "All of the primary evidence we have in early [human ancestors] is anti-aggression," he says.

AGGRESSION OUT, AGRICULTURE IN

It's hard to pin down the biological basis for the changes that took place in early human ancestors and domesticated animals as they developed lower levels of aggression. No one is sure which genes are involved in domestication, but they may have something to do with controlling the release of cortisol and testosterone, the hormones involved with fear and competitive behavior, into the bloodstream.

"There are maybe 10 genes, or 50, or hundreds involved in domestication syndrome," says Carlos Driscoll, chair of conservation genetics at the Wildlife Institute of India of the National Institutes of Health. Driscoll was part of a team

***Ardipithecus ramidus*' smaller canine teeth hint at self-domestication.**

TOP: VANESSA WOODS/LOLA YA BONOBO. BOTTOM: RICHARD T. NOWITZ/SCIENCE SOURCE

The behavior of our species is a blend of the same tendencies seen in aggressive chimpanzees (left) and more social, prosexual bonobos (right).

that analyzed the genomes of domestic and wild cats to understand the biology of domestication.

With the dawn of agriculture more than 10,000 years ago, our ancestors began settling in villages and living in larger groups, making tolerance of other people and cooperative behavior increasingly necessary. That lack of competitive drive may show up in the faces of modern men. Males with generally higher testosterone levels are known to have thicker brow ridges and cranial bones than men with lower testosterone. High testosterone also makes people prone to competitive rather than cooperative behaviors. Churchill and Hare were part of a group that studied a sample of *Homo sapiens* skulls dating from 200,000 years ago through to the present. While the study couldn't control for every variable that might have affected the shape of the skulls, the trend the researchers found was toward thinner craniums and less prominent brow ridges starting around 80,000 years ago and possibly earlier. This trend was more pronounced in the most recent samples, from individuals who lived in villages or cities, than it was in hunter-gatherers who tended to live in smaller groups.

Bonobo social tolerance may also be related to the hormones that the animals' bodies produce when reacting to stressful situations. When they anticipate having to compete for food, bonobos show a spike in the amount of the hormone cortisol, which is associated with fear and anxiety. Chimpanzees, on the other hand, show a spike in testosterone. According to Hare, some of the differences between chimps and bonobos may be rooted in these hormonal differences. The more aggressive chimpanzees are likely to deal with competition through violence while bonobos are more likely to calm themselves through sex.

The more aggressive chimpanzees are likely to deal with competition through violence while bonobos are more likely to calm themselves through sex.

Despite the millions of years since we shared a common ancestor, humans still retain some tendencies in common with chimpanzees. Churchill believes that human behavior is actually something of a mosaic of traits demonstrated by chimpanzees and bonobos. "In some respects, we are very chimpanzee-like. We have a remarkable propensity for violence and warfare," he says, "and in some respects, we can be very bonobo-like. We can be very prosocial and sexual."

By studying the differences of these two equally distant relatives, we can come to a better understanding of our own species. "The more we understand why in some cases we behave like chimps and why in some cases we behave like bonobos, the better off we'll be," says Churchill. D

Zach Zorich *is a freelance journalist based in Colorado, and is definitely more bonobo than chimpanzee.*

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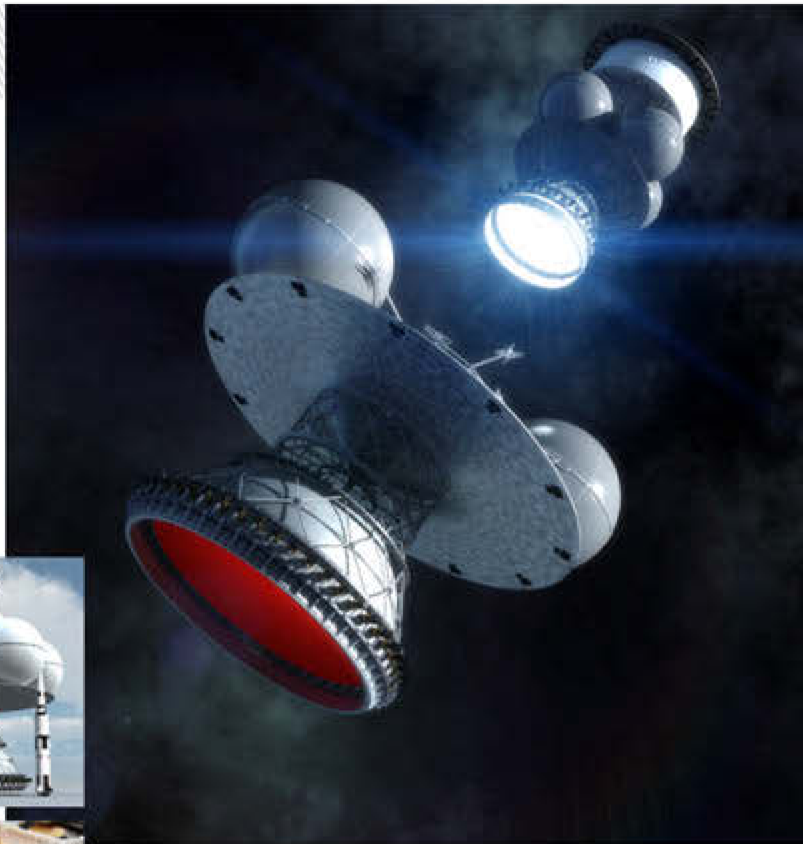


Where's My Warp Drive?

A group of true believers is hard at work on machines that could take us to the stars. (Some patience required.)

BY **COREY S. POWELL**

You know what it's like to have an itch that you just can't scratch? That's how I feel whenever astronomers discover an intriguing new planet around another star — especially the recent reports of planets like Kepler 438b and Gliese 667 Cc that seem similar to Earth in size and temperature. Are they host to alien life? Are they strange, deadly worlds like Venus, or something completely bizarre, unlike anything we've seen before? I am restless to go there and get a look.

Judging by the many comments I've received and seen online, I'm not the only one. But man, is it a hard itch to scratch. The distances between stars are immense. Consider Voyager 1, the fastest spacecraft in the solar system. It took 18 months to reach Jupiter. Thirty-eight years after launch, it has fled 12 billion miles from the sun. At this rate, it will travel the distance to Alpha Centauri, the nearest star system, in about 70,000 years. Getting to Kepler 438b would take a boggling 8 million years, considerably longer than our species has been around.

I'm not crazy enough to imagine full-on, USS Enterprise-style technology in which trips to the stars happen in a matter of days (or rather, in the span from one episode to the next). But I would at least like to see a mission that could be completed in a single human lifetime. Physicist Marc Millis agrees. "Seventy-one years or so might be the threshold where it's interesting enough to go forward and actually do it," he says. For three decades, Millis worked at NASA, where he led the Breakthrough Propulsion Physics Project at the Glenn Research Center. Now he is the founder and director of the Tau Zero Foundation, dedicated to — here we go — the pursuit of interstellar flight.

Marc Millis studies interstellar travel; the Daedalus (inset and above) was one of the first designs for a ship capable of it.

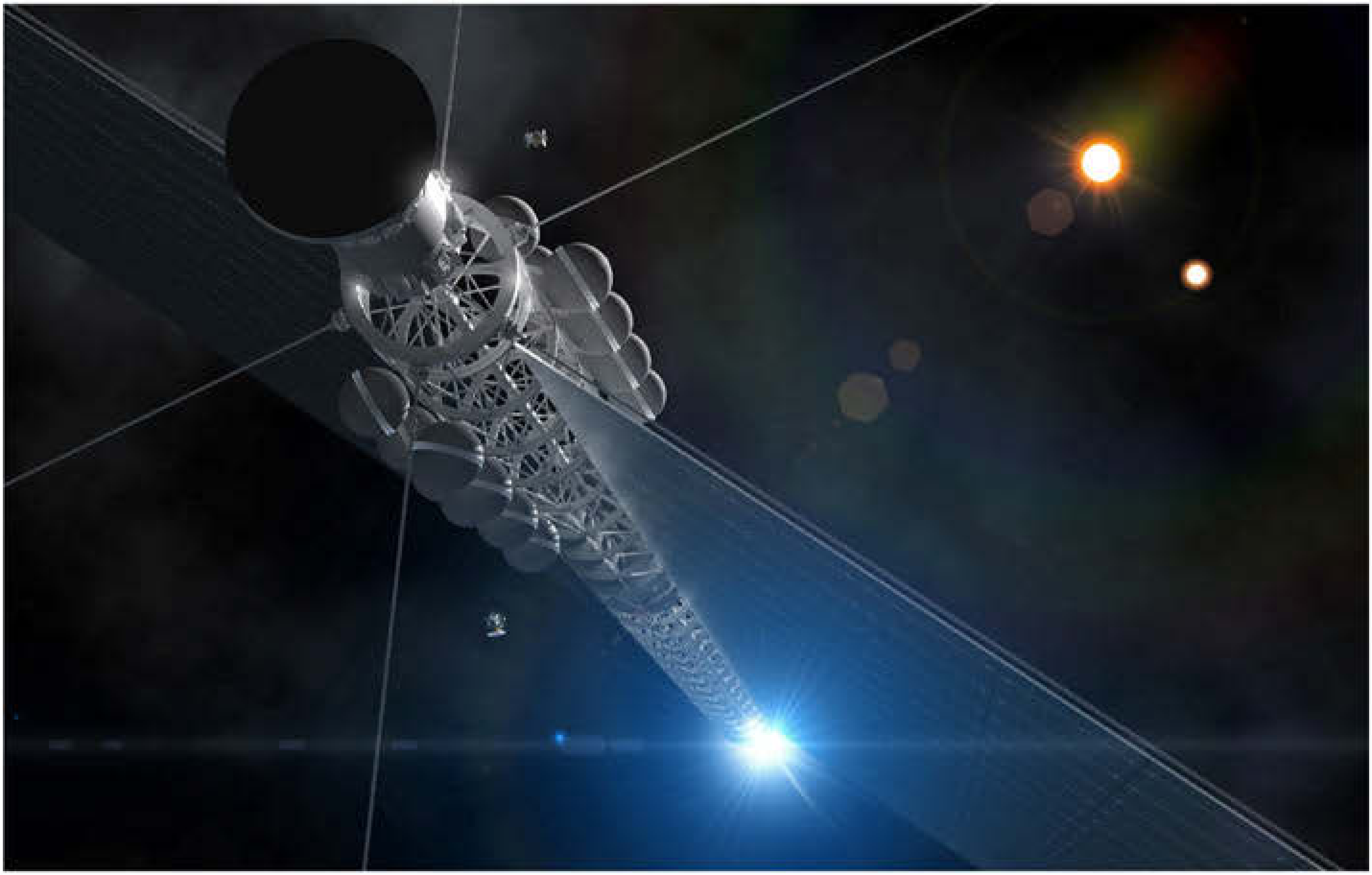
It's telling that Millis is no longer a NASA employee. Interstellar travel receives almost no support from traditional research institutions, either here or abroad. Other than one small joint project with DARPA (the advanced-concepts arm of the Department of Defense), NASA has been forced to defer work on the problem due to budget cuts and shifting priorities. But Millis and a hardy band of like-minded scientists carry on, driven by a whole range of motives that he lumps together as "hope for the future."

SEPARATING WHEAT AND CHAFF

The first step in plotting a course to another star is figuring out what directions *not* to pursue. A far-out project like this tends to attract an enormous amount of wishful thinking and unrealistic claims. Case in point: Last summer, a group of NASA-affiliated researchers at Eagleworks Labs reported measuring thrust from an EM-Drive, an experimental space engine that uses no propellant. That makes as much sense as saying you figured out a way to propel your car while pushing it from the inside.

"The EM-Drive and warp-drive stuff is not in the category of what I'd call 'behaving scientifically,'" Millis sighs when I mention the Drive. He has a whole category for "idea zombies — bad ideas that won't stay in their graves." In an influential review paper, he picked through more

FROM TOP: ADRIAN MANN/BISBOS.COM (2); CARLY MILLIS



Fusion-powered ships, such as the one in this Project Icarus concept, might be our best bet at achieving short-term interstellar flight.

ADRIAN MANN/BISBOS.COM

than a dozen proposed interstellar propulsion technologies and ruled out many of them as either improbable or impossible. The zombie category includes gravity-blocking devices, such as the Podkletnov disk, that still occasionally get touted in online conversation and future-tech blogs.

OK, then, so where should we focus our efforts? "Rather than pick favorites, we should chip away at all the unknowns," Millis says. It sounds like an evasive answer, but as we talk further, I realize that it is the single most important idea in interstellar travel. Humans simply do not know enough yet to figure out the best way to reach another star within a lifetime.

Any such voyage would require not one but multiple technological breakthroughs and probably would rely on completely new scientific concepts — perhaps including the fabled, but still utterly speculative, warp drive. Working on many approaches at once maximizes the likelihood of success and pretty much guarantees meaningful advances whether or not they lead specifically to workable starships.

The first step in plotting a course to another star is figuring out what directions *not* to pursue. A far-out project like this tends to attract an enormous amount of wishful thinking.

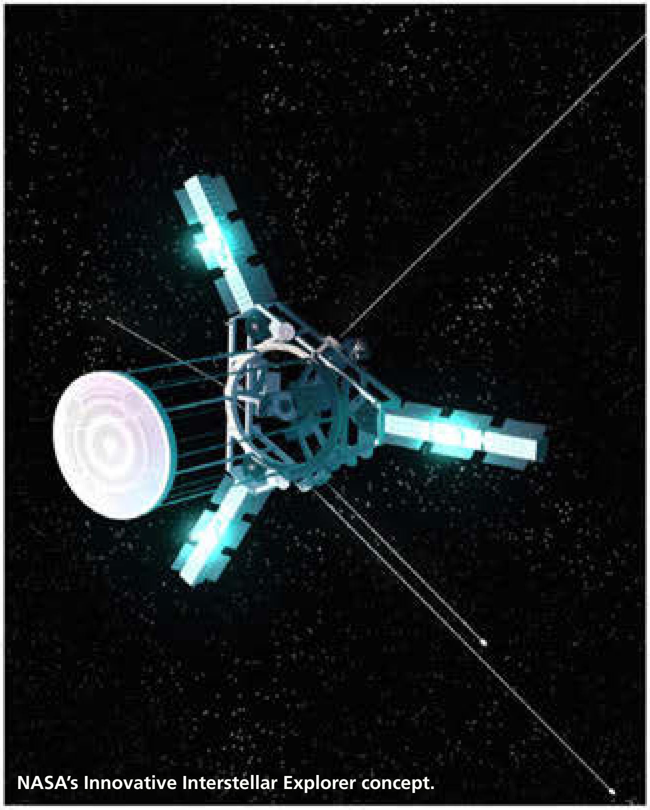
Millis has far more specific thoughts about *when* interstellar travel will happen. The secret is to think of the problem in terms of kinetics, not technology. Regardless of the mode of propulsion, moving a certain amount of mass from Earth to Alpha Centauri in a certain amount of time consumes a well-specified amount of energy. (I'm ignoring the sci-fi dream of a self-powering device that ignores the laws of physics. If it were possible, it would negate this entire discussion.)

The logic here is straightforward. Look at the fraction of total world energy output devoted to exploratory space launches today — about 1 part in a million. Look at the long-term trend in the growth of the world energy supply. Then figure out when the total supply (or, equivalently, the global economy) will be great enough to support a 75-year interstellar mission. If you assume moderate growth of about 2 percent a year, then the energy equations say that humans will be able to launch a 20,000-pound space probe to Alpha Centauri sometime in the 26th century.

I am starting to itch again.

SMALL STEPS TO THE STARS

Fortunately, the story does not end here. There are ways to get going a lot sooner: by making the probe smaller, by accepting a longer trip, or both. Tau Zero and the British Interplanetary Society — its older, more established counterpart across the pond — are collaborating on Project Icarus, a blueprint for interstellar travel by the year 2100, and on its associated foundation, called Icarus Interstellar.



NASA's Innovative Interstellar Explorer concept.

Project Icarus does not specify mass and speed goals, but it endorses a well-established energy source: nuclear fusion. Scientists can already trigger limited fusion reactions in the lab and abundant (if somewhat uncontrolled) reactions in a hydrogen bomb. Achieving a fusion rocket before the end of the century doesn't seem out of the question. Working on a similar time scale, the NASA-DARPA collaboration I mentioned earlier has spawned a private foundation called the 100-Year Starship. The "100 years" refers not to travel time but to how long the project would need to run to develop interstellar technology.

In keeping with Millis' "chip away at all the unknowns" philosophy, these groups promote a whole host of propulsion ideas. Millis ticks off a range of promising near-term technologies. In addition to fusion, his list includes laser- or maser-driven sails, electromagnetic rockets and an antimatter drive. (An antimatter production line already exists in Geneva, although it produces exceedingly tiny quantities.) Really, there is no shortage of ideas. There is just very little funding to support them.

In addition to nuclear fusion, promising near-term technologies include laser- or maser-driving sails, electromagnetic rockets and an antimatter drive.

The solution, Millis argues, is to start small. A few years back, NASA sponsored a study for the Innovative Interstellar Explorer, which would use a beefed-up version of the ion engine on the current Dawn spacecraft to dip into the near edge of interstellar space. Icarus Interstellar is supporting a study called Tin-Tin, which would also use an ion drive or similar tech to send a 20-pound probe to Alpha Centauri. Target travel time: 25,000 years.

Before you scoff at that number, remember that this is just phase I, a developmental project ambitious enough to be inspirational but limited enough to be affordable. Building Tin-Tin would require staggering improvements in autonomous computing, communication, miniaturization, radiation resistance and device longevity. These are the kinds of engineering challenges that have traditionally sparked the most important innovations to come out of the space program.

All of which circles back to Millis' central theme. The point of these interstellar programs is not, as I had initially hoped, to send back postcard pictures of another Earth in my lifetime. The goal is to mark out a path, one that will produce substantial, tangible benefits along the way. "There's an expectation that interstellar travel is going to be really expensive, and yeah, the implementation might be," Millis says. "But these baby steps we're taking? If we had on the order of $10 million a year — which, compared to many things, isn't a lot — we could make a huge amount of progress."

It is like investing for retirement: Small contributions now yield a huge benefit later. I just wish I could be around to witness the final payout. D

__Corey S. Powell__, editor at large of Discover, *also writes the magazine's Out There blog. Follow him on Twitter,* ***@coreyspowell***

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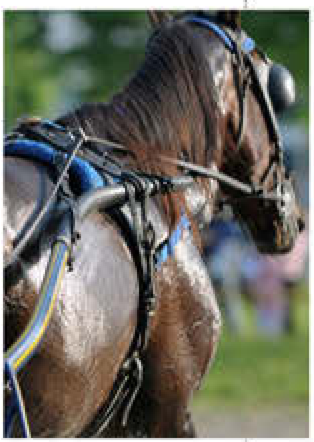
CLASSIFIEDS

TRAVEL

Sweat

BY **JESSICA FESTA**

1 Composed of about 99 percent water, sweat evaporates on the skin's surface, cooling the body and keeping it from overheating. **2** Sweat secretions help you in other ways, too. They include dermcidin, an antibiotic peptide that appears to regulate bacteria growth on the skin and may fight infection. **3** Not all humans sweat equally. Men sweat up to twice as much as women, and both sexes sweat less with age. **4** The sensation of touch can trigger a "sweat reflex" on the opposite side of the body from the spot that is touched. **5** Sweat can trigger other responses: People with atopic dermatitis, a skin condition, can experience an immediate and serious allergic reaction to a fungal protein called MGL_1304 that's found in sweat. **6** Aside from humans, horses are one of the few mammals that thermoregulate by sweating. Horse sweat is high in latherin, a protein that helps the water in sweat travel from the skin, past the animals' heavy waterproof pelt and to the air, where it can evaporate and keep them cool. **7** Hippos actually produce a red-colored sweat, which acts as an antibiotic and sunscreen. **8** If you're sweating red and you're not a hippo, you might have a rare condition called hematohidrosis. Blood vessels rupture and run into sweat glands in affected individuals, causing them to actually sweat blood. **9** Another rare condition, chromhidrosis, causes humans to sweat orange, blue or other colors. While the condition can sometimes be traced to ingesting certain drugs, the cause often remains a mystery in otherwise healthy people. **10** It's no mystery, however, why the sweat of healthy people often smells different from that of sick individuals. The body emits volatile organic compounds based on metabolic condition, which can change when disease or infection is present. **11** Cystic fibrosis can be detected with a sweat test. Sodium and chloride are much more concentrated in the sweat of individuals with the condition. **12** Emotions can trigger changes in the composition of your sweat. In an Austrian study, participants wore pads that collected their sweat while watching scary films first, and then neutral films the next day. A second group of volunteers smelled the pads and was able to distinguish which pads were worn during the scary movie. **13** In a similar experiment, female participants judged the sweat of non-meat-eating men to be more attractive than that of meat eaters. **14** Regardless of your health, feelings or diet, your sweat is distinctly yours. While other components of sweat may fluctuate, an individual's sweat "fingerprint," a unique blend of 373 volatile compounds, remains consistent over time. **15** Each of us has a unique sweat fingerprint, but the two types of sweat glands, apocrine and eccrine, are universal to humans. We have eccrine glands over most of our bodies, but apocrine glands only in our armpits and genital region. **16** Our bodies produce very little apocrine perspiration, but it's responsible for most of the odor because it's high in water and waste products that promote the growth of smelly bacteria. **17** Clear, fluid eccrine sweat, produced in much larger quantities, spreads the apocrine over a larger surface area — and the stench along with it. **18** What to do with all that sweat? UNICEF and Swedish engineer Andreas Hammar teamed up in 2013 to draw attention to millions of people without clean drinking water by creating the Sweat Machine, which pulled sweat from clothing and turned it into potable water through a process of spinning, heating and filtering. **19** The Sweat Machine was more awareness-raising stunt than solution. A sweaty T-shirt yielded just 2 teaspoons of purified water, and organizers admitted there were no plans to mass-produce the gizmo. **20** Maybe the Sweat Machine would have been more productive if they'd used socks instead. A pair of human feet has 250,000 sweat glands, emitting a half pint of liquid every day. D



Aside from humans, horses are one of the few mammals that sweat to regulate body heat.

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LEFT: VESILVIO/SHUTTERSTOCK. RIGHT: JAVI_INDY/SHUTTERSTOCK

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