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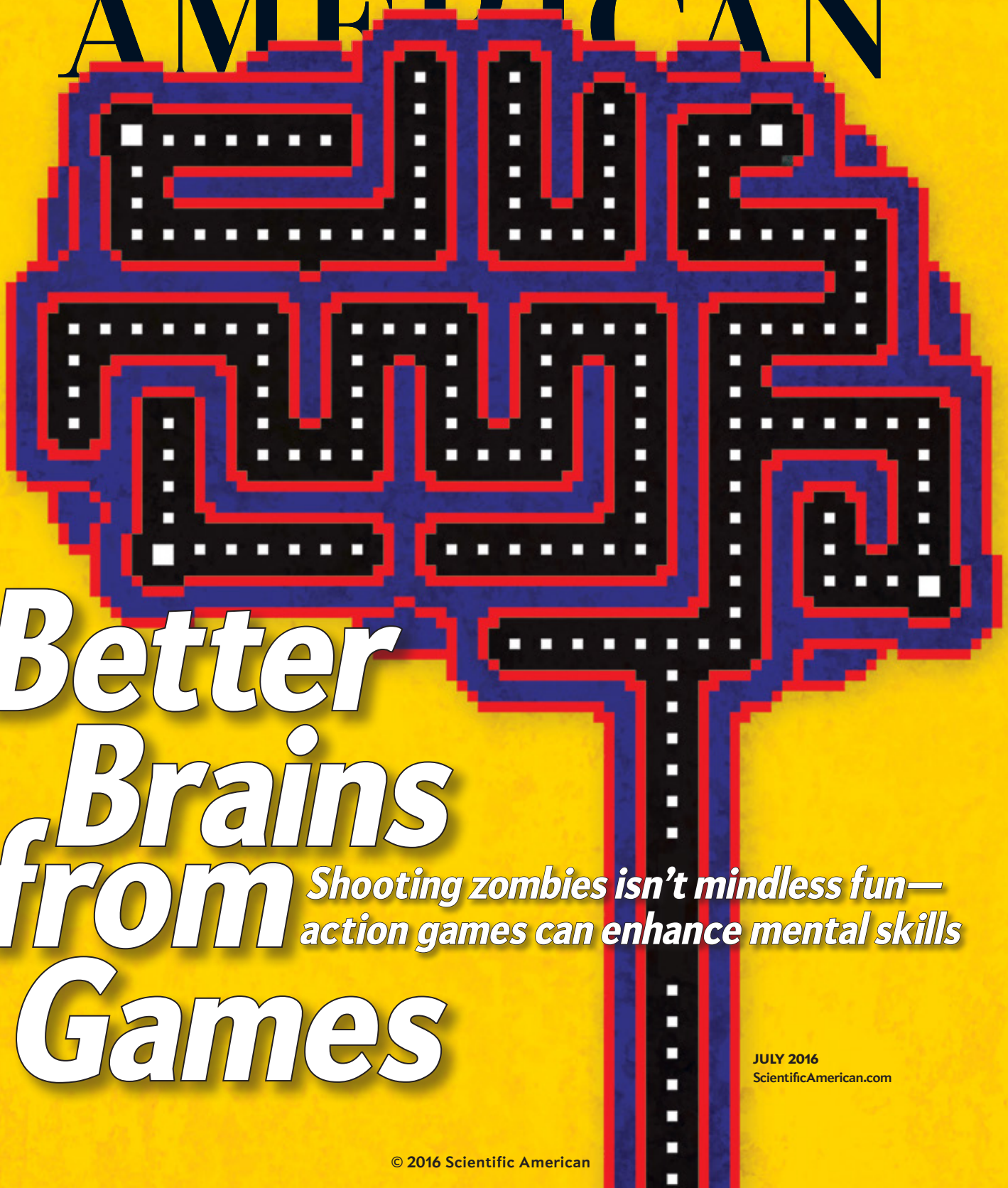

Better Brains from Games

Shooting zombies isn't mindless fun—action games can enhance mental skills

JULY 2016
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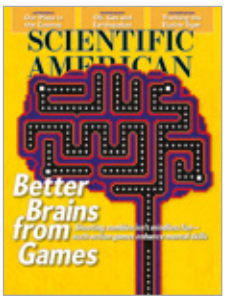

ON THE COVER

Playing action video games, at times reviled as mindless entertainment, has unforeseen benefits. It improves some types of mental functioning, enhancing attention and the ability to process information quickly. What is more, players make greater gains than those who indulge in techniques billed explicitly as brain training. **Illustration by Jude Buffum.**

Photograph by Jeff Wilson

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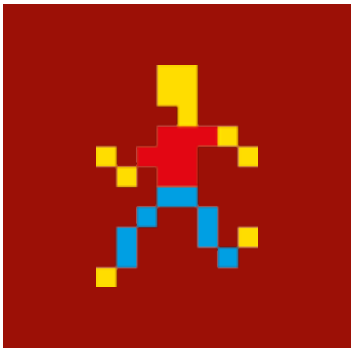
Mariette DiChristina is editor in chief of *Scientific American*. Follow her on Twitter @mdichristina

Serious Benefits from Games

Remember the congressional hearings some years ago on the negative effects of video games? To many parents, it made intuitive sense that zapping aliens and zombies probably was a complete waste of time in any case. I know I've sometimes chided my daughters about what they are missing "IRL" when they play games on their mobile phones while, for instance, simultaneously trying to attend to a conversation or follow the plotline of a movie.



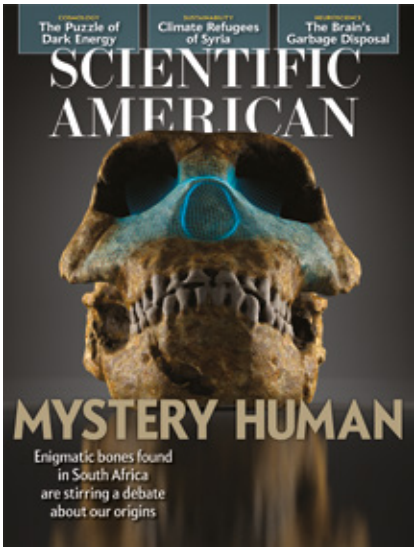
Not so fast, say scientists, who have been studying what actually happens to our brain when we play action games. In this issue's cover story, "The Brain-Boosting Power of Video Games," psychologists Daphne Bavelier and C. Shawn Green explain how fast-paced "shooter" games enhance certain cognitive functions, including bettering attention, reaction times and switching from one task to another. The work could lead to designs for games that could provide similar benefits without some of the disturbingly violent content of the action genre. Surprisingly, popular marketed "brain-training" games don't seem to evince the same kinds of benefits. For further cognitive enlightenment about this research, turn to page 26.

Once upon a time we also thought that we could not cause major effects on the environment, such as climate change. But scientists are increasingly finding that human activity writ large can elicit some profound responses from the planet. Unfortunately, regulators are not keeping up with the science. In "Drilling for Earthquakes," starting on page 46, contributing editor Anna Kuchment describes the strengthening link between temblors and the production of oil and gas. Rates for earthquakes in Oklahoma and Texas have risen sharply since 2008 as wastewater injection from extracting fuels has increased.

The West Africa Ebola outbreak has been declared over—or is it? Some 60 percent of the supposedly virus-free survivors have continuing distress from eye problems, muscle aches and neurological difficulties. To report her story, "Ebola's Second Coming," beginning on page 40, writer and medical doctor Seema Yasmin traveled to Liberia in search of answers to why some 17,000 people are at risk for symptoms called post-Ebola syndrome.

"Science is what scientists do, not what nonscientists think they do or ought to be doing," said Dennis Flanagan, who edited *Scientific American* for decades, starting in 1948. Elsewhere in this issue, for instance, our authors report on "Tracking Tigers" in India (conservation biologist K. Ullas Karanth, page 54) and "Our Place in the Cosmos" (cosmologist Noam I. Libeskind and astronomer R. Brent Tully, page 32). I like to think that Flanagan would approve, and I hope you do as well. SA

Illustration by Jude Buffum (video game), Illustration by Nick Higgins (DiChristina)



March 2016

EXPANDING UNIVERSE

Has any scientist measured the rate of the acceleration of the universe's expansion, as discussed in "The Puzzle of Dark Energy," by Adam G. Riess and Mario Livio? And were that acceleration turned back nearly 14 billion years, would it conform with the current models of the big bang?

Aaron Hackett
Howell, N.J.

As I recall, our galaxy is bound to merge with Andromeda. Would this be delayed by an expanding universe?

Dov Menkes
Fullerton, Calif.

RIESS AND LIVIO REPLY: Regarding Hackett's letter: One of us (Riess) has recently measured the rate of the universe's expansion, including the acceleration, with an unprecedented precision (an uncertainty of only 2.4 percent): it is 73.0 kilometers per second per megaparsec. There is some discrepancy between the value of the rate of expansion obtained from measurements of the cosmic microwave background and the more local measurement. It is not known yet whether that discrepancy reflects an underestimate of the potential errors or rather points to some new physics (such as an additional family of neutrinos or a dark energy that changes with time).

Current models of the big bang start with an "inflation," a stupendous expansion that happened when the universe was a tiny fraction of a second old. That expansion is thought to have been driven in a very similar fashion to the accelerating expansion we see today.

In answer to Menkes's question: The local group of galaxies is gravitationally bound by the matter they contain, so if the dark energy is indeed a cosmological constant, then the acceleration will have no effect on the collision, which will still happen in about four billion years. If it turns out that dark energy's so-called equation of state parameter (the ratio of its pressure to its density) is more negative than –1, then our universe will advance toward a "big rip" in which galaxies, stars, atoms and even nuclei will be ripped apart in succession. But that would likely occur well after our future merger with Andromeda.

"The link between the brain's disposal system and sleep demonstrates that it would be better to start treating insomnia with the gravity that this condition deserves."

JORGE CRUZ *LONDON, ONTARIO*

PANGAEA'S PIECES

In "Anatomy of a Mass Murderer," by Howard Lee, I noticed on the world map showing the "where and when" of the large areas strewn with volcanic vents called large igneous provinces (LIPs) that the locations of those in the Central Atlantic LIP (except for the one on the upper East Coast of North America) appear like they would "fit" together where North America, South America and Africa were located in that period of time when Pangaea was in existence. Is there a relation between where the Central Atlantic provinces are now located and Pangaea?

Mike Keck
via e-mail

LEE REPLIES: The Central Atlantic LIP does indeed mark the "bleeding wound" of Pangaea's dismemberment. Parts of the LIP now separated by the Atlantic Ocean were connected at the time of its eruption, as you deduced. The counterpart to the northeastern U.S. is in northwestern Africa, particularly Morocco.

BRAIN WASH

The discovery of the glymphatic system, the brain's pathway for eliminating waste products, as described by Maiken Nedergaard and Steven A. Goldman ["Brain Drain"], has far-reaching implications. I have always slept short and irregular hours, so it is alarming to read that the brain's flushing of waste matter such as beta-amyloid is accomplished mainly during sleep and that short sleepers are at more risk of dementia. Yet in my 80th year I have at least as much mental energy, and almost as much physical, as when I was 20. I wonder whether it could be that the glymphatic flushing occurs most strongly in the first 90 minutes of deep sleep?

Guy Ottewell
Dorset, England

The link between the brain's disposal system and sleep demonstrates sleep's importance once again. It is not surprising that there is a relation between sleep health and neurological diseases such as Alzheimer's and Parkinson's because both insomnia in the middle-aged and neurological diseases in the elderly affect a high proportion of the population. Wouldn't it be better, then, to start treating insomnia with the gravity that this condition deserves? I am an insomniac frustrated trying to find the cause and solution for my condition; I recently visited a sleep clinic, and the only diagnosis was: "It is not apnea."

Jorge Cruz
London, Ontario

POLITICS AND EDUCATION

I cannot think of a scarier educational reform than Michael Shermer's suggested cure in "Left Behind" [Skeptic] for what he sees as a lack of political diversity in American colleges and universities. Given that so many U.S. institutions are explicitly conservative (the military, most government agencies, many of our religious or-

ganizations, a growing portion of the media, much of business and industry, and religious-based colleges and universities), higher education has been a lone habitat for liberal and progressive thinking.

JOSEPH ADAM CHEREPON
Ashford, Conn.

SHERMER REPLIES: My proposal for "viewpoint diversity" includes not only political views but economic, social, religious and ideological perspectives. As for the military, according to a 2012 Time *magazine article, troops and veterans are "not the monolithic bloc many believe." One in three officers opposed the Iraq War, and although officers lean conservative, enlisted soldiers may lean liberal, and they outnumber officers four to one. That could account for political donations from military personnel in the 2012 presidential election, including $678,611 to Barack Obama compared with $398,450 to Mitt Romney. Nationally, according to a 2015* Wall Street Journal*/NBC News poll, conservatives are no longer the largest political cohort: 33 percent identify as conservative, down from 37 percent in 2014, whereas 26 percent identify as liberal, up from 23 percent. Moderates are now the plurality at 38 percent. Students need to hear all perspectives, and liberals do not need a safe haven.*

ERRATA

"Brain Drain," by Maiken Nedergaard and Steven A. Goldman, stated that the brain replaces "half a pound of detritus a month and three pounds" a year. It should have given the figures as half a pound each month and nearly six pounds each year.

"Editing the Mushroom," by Stephen S. Hall, should have said that the oil produced by soybean strains created by the company Calyxt had higher levels of monounsaturated fats than olive and canola oils, not monosaturated fats. Further, it erroneously referred to the removal of developing horns among male Holstein cows. Cows are female by definition, and the practice is performed on male and female Holstein cattle.

In addition, a caption in the box "Genetic Modification by Any Other Name" said when a cell repairs DNA cut by the Cas9 enzyme, it adds several base pairs at the site. In fact, it may add or delete base pairs.

LETTERS TO THE EDITOR

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Don't Let History Die

Before war and time destroy more of our important cultural sites, we need to save them in 3-D digital libraries

By the Editors

Across 163 different countries, 1,000 natural and cultural historic places constitute our most precious human heritage. UNESCO calls them World Heritage Sites, and they range from the Democratic Republic of the Congo's endangered Virunga National Park to Syria's ancient city of Palmyra to Mount Rushmore in the U.S.

We lose a little of that heritage every day. War, climate change and pollution take a toll, as do wind and rain. Already gone are the Buddhas of Bamiyan in Afghanistan (dynamited by the Taliban in 2001) and Palmyra (partially destroyed by ISIS in 2015). The $4 million a year that UNESCO allocates for preservation is not nearly enough to take care of even the four dozen sites considered at imminent risk of being lost forever. But there is an alternative. New digital-conservation technologies let us hold on to them, at least virtually, through 3-D scanning, modeling and digital storage. Such projects can be accomplished through partnerships of governments, universities, industry and nonprofits.

To make a 3-D model, a laser scanner bounces light off an object and collects the resulting topological cloud of points. To reproduce every nook and cranny, the scanner snaps overlapping images from all possible angles. A computer then sews together one large surface image and draws lines from one point to another to create a wire-frame model. High-resolution digital cameras add color and texture. When fully assembled, the models can be viewed, printed or manipulated.

These scans do more than pickle a memory in a database. With highly accurate measurements, archaeologists can find hidden passages or reveal ancient engineering tricks. Schoolkids can explore places they might otherwise never see. And when a site is destroyed, the scans can even be used to reconstruct what was there. That has already happened for one World Heritage Site, the Kasubi Tombs in Uganda. Built of wood in 1882, they were destroyed by fire in 2010 and rebuilt in 2014, based in large part on 3-D models made in 2009. More than 100 World Heritage Sites have been already preserved as 3-D models, and conservationists are racing to record as many more as possible, especially in the conflict-torn Middle East and northern Africa.

In 2003 Ben Kacyra, an Iraqi-American born in Mosul, cofounded the nonprofit CyArk, now a leader in 3-D digital preservation. Kacyra made his fortune developing and deploying the world's first portable 3-D-laser-scanning systems; his organization was also the first—and is now the largest—to apply that technology to preservation on a grand scale. The CyArk 500 project aims to digitally preserve 500 World Heritage Sites, mixing public and private financing, government support and cutting-edge research to make the work as accurate and useful as possible. All projects are archived on public servers and in safe database bunkers.

Conservationists around the world are emulating CyArk's methods. To scan Mount Rushmore, the nonprofit provided people, expertise and some funding. The U.S. National Park Service added funding plus a technical climbing team to scan the presidents' nostrils and underneath their eyebrows. A local engineering firm and university mining department consulted on the local geology. Historic Scotland, the Scottish National Heritage agency and the Digital Design Studio of the Glasgow School of Art collected data and deployed them as tools for visualizing and conserving the mountain.

Buildings of local importance can also be preserved this way. Because engineering, architectural and other firms use 3-D scanning in their work, many cities have local scanning companies. Tim Crammond, manager of Pittsburgh-based Laser Scanning America, charges about $1,000 a day to acquire and process data, but, he says, "despite the numerous requests we receive from entities interested in using 3-D scanning for historic preservation, the funding doesn't seem to be in place for it."

Although each one is unique, a typical World Heritage scanning project costs roughly $50,000. For $50 million, models of all 1,000 World Heritage Sites could be stored forever. We urge governments, universities and nonprofits to support digital conservation to capture our history before it is lost. SA

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Illustration by Deshi Deng

Clive R. Neal is a professor of geology at the University of Notre Dame. His research explores the origin and evolution of the moon, and he recently chaired the senior review panel for extended space missions for NASA's Planetary Science Division.

A Return to the Moon Is Crucial

It's not just a way station to Mars—it's a way to build new industries

By Clive R. Neal

A few months ago, when European Space Agency director general Johann-Dietrich Woerner laid out a vision for his agency to lead the way in establishing an international Moon Village, I had a feeling of déjà vu. In January 2004 President George W. Bush announced his own Vision for Space Exploration, in which the U.S. would lead the world back to the moon. Once we had gone there, and humans had learned to live and work successfully on another world, we would head on to Mars as the ultimate destination.

Bush's idea was inspiring enough that, in addition to NASA, no fewer than 13 international space agencies signed on to participate in developing a plan for reaching the moon. Unfortunately, the plan's implementation was badly flawed. NASA tried to relive the glory days of Apollo by focusing on one-use vehicles that would transport everything to the moon from Earth. Apollo was a fantastic achievement, but it was not sustainable, which was in part why the program was canceled in the early 1970s. Bush's vision proved too expensive to sustain as well, and in 2010 President Barack Obama declared that the U.S. had no need to go back to the moon, saying, in essence, that we've been there, done that. Instead, he said, we would go to Mars without taking that interim step.

But a return to the moon is crucial to the future of human space exploration—and not just for the experience it would give us in off-world living. Our satellite is also rich in resources, notably water ice, which can be split via electrolysis into oxygen and hydrogen. These elements can then be used in fuel cells and in making liquid rocket fuel. If we are ultimately heading to Mars (or anywhere else), hauling that fuel off the surface of Earth is terribly inefficient. Much better to launch it from the moon, where gravity is one sixth as strong.

A return to the moon could also inspire the next generation and advance technology just as Apollo did—but do so in a sustainable, stepwise manner. The taxpayer needs to see a return on investment for this endeavor and not only in technology development. For example, a spacecraft-refueling depot orbiting the moon—supplied with fuel refined from lunar resources, privately operated and selling its products to various space agencies—is one commercial on-ramp to bring the moon into our economic sphere of influence. Such activities could result in a major reduction in launch mass from Earth's surface, thereby cutting the cost of space missions. This has the potential to create a slew of industries that in turn create high-tech and well-paid jobs.

The immediate next step in lunar exploration should be robotic prospectors on the lunar surface to define the extent, form, distribution, and ease of extractability and refinement of those resources identified from orbit. An international effort could facilitate this critical operation. NASA does have a Resource Prospector mission in development, but it is being done on a shoestring budget that could be cut at any time. Russia also has a Lunar-Resurs program under development, partnering closely with the European Space Agency. And let us not forget China, which became in 2013 the third nation to successfully soft-land on the moon. China plans to return lunar samples to Earth within the next couple of years, again following the U.S. and Russia.

Currently the U.S. vision for human space exploration is to use a robotic spacecraft to capture a small boulder from an asteroid, about one meter in diameter, and redirect it to an orbit around the moon. Humans will then explore that boulder as practice for an eventual voyage to Mars. But this so-called Asteroid Redirect Mission will have no applicability to Mars, largely because working in microgravity is a very different proposition from working on the surface of a planet. Basically, it is a fast track to nowhere.

Which brings us back to Woerner's Moon Village, which spacefaring nations applauded when it was presented at the ESA-led "Moon 2020-2030" meeting last December. Right now the U.S. is standing on the sidelines, watching other nations move on. Yes, Mars is the ultimate destination, but our country has an ill-defined pathway on how to get there. The moon is the enabling asset and the key to our achieving that goal. We need to redefine the way we look at human space exploration such that any money spent on space travel can be viewed as an investment in the future. SA

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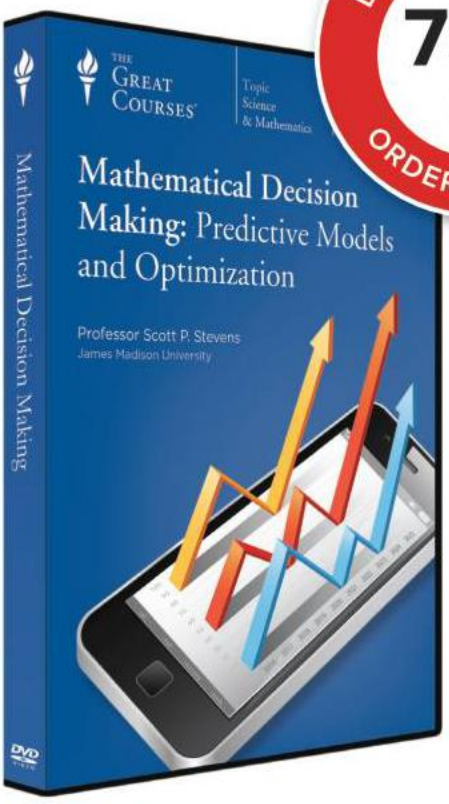

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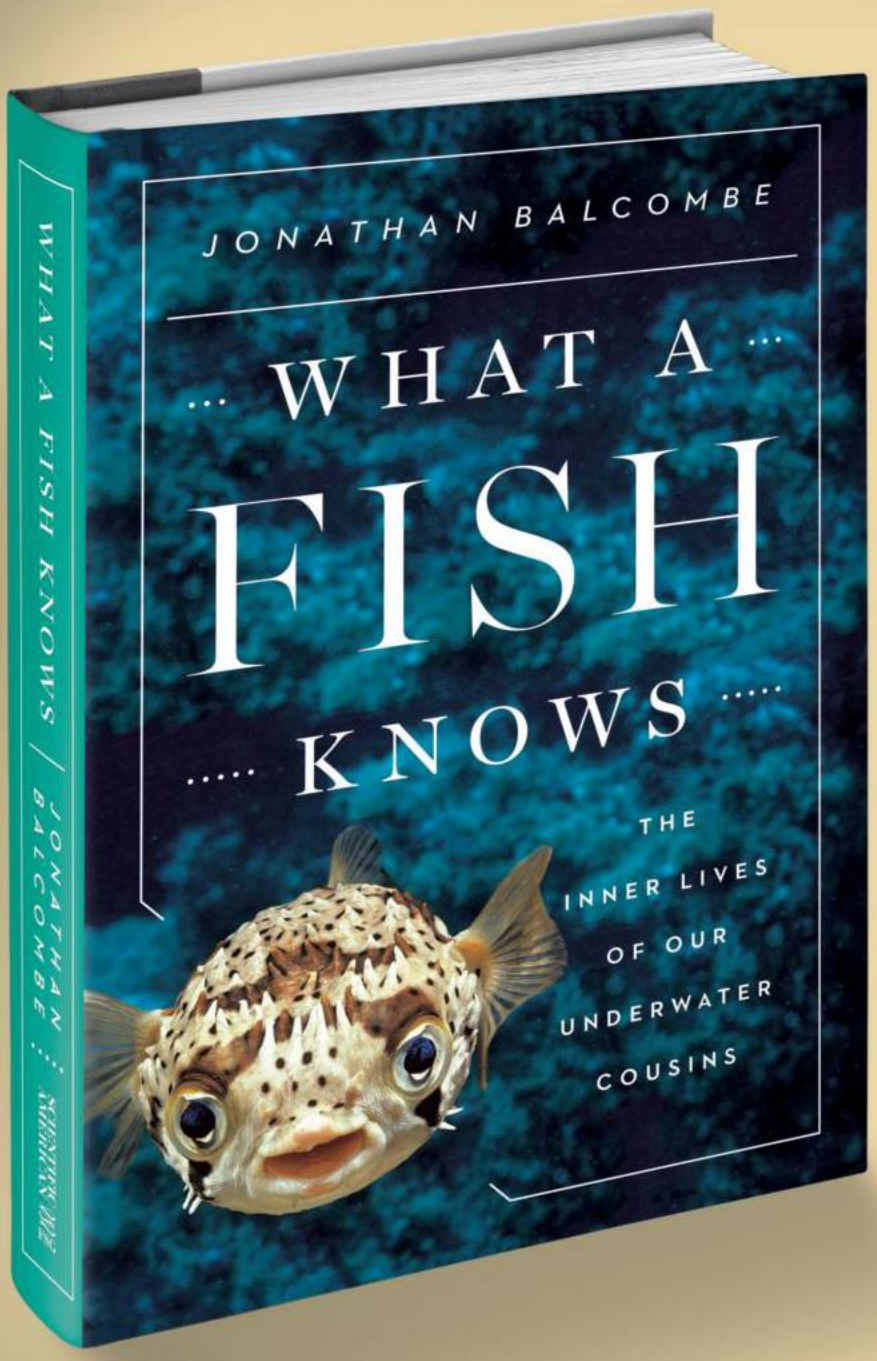

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SPACE

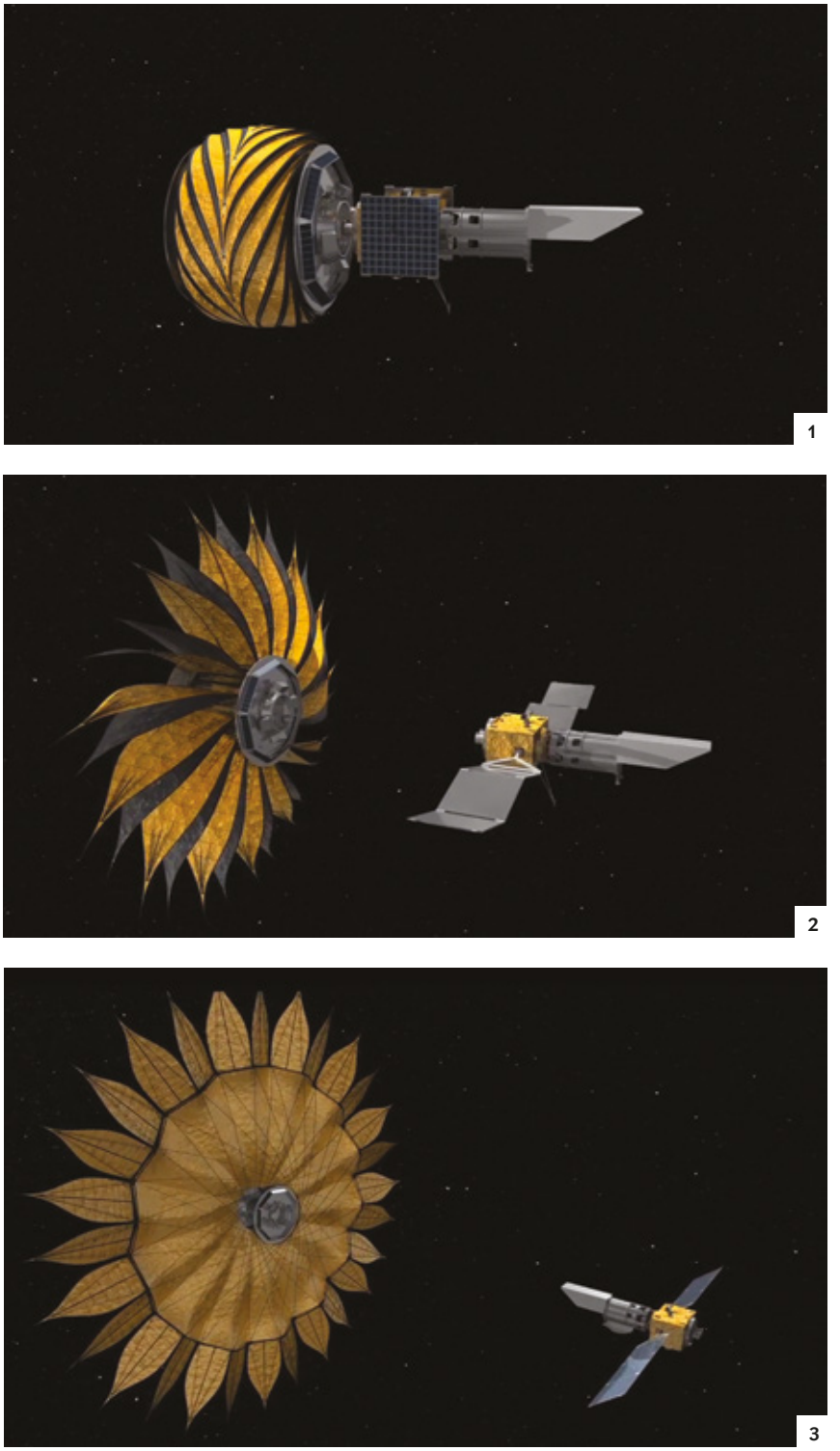
How to Find Another Earth

A "starshade" flying in front of NASA's upcoming big telescope could deliver images of potentially habitable worlds decades ahead of schedule

Can a next-generation NASA space telescope take pictures of other Earth-like planets? Astronomers have long dreamed of such pictures, which would allow them to study worlds beyond our solar system for signs of habitability and life. But for as long as astronomers have dreamed, the technology to make it happen has seemed many decades away. Now, however, a growing number of experts think NASA's Wide-Field Infrared Survey Telescope (WFIRST) could take snapshots of other "Earths"—and soon. The agency formally started work on the observatory in February of this year and plans to launch it in 2025.

When WFIRST launches, it will sport a 2.4-meter mirror that promises panoramic views of the heavens and will use its wide eye to study dark energy, the mysterious force driving the universe's accelerating expansion. But another hot topic—the existential quest to know whether we are alone in the universe—is already influencing the mission.

Researchers have discovered more than 3,000 planets around other stars and expect to find tens of thousands more within the next decade. Rough statistics suggest that



These sequential images show how a starshade could be deployed with a future space telescope. Initially folded up for launch into space (*1*), the starshade would detach and unfurl (*2*) and then fly away (*3*) to its station tens of thousands of kilometers ahead of the telescope.

COURTESY OF NASA/JPL-CALTECH

every star in the sky is accompanied by at least one such exoplanet and that perhaps one in five sunlike stars bears a rocky orb in a not too hot, not too cold "habitable zone" where liquid water can exist. The best way to learn whether any of these worlds are Earth-like is to see them, but taking a planet's picture from light-years away is far from easy. A habitable world would be a faint dot lost in the overpowering glare of its larger, 10 billion times brighter star.

Earth's turbulent, starlight-blurring atmosphere is also a severe obstacle to imaging faint planets from ground-based observatories, and most experts agree that the solution is to use space telescopes. But neither NASA's Hubble Space Telescope nor its supersize successor, the James Webb Space Telescope set for launch in 2018, comes close to the high contrast needed. To help capture planetary shots, WFIRST will have an advanced planet-imaging coronagraph, an instrument inside the telescope that filters out starlight using a complex series of masks, mirrors and lenses. But this instrument was a late addition to WFIRST, which is not optimized for a coronagraph. Consequently, most experts predict that its coronagraph will fall short of the contrast required to image other Earths. Indeed, snapping such images is so challenging that NASA's tentative plans call for putting it off for perhaps 20 years or more as the agency develops the technology and budgetary breathing room to build an entirely new space telescope after WFIRST.

A device called a starshade might offer a shortcut. A starshade is a sunflower-shaped, paper-thin screen half as big as a football field that would float tens of thousands of kilometers directly ahead of WFIRST, blocking out a target star's light in much the same way one might blot out the sun in the sky with an extended thumb. Because starshades work with practically any telescope, one on WFIRST could cast a deeper shadow and see fainter planets than a coronagraph. Working in tandem, the starshade and the telescope could take pictures of perhaps 40 planets, including a few that in size and orbit would mirror Earth. "If and only if it had a starshade, WFIRST could give us images of a few true-blue Earths late next decade rather than waiting for another 20 years," says Jeremy Kasdin, a Princeton University professor and lead scientist for WFIRST's coronagraph. "This is a real opportunity to find another Earth sooner and for less money before making a huge investment in NASA's next giant space telescope."

Despite WFIRST being nearly a decade away from launch, the decision to move forward with preparations for a starshade rendezvous must come soon because WFIRST must receive minor modifications to allow it to sync up with a starshade across tens of thousands of kilometers of empty space. As such, an official starshade mission does not exist. Instead Paul Hertz, director of NASA's astrophysics division, says the agency is "in a 'don't preclude a starshade' mode." So far not precluding a starshade closely resembles a concerted effort to build one: when NASA first announced the formal start of WFIRST, it also confirmed that the telescope would be launched into an orbit 1.5 million kilometers from Earth, where conditions are tranquil enough for a starshade to function. In addition, the agency recently formed the StarShade Readiness Working Group and officially designated the starshade as a "technology development activity"—moves that could accelerate the agency's progress.

In fact, in the basement of Princeton's sprawling Frick Chemistry Laboratory, Kasdin is already working on a test bed:

MODEL ORGANISMS

Lab Mice Are Too Clean

Housing lab-grown mice with "dirty" rodents from pet stores makes for better human models

Scientists usually order laboratory mice online, but immunologist David Masopust went to more trouble. While doing research years ago at Emory University, he drove to a barn several hours away to trap the rodents himself. He suspected that commercially provided lab mice were missing some key immune cells because they had inexperienced immune systems—a result of being raised in extremely hygienic facilities. Masopust, now a professor at the University of Minnesota, went on to formally test his suspicion over the course of a decade and has found that it was correct: lab mice used by the scientific community and pharmaceutical world to test drugs and vaccines for human diseases are in some ways poor models of the human adult immune system.

As published this spring in the journal *Nature,* Masopust and his colleagues discovered that mice raised in germ-free facilities had immune systems that looked more like those of human babies than adults, as judged by the types of immune cells present and the genes that were active in those cells. For example, memory $CD8^+$ T cells that serve as first responders to infection were virtually undetectable in adult lab mice but clearly present in barn mice and mice from pet stores. "We've 'known' this, but it's good to finally see it proven," says Purvesh Khatri, a computational systems immunologist at Stanford University who was not involved in the study.

What is more, when the researchers housed "clean" lab mice with "dirty" pet store mice (which carried germs), about a fifth of the lab mice died of infections within a few months. The mice that survived, however, developed more robust immune repertoires, and the gene activity of their immune cells shifted to resemble those of adult humans. In follow-up experiments, those mice fought off

Illustrations by Thomas Fuchs

a meter-wide, 75-meter-long tube with a camera at one end, a laser at the other and a scaled-down starshade in between. By the end of the summer, he predicts, the test bed will have demonstrated the necessary contrast ratio that, scaled up to full size, could enable the imaging of Earth-like planets. Meanwhile aerospace company Northrop Grumman has tested miniaturized starshades at a dry lake bed in Nevada and at a giant solar telescope in Arizona. And at the NASA Jet Propulsion Laboratory, researchers are demonstrating how to fabricate a larger-scale starshade's delicate petals, fold the entire structure up inside a rocket, and deploy and unfurl it to the size of a baseball diamond.

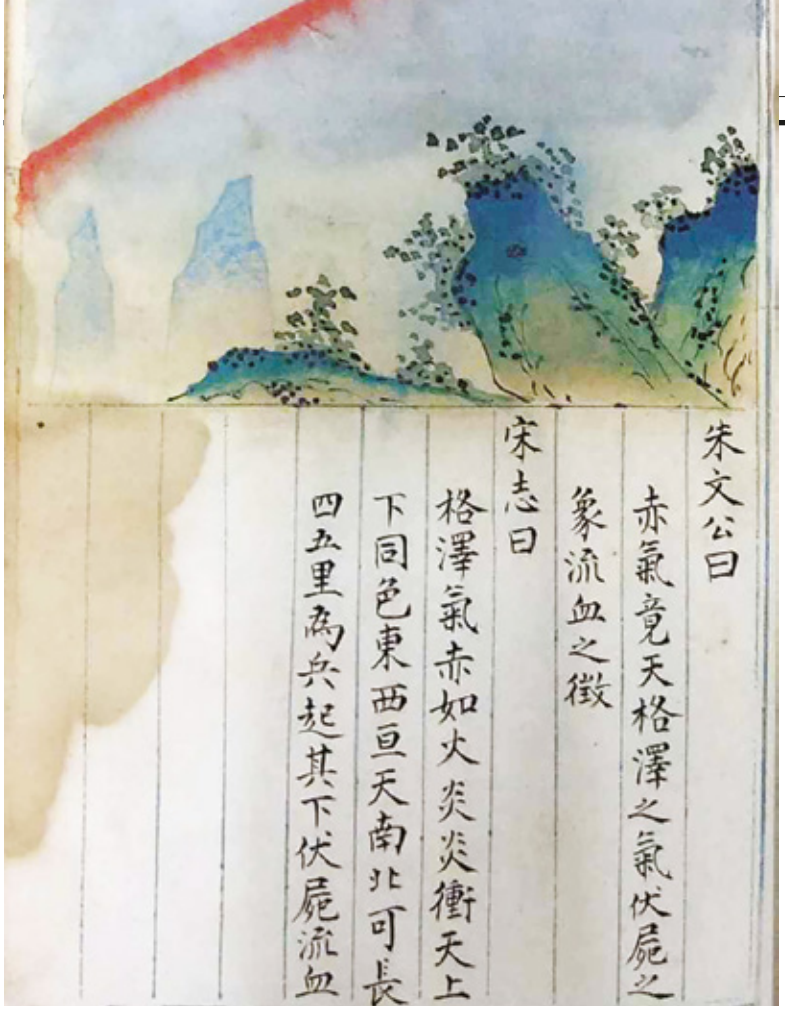
Not all the obstacles to a starshade are technological. One for WFIRST could easily cost a billion dollars—far too much extra money for the telescope's budget to bear. Consequently, it would have to first be proposed and approved as an independent project with its own substantial supply of NASA funding. That's a high hurdle for a still nascent technology to clear, but the payoff could be historic: delivering the first image of an alien Earth is an event that can happen only once. Should we try to do it as quickly as possible or delay it for decades more? NASA and the astronomical community must decide soon. —*Lee Billings*

The study could partially explain why therapeutics tested in animals often fail in human trials.

bacterial infections just as well as mice vaccinated against the pathogens.

These results suggest that having lab mice share space with animals from the wild or from pet stores could give researchers a more realistic view of disease progression and treatment responses in human adults. Additionally, by showing that lab mice fail to model key immune features, the study could partially explain why therapeutics tested in animals often fail in human trials. "Variables that matter in the real world aren't present in controlled experiments," Khatri explains.

—*Esther Landhuis*



A premodern drawing of what may be an aurora in the Chinese manuscript "Tiānyuán Yùlì Xiángyìfù."

ASTRONOMY

Solar Sleuths

Ancient documents reveal the sun's activities prior to the scientific record

Until Galileo kick-started modern astronomy in the early 1600s, the record of the sun's activities was basically blank—or so scientists thought. To shed light on our star's history, researchers at Kyoto University in Japan have begun to comb through ancient texts. So far they have found dozens of apparent references to sunspots, auroras and other solar events that date as far back as the seventh century—albeit in terms that require more interpretation than Galileo's drawings.

"Although [scientists] can use ice cores, tree rings and sediments for clues as to past weather and climate change, things like space weather and auroras leave little or no trace," says Bruce Tsurutani, a space plasma physicist at NASA who is not involved in the Kyoto research. "So we need information that man has taken himself."

To that end, a team of historians and astronomers in Kyoto analyzed hundreds of handwritten Tang Dynasty documents from China as well as Japanese and European manuscripts from around the same period, the seventh to 10th centuries. As reported online in April in *Publications of the Astronomical Society of Japan,* the researchers came across the terms "white rainbows" and "unusual rainbows" again and again. In fact, such spectacles were written about on the same dates in the documents from all three regions. Because people in such geographically distant locations simultaneously reported the phenomenon, the descriptions can only be explained as auroras, says lead author Hisashi Hayakawa, who is a student at Kyoto University's Graduate School of Letters. Auroras are caused by charged particles from the sun colliding with particles in Earth's atmosphere. They usually occur as rings around our planet's magnetic poles.

Last year the group also published a comprehensive list of what most likely are sunspots mentioned in the official history of China's Song Dynasty (10th to 13th centuries), where the spots are described as plums, peaches or eggs in the sun. Overall they have recorded 38 sunspots, 13 unusual or white rainbows, and 193 other auroralike events, which are compiled into a searchable, open database online.

There is no way to know for sure whether the texts refer to the work of our solar system's star, says Hiroaki Isobe, an astronomer and one of the paper's authors. The interpretation of antiquated language usages is a unique challenge in this endeavor, as is deducing the true nature of events that ancient authors often interpreted as omens. "[Descriptions of] tsunamis and earthquakes are clear, but for historians it's quite difficult to know what a description like 'the sky was red' means," Hayakawa says. The Kyoto team hopes to gather more evidence that its conclusions are correct by collaborating with researchers in Europe, Saudi Arabia and South Korea, who are also conducting historical studies of solar events.

A long-term record of the sun's activities could ultimately reveal patterns that, for example, tell scientists more about the shifting of Earth's magnetic poles and the effect, if any, the sun's magnetic activity has on our planet's climate. Such a record could also provide a better understanding of solar flares, which can fry satellites, cause electrical blackouts and disrupt telecommunications. "In predicting the future, we have to know the past," Isobe says.

—*Rachel Nuwer*

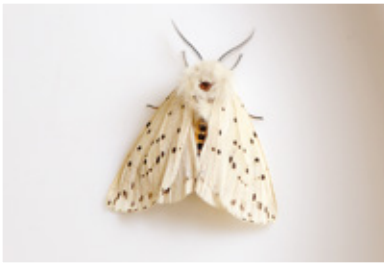
The researchers came across the terms "white rainbows" and "unusual rainbows" again and again.

COURTESY OF NATIONAL ARCHIVES OF JAPAN

ANIMAL BEHAVIOR

Lights Don't Lure Urbanite Moths

Some city-dwelling moths have evolved to avoid lamps, but is the adaptation helpful?



ASHLEY COOPER *Alamy (top)*; GETTY IMAGES *(bottom)*

The saying "like a moth to a flame" might have to be snuffed out. Some moths in light-flooded urban areas have evolved to resist artificial lights, according to a new study in *Biology Letters*.

While in graduate school in Basel, Switzerland, evolutionary biologist Florian Altermatt kept tabs on the number of nocturnal insects that flocked to street lamps. "I was mostly interested in what species were coming to the light, and then I noticed there were fewer species coming to the light when in a city," says Altermatt, who is now at the University of Zurich. The data were set aside in favor of his Ph.D. research, but the question of whether or not insects in cities were impervious to light's siren call stuck with him. Five years later he and Dieter Ebert, an environmental scientist at the University of Basel, decided to formally investigate.

The researchers first collected ermine moth larvae from urban and rural sites throughout France and Switzerland. The moths were raised to maturity. Then, in one go, the scientists released all the adults—320 country moths and 728 city moths—into a dark room with a fluorescent lamp at the far end. Nearly all the moths born in the countryside flew to the lamp, but only about two thirds of the urban moths did the same. The rest of that group remained near their starting point opposite the light.

These results suggest an evolutionary adaptation to light-polluted areas. Such a change could save the lives of many moths: every night hundreds of insects can die of starvation at one street lamp, according to previous studies. But this behavior could also have downsides. "I don't think that this adaptation can really compensate for damage caused by light pollution," Altermatt warns. For example, in an effort to avoid bright lights, city-dwelling moths may keep to smaller areas of land and thus pollinate fewer plants and encounter fewer mates.

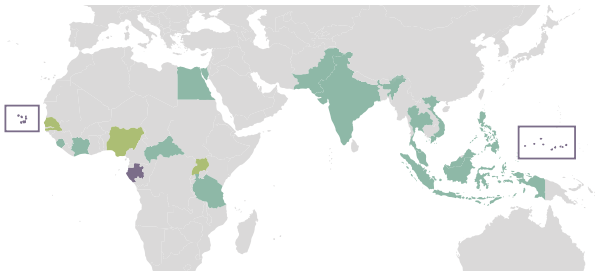
—Jennifer Hackett

HEALTH

Zika's Global Connections

Zika is more pernicious than public health officials anticipated. At present, it is circulating in more than 50 countries. And as of mid-May, seven countries or territories have reported cases of microcephaly or other serious birth defects linked to the virus, which is transmitted by mosquito bite, blood transfusion or sexual contact with an infected human. It can also be passed from mother to fetus during pregnancy.

Despite Zika's vast range over almost 70 years (*right*), there is little genetic difference among the various strains (*below*), according to an analysis by researchers at the University of Texas Medical Branch at Galveston. For example, the strain currently in the Americas and another previously detected in French Polynesia are practically indistinguishable from each other (*group in gray box*). If the virus has changed so little over time, why is it rearing its ugly head now? Scientists are not sure yet, but new experimental work in mosquitoes suggests that the virus was capable of causing detrimental health effects and outbreaks all along. Therefore, it is unlikely mutations enabled new abilities. Instead public health officials probably did not understand Zika's potential because the virus circulated mostly in remote locations until recently. —*Dina Fine Maron*



Virus detected 1947–2007
- Evidence in insects, monkeys or humans
- Confirmed human cases

2007–2014 outbreaks
- Confirmed human cases

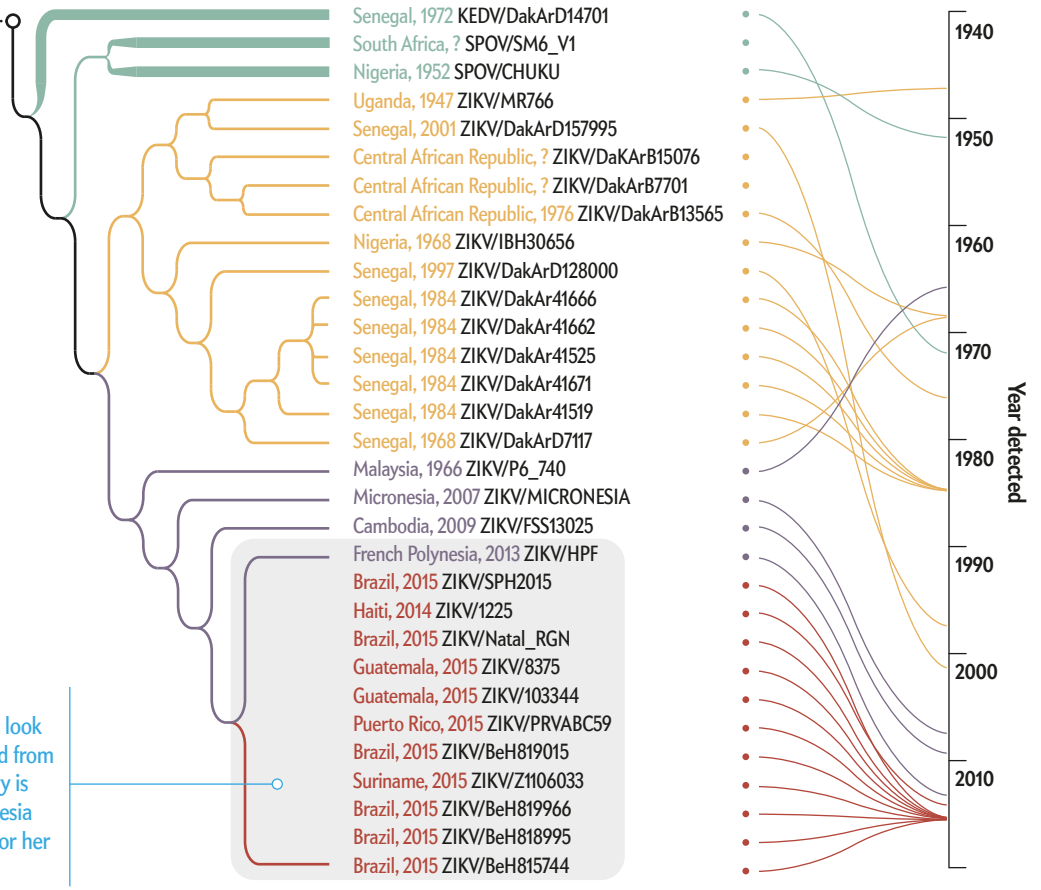
Ancient ancestor to Zika and other African flaviviruses

The branches of this evolutionary tree joined closest to one another show virus strains with the least genetic divergence and thus the most relatedness.

- African sister flavivirus
- African lineage
- Asian lineage
- Americas, 2015

Genetic divergence from nearest related strain

0%–20% 40%–50%



Genetically, the Zika strains now circulating through the Americas look as if they most directly descended from strains of Asian origin. One theory is that a traveler from French Polynesia brought the virus to Brazil in his or her bloodstream in 2013.

SOURCES: "ZIKA VIRUS VECTORS AND RESERVOIRS," BY SCOTT C. WEAVER, UNIVERSITY OF TEXAS MEDICAL BRANCH, FEBRUARY 26, 2016; "ZIKA VIRUS OUTSIDE AFRICA," BY EDWARD B. HAYES, IN *EMERGING INFECTIOUS DISEASES*, VOL. 15, NO. 9, SEPTEMBER 2009; CENTERS FOR DISEASE CONTROL AND PREVENTION

SCIENTIFIC AMERICAN ONLINE To read more about Zika's evolution, visit ScientificAmerican.com/zika-evolution

Graphic by Tiffany Farrant-Gonzalez

ENERGY

Water Power

Extracting uranium from seawater could offer reliable fuel for nuclear power plants

The earth's oceans hold enough uranium to power all the world's major cities for thousands of years—if we can extract it. A project funded by the U.S. Department of Energy is making notable advances in this quest: scientists at Oak Ridge National Laboratory and Pacific Northwest National Laboratory have developed a material that can effectively pull uranium out of seawater. The material builds on work by researchers in Japan and consists of braided polyethylene fibers coated with the chemical amidoxime. In seawater, amidoxime attracts and binds uranium dioxide to the surface of the braids, which can be on the order of 15 centimeters in diameter and run multiple meters in length depending on where they are deployed. Later, an acidic treatment recovers the uranium in the form of uranyl ions, a product that requires processing and enrichment before becoming fuel. The procedure was described in a special report this spring in *Industrial & Engineering Chemistry Research*.

The process is still inefficient and expensive, but finding alternatives to uranium ore mining is a necessary step in planning for the future of nuclear energy, says Stephen Kung of the DOE's Office of Nuclear Energy, who was not involved in the project. Terrestrial sources of uranium are expected to last for only another 100 to 200 more years. "We need to take the longer view on this resource," Kung says. —*Jennifer Hackett*

BY THE NUMBERS

3.3
MICROGRAMS PER LITER
Concentration of uranium in seawater

4
BILLION TONS
Total uranium available in all Earth's seawater

6
GRAMS
Weight of uranium extracted per kilogram of adsorbent material

8
WEEKS
Time required to extract 6 grams

27,000
KILOGRAMS
Amount of uranium fuel needed to run a 1-gigawatt nuclear power plant for one year

SOURCES: COSTAS TSOURIS *Oak Ridge National Laboratory (first, third and fourth items)*; COSTAS TSOURIS *Oak Ridge National Laboratory* AND STEPHEN KUNG *Office of Nuclear Energy, Department of Energy (second item)*; WORLD NUCLEAR ASSOCIATION *(fifth item)*

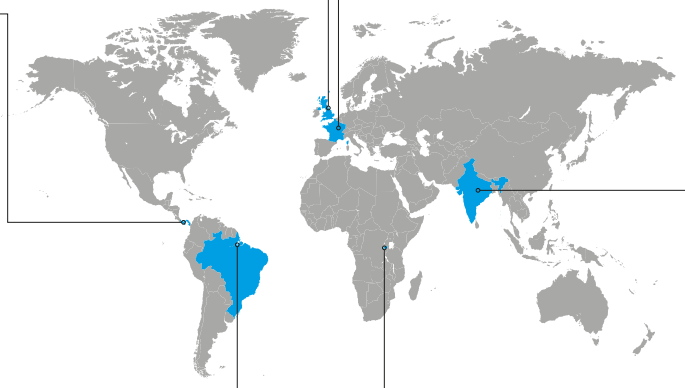
IN THE NEWS

Quick Hits

U.K.
Britons have a reputation for heavy drinking, but research from the University of Sheffield found that only about 10 percent of adults regularly consume large amounts of alcohol in one sitting, making the unhealthy behavior still common but not rampant.

FRANCE
A humanoid robot recovered a vase and other artifacts from the wreckage of *La Lune*, a 17th-century French ship that lies off the country's southern coast at a depth of 100 meters. Stanford University roboticist Oussama Khatib built the device with dexterous humanlike hands and controlled its movements via his own from a nearby boat.

PANAMA
Fossilized 21-million-year-old monkey teeth unearthed during expansion work on the Panama Canal are the first evidence of the mammal's presence in North America. Most researchers previously thought New World monkeys evolved in isolation in South America before the continent connected with its northern counterpart 3.5 million years ago.



INDIA
The country's space agency launched the seventh and final satellite needed to create its own GPS system. The U.S., Russia, China and Europe also have dedicated satellite-navigation networks.

BRAZIL
Oceanographers were surprised to find that a 9,300-square-kilometer coral reef system thrives at the mouth of the Amazon River. The reef, which exists in a pocket of clear water in an otherwise muddy river, has fewer species than is typical for a coral reef but is still a hotbed of marine life.

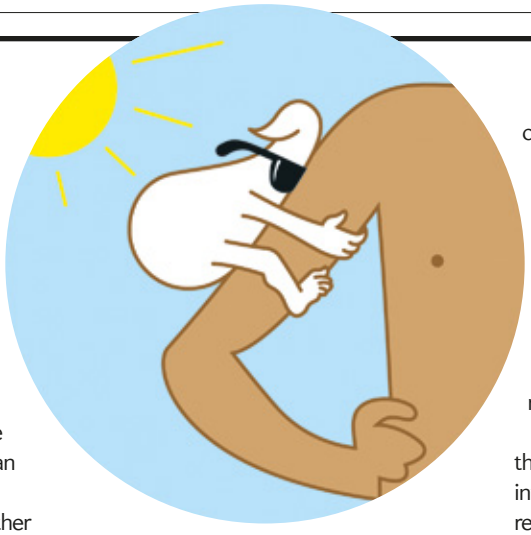
RWANDA
Fixed-wing drones are scheduled to start delivering blood and emergency medicine to remote clinics this summer. The drones can autonomously navigate to 21 facilities and travel up to 120 kilometers in one trip.

For more details, visit www.ScientificAmerican.com/jul2016/advances

MATERIALS SCIENCE

Skin Deep

Dermatologists and bioengineers develop a sunscreen that will stay put



Under intense summer rays sunscreen can help protect against a wicked burn, but some of the common active ingredients in these sprays and lotions can also seep through the skin and enter the bloodstream. Although it is unclear whether this poses any risks, Yale University dermatologist Michael Girardi thinks it is worthwhile to develop alternatives. In collaboration with the university's bioengineering department, he has developed a sunscreen formulation designed to keep chemicals on the skin's surface.

The sunscreen chemicals that absorb the sun's dangerous ultraviolet radiation are typically organic molecules (as opposed to the metal oxides that block the sun's rays in sunblock). There is no evidence that these absorbing molecules can directly harm humans. A small body of research that includes animal and cell-culture studies, however, shows that some of them can bind to hormone receptors. The results may suggest a potential to disrupt the body's endocrine system, the traffic of hormones that regulates reproduction and other functions.

In an attempt to develop a sunscreen that would not soak into the skin, Girardi and his team encapsulated the molecules of the common UV absorber padimate O in nanoparticles of a biodegradable polymer that binds to proteins on skin cells. The nanoparticles stick to those cells even when wet and come off only when toweled. The new formulation protected mouse skin from UV damage just as well as a conventional padimate O sunscreen, according to Girardi's recent study in *Nature Materials*.

Kenneth Kraemer, a dermatologist at the National Cancer Institute who was not involved in the project, is impressed by the results. "If you can minimize the risk of sunscreen entering the bloodstream, it's probably a good thing," he says. Still, it will be a long time before the formulation appears in beach bags. This summer Girardi will carry out a pilot study involving an estimated 25 people to establish the SPF of the nanosunscreen at various concentrations. Meanwhile any sunscreen is better than going outside unprotected when it comes to avoiding sunburns, wrinkling and UV damage that can lead to cancer.

—*Katherine Bourzac*

SPACE

Journey to Jupiter

NASA's Juno spacecraft reaches the planet after a five-year voyage

The first spacecraft to probe deep underneath Jupiter's thick clouds is scheduled to arrive at the gas giant on July 4. Named Juno, the NASA orbiter will collect data that could elucidate the planet's origins and evolution, gather details about its long-lived storm (the Great Red Spot) and send back the highest-resolution color images of Jupiter to date.

Jupiter was apparently born from the leftover gas and dust of the primordial nebula that formed our sun, yet exactly how that birth occurred, or even whether the planet has a solid core, is unknown. "Learning about the formation of Jupiter enlightens us about the formation of all the planets and what went on in the early solar system," says Scott Bolton, the project's principal investigator. With that objective in mind, the NASA team has programmed the sensor-laden Juno to measure the chemical composition of the planet's atmosphere and to map its gravitational and magnetic fields. The craft's microwave radiometer will also "see" about 550 kilometers below the clouds covering Jupiter's surface.

Juno is only the second space mission dedicated to the King of Planets, after the Galileo orbiter arrived in 1995 and spent eight years there. Juno's rendezvous will be much shorter: it will deorbit and burn up within Jupiter's atmosphere after about 20 months. —*Bryan Lufkin*

BY THE NUMBERS

2.8
BILLION KILOMETERS
Total distance traveled

11
SOLAR PANELS
Juno is the first solar-powered spacecraft to operate this far from the sun

37
Number of times Juno will orbit Jupiter's poles

$1.1
BILLION
Cost of mission to date

MISSION TIMELINE

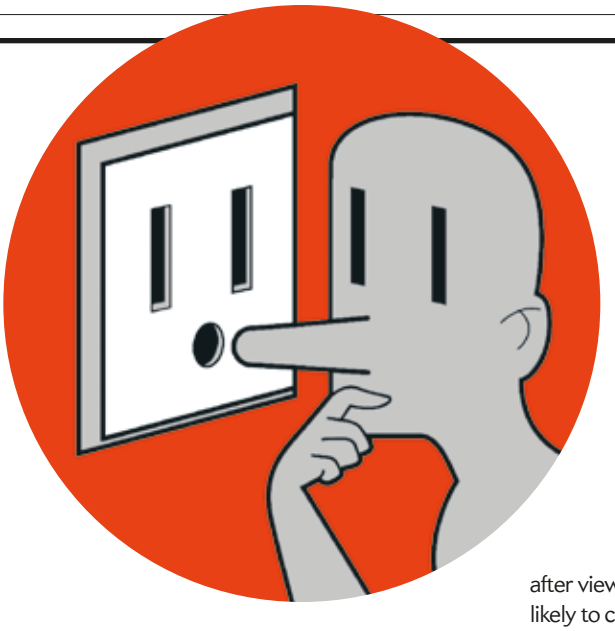
AUG. 5, 2011	OCT. 9, 2013	JULY 4, 2016	FEB. 2018
Juno launches	Earth flyby gravity assist	Arrival at Jupiter	Mission ends

COURTESY OF NASA/JPL/SPACE SCIENCE INSTITUTE (*Jupiter*); SOURCE: NASA (*By the Numbers*)

PSYCHOLOGY

Morbid Curiosity

The human desire to know is more powerful than we have thought



Curiosity is often considered a good instinct, but sometimes such inquiry can backfire.

Why do people seek out information about an ex's new relationships, read negative Internet comments and do other things that will obviously be painful? Because humans have an inherent need to resolve uncertainty, according to a recent study in *Psychological Science*. The new research reveals that the need to know is so strong that people will seek to slake their curiosity even when it is clear the answer will hurt.

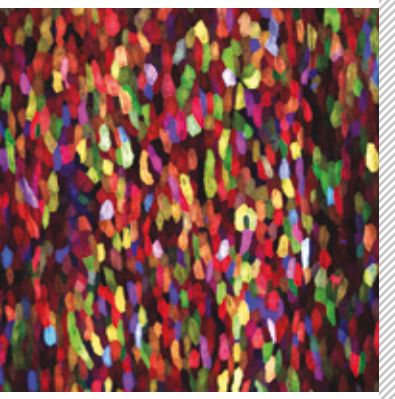
In a series of four experiments, behavioral scientists at the University of Chicago Booth School of Business and the Wisconsin School of Business tested students' willingness to expose themselves to aversive stimuli in an effort to satisfy curiosity. For one trial, each participant was shown a pile of pens that the researcher claimed were from a previous experiment. The twist? Half of the pens would deliver an electric shock when clicked.

Twenty-seven students were told which pens were rigged; another 27 were told only that some were electrified. When left alone in the room, the students who did not know which ones would shock them clicked more pens and incurred more jolts than the students who knew what would happen. Subsequent experiments replicated this effect with other stimuli, such as the sound of fingernails on a chalkboard and photographs of repulsive insects.

The drive to discover is deeply ingrained in humans, on par with the basic drives for food or sex, says Christopher Hsee of the University of Chicago, a co-author of the paper. Curiosity is often considered a good instinct—it can lead to new scientific advances, for instance—but sometimes such inquiry can backfire. "The insight that curiosity can drive you to do self-destructive things is a profound one," says George Loewenstein, a professor of economics and psychology at Carnegie Mellon University who has pioneered the scientific study of curiosity.

Morbid curiosity is possible to resist, however. In a final experiment, participants who were encouraged to predict how they would feel after viewing an unpleasant picture were less likely to choose to see such an image. These results suggest that imagining the outcome of following through on one's curiosity ahead of time can help determine whether it is worth the endeavor. "Thinking about long-term consequences is key to mitigating the possible negative effects of curiosity," Hsee says. In other words, don't read online comments.

—*Roni Jacobson*



COURTESY OF CHEN-HUI CHEN *Duke University*

BIOLOGY

A Coat of Many Colors

As if the magenta fish darting around Kenneth Poss's tanks weren't flashy enough, under ultraviolet light they morph into miniature rainbows. Poss, a cellular biologist at Duke University, and his colleagues genetically engineered this line of zebra fish to have skin that fluoresces in all colors. In fact, each skin cell can glow a unique shade to create a "bar code" that lets researchers track hundreds of cells simultaneously. In this way, they can observe in real time how individual cells respond to injuries and close wounds. As reported in March in *Developmental Cell*, the team found that after an injury, such as an abrasion or fin amputation, some of the fish's skin cells grew larger to compensate for a loss of neighboring cells. Others left their original locations and traveled to a new area to patch a hole.

The coloring technique could also help scientists better understand how skin cells react to drugs or behave when cancerous, Poss says. He adds: "This is just scratching the surface." —*Lydia Chain*

Ellen Ruppel Shell co-directs the graduate program in science journalism at Boston University. She wrote about allergy tests in the November 2015 issue.

Gauging the Effects of Lead

Research suggests that exposure to lead-tainted water in Flint, Mich., need not cause lasting harm

By Ellen Ruppel Shell

Parents around the country have voiced alarm since the 2015 revelations of staggeringly high lead levels in the drinking water of Flint, Mich., and more recent reports of spikes in other cities and states. It is easy to understand why people are upset. "Children are particularly vulnerable to the neurotoxic effects of lead," states the World Health Organization on its Web site. It goes on: "Even relatively low levels of exposure can cause serious and in some cases irreversible neurological damage." After learning that Flint's water was tainted, some medical professionals have said the lead would permanently harm young brains and possibly other organs. Personal injury attorneys, pressing lawsuits, use phrases such as "irreparable damage" and "lead poisoning."

Yet the Flint children and others like them are not doomed. The WHO statement uses words like "relatively" and "can," but it does not say damage is certain. Water lead levels in Flint were extremely high, and blood lead levels did rise after the exposure. But experts involved in setting lead-exposure standards say the blood levels linked to Flint—thought to have peaked between five and 10 micrograms per deciliter (μg/dL) in most cases, although exact numbers have not been made public—generally do not result in permanent neurological deficits. There is even evidence that an anatomical feature called the blood-brain barrier may keep low levels of lead from entering brain cells.

Such insights, scientists emphasize, are no excuse for inaction. To the contrary, researchers argue that public officials must not only eliminate lead sources but improve nutrition and education because studies indicate these measures could reduce lasting ill effects of environmental insults. Still, the common belief that children with low blood lead levels are poisoned or mentally deficient is not only untrue, it can result in hurtful stigma and stress for children and their families. "Poisoning is obviously a loaded word," says Marc Edwards, the Virginia Polytechnic Institute environmental engineer who documented the shocking levels of lead in the Flint water supply. "I've spoken to many parents in Flint, and I'm concerned because I don't want children there defined by what happened to them."

MURKY DATA

MUCH OF THE WORRY over lead in Flint stems from the discovery that between 2013 and 2015 the percentage of children with blood lead levels at or above 5 μg/dL doubled, rising from 2.4 to 4.9 percent. Alert parents, scientists and advocates forced public officials to stop denying the problem and remove the cause: water from the Flint River so corrosive that it leached lead from aged city water pipes.

What does a blood level of 5 μg/dL actually mean? In 2012 neuropsychologist Kim Dietrich of the University of Cincinnati College of Medicine helped the Centers for Disease Control and Prevention set that level as a threshold for official action. He explains that the number was based on what public health experts call the "precautionary principle"—the idea that when an activity raises threats of harm, we should take measures to stop it, even if some cause-and-effect relations are not fully established scientifically. "This does not mean that children at this level are poisoned," Dietrich says. "There are very few studies of low-level lead exposure, but there is nothing in the data that suggests that children will have negative impacts of short-term low-level exposure" over their lives. In fact, he notes, the 5 μg/dL figure was set because 97.5 percent of young children fall below it, not because blood lead levels at that threshold result in permanent harm.

Although some studies have found an association between low blood lead levels and cognitive deficits, none has established a causative link. Robert Fischer, a social scientist at Case

Illustration by Christina Ung

Western Reserve University, is an expert on study evaluation who has monitored the lead problem for decades. He says these studies have been repeatedly confounded by other factors in the environment that affect cognitive performance. "Lead exposure also correlates with extreme poverty, low resource availability and poor schools," he says, noting that there are so many intertwined factors that it is nearly impossible to tease them apart. An exhaustive study of children with blood lead levels averaging more than 17 μg/dL, published in 2013 in *NeuroToxicology,* concluded: "It is unclear whether lead exposure or early childhood confounders were driving these associations" between lead and long-term cognitive impacts. Norman Paradis, a physician who studies clinical trial design at Dartmouth-Hitchcock Medical Center in New Hampshire, adds that at low lead levels it is difficult to get a reliable statistical signal with so many other variables in play.

How different levels of lead in the blood affect the brain may also depend on the effectiveness of the blood-brain barrier, a network of specially lined blood vessels that blocks many toxic substances from entering the brain. Prolonged exposure to lead at high levels—probably well in excess of 5 or 10 μg/dL—does subvert this system. But for the blood levels seen in Flint, it is not clear that the same can be said, according to endocrinologist William Pardridge. Author of five books and more than 400 journal articles on the blood-brain barrier, Pardridge is a distinguished professor emeritus of medicine and member of the blood-brain barrier research laboratory at the University of California, Los Angeles. He says that most lead in the blood is carried within red blood cells and that red blood cells do not cross the barrier. Thus, there is little lead available for transport from blood to brain, and it comes from blood plasma, a much smaller source. Indeed, a 1993 study in *NeuroToxicology* found that although severe lead poisoning in rat pups and in young children may damage the blood-brain barrier, "there is little evidence that there is either damage or even disturbance" when levels are below 80 μg/dl. At lower thresholds, lead may find its way beyond the barrier but most likely in only a small fraction of the concentration found in the blood.

REMEDIES

STILL, WHAT WORRIES Mona Hanna-Attisha, a pediatrician and director of the Pediatric Public Health Initiative at Hurley Children's Hospital in Flint, is that any cognitive deficits associated with lead exposure—at whatever level—seem to be made worse by poverty, and poverty is rampant in Flint. "No one is saying that these children are all going to have problems. Most should be fine," she wrote me in an e-mail. "But we are not going to wait to see who is fine and not fine. We are trying to build robust wraparound services in nutrition, education and health to mitigate the potential impact of this exposure."

Howard Hu, a physician and dean of the Dalla Lana School of Public Health at the University of Toronto who has published widely on lead's effects, agrees that the interlaced issues of lead exposure and social inequality point to strategies for intervention. "Certainly some children are more susceptible to lead than others—we are just beginning to look at this variance," he says. But a reason for hope, he adds, is that "low-level lead exposure can be mitigated by good parenting, good schooling and good nutrition."

Hu is among several scientists who have found that in children, nutritional deficiencies in iron, calcium or zinc increase the danger of lead exposure by encouraging lead absorption. Making certain that children have sufficient amounts of these essential nutrients can reduce this risk, he says. But diet is only one part of a very complex problem. A lack of mental stimulation—as can occur when children get little adult attention and when schools lack resources—also appears to exacerbate lead's effects, although again scientists are not sure how much to blame on lead and how much to blame on the surroundings.

Although there are no controlled human studies, research in animals suggests that an arousing environment might begin to compensate for lead-induced brain damage. Bruce Lanphear, a public health expert at Simon Fraser University in British Columbia, is principal investigator for a study examining fetal and early-age exposure to lead and other neurotoxic chemicals. "Studies in rats have shown that the effects of lead exposure can be attenuated by environmental stimulation," Lanphear says. Early research showed that animals exposed to lead yet provided with enriched environments (cages with other rats as well as water mazes, exercise wheels and other stimuli) showed fewer deficits than did those from deprived situations.

Low-level lead exposure can be mitigated by good parenting, good schooling and good nutrition.

The best approach is to minimize lead exposure while improving surroundings, says Stuart Shalat, director of the division of environmental health at Georgia State University's School of Public Health. Shalat says that poor children are both most likely to be exposed to lead—from factory smelters, dust, soil and paint—and to suffer the worst effects of that exposure because of inadequate access to health care, proper nutrition and high-quality schools. "There should be a sense of urgency to evaluate and minimize exposure," he says. But when kids do meet lead, "it is increasingly clear that some of the toxic damage can be mitigated by commonsense practices. What we need to focus on is doing everything we can to see that every child has the opportunity to develop his or her potential." SA

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

At Your Command

The Internet of Things will remain a cumbersome wireless landscape until it finds a way to connect to us

By David Pogue

In the late 1970s my parents bought a new family TV, the first we'd ever owned that came with a remote control. My mom was appalled: "How hard can it be to walk six feet from the couch to change the channel?"

Ah, but here's the thing: History shows us that convenience is a key driver in consumer acceptance of new technology. No matter how trivial the gift to our laziness, a product that saves us effort is likely to be a winner.

That, for example, was supposed to be the appeal of the Internet of Things.

That awkward term refers to everyday objects that have been blessed with wireless networking. Usually it means that you can use phone apps to control them: lights, thermostats, refrigerators, baby monitors, coffeemakers, security cameras, lawn sprinklers, doorbell cams, robo vacuums, and so on.

You can start your car remotely a few minutes before you leave the house, so its heat or A/C has had some time to kick in. You can see who's ringing your doorbell when you're away and even unlock the door if you're expecting them.

So far, though, the Internet of Things has turned out to be the Internet of Poor Sales. At this moment, it's a good bet that you, dear reader, cannot control your washer/dryer from your phone.

But if convenience always wins, why isn't the public eating this stuff up?

Ironically, it's because today's Internet of Things things just aren't very convenient.

The first moments of ownership usually involve downloading an app, creating an account and connecting the thing to your Wi-Fi network. Sometimes that all goes well. Sometimes there goes your Saturday afternoon.

Then you've got the Tower of Things Babel to contend with: The apps don't talk to one another. You must open one app to adjust the lighting, another to change your speakers' volume, a third to tweak the temperature.

The industry knows about these problems. They're frantically developing standards to unify all this stuff. Trouble is, each big company has developed its *own* standard. There's Thread (from Google), HomeKit (Apple), AllJoyn (originally Qualcomm) and SmartThings (Samsung), among others.

That's right: the very act of trying to settle the standards war has resulted in … a new standards war.

Then there's security. Do we really want to connect our kitchens, heating and cooling, and other home systems to the great wide world of hackers? Especially our door locks?

Now, it's not true that *nobody* is buying Internet of Things things. Internet-connected thermostats, such as those from Nest and Honeywell, have had mild success. So have the home security cams.

But the surprise hit of the fledgling Internet of Things era is the Amazon Echo: a black cylinder that responds to voice commands, like a Siri voice assistant for your home. From across the room, you can command it to play any kind of music, answer questions, check the weather, and so on.

With each passing month, Amazon has been adding more features to the Echo—and quietly making inroads into the Internet of Things. Your spoken Echo commands can now control your networked thermostat ("Set the temperature to 70"), lights ("Turn off the downstairs lights"), music system ("Play romantic guitar on Sonos") and power-strip outlets ("Turn on the fan"). It does all this, you understand, without your having to find (or even own) a phone or open an app.

Voice control is, in other words, a breakthrough in convenience—in exactly the place where the Internet of Things is least convenient.

But even the Echo and its inevitable imitators don't fully solve the Internet of Things' problems. Voice control doesn't address the security problems or the initial setup hassles and works only with certain compatible devices. Above all, it doesn't tackle the biggest challenge: that maybe, just maybe, people don't *want* phone control of their appliances. Sometimes you might as well walk the six feet from the couch. SA

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THE ODDEST "INTERNET OF THINGS" THINGS:
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Illustration by James Olstein

THE BRAIN-BOOSTING POWER OF VIDEO GAMES

COGNITIVE SCIENCE

Shooting zombies and repelling aliens can lead to lasting improvement in mental skills

By Daphne Bavelier and C. Shawn Green

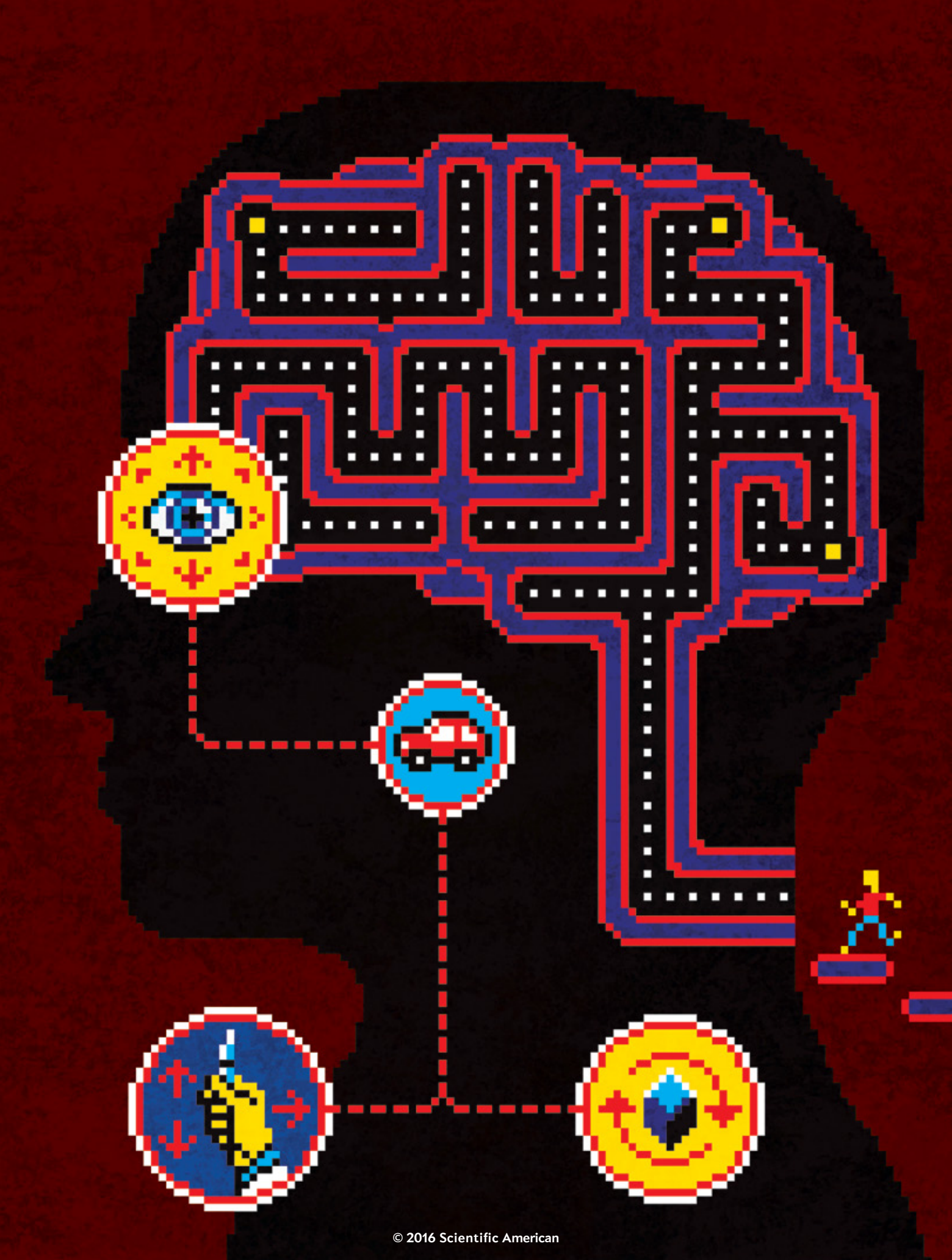
IN BRIEF

Fast-paced shooter games did not always grace lists of brain-enhancing activities. For the past 15 years, however, a number of studies have found that playing them frequently changes various aspects of cognition for the better.

A range of mental skills appears to benefit from game play, including attention, faster processing of information, flexibility of switching from one task to another and visualizing the rotation of an object. Rigorous testing has provided evidence for these gains.

Concerns persist about whether games foster aggression or addictive play. Now that researchers have determined how games help to hone some mental skills, they have begun to design nonviolent action games geared toward people with cognitive deficits.

Illustration by Jude Buffum



Daphne Bavelier is a professor in the department of psychology and educational science at the University of Geneva in Switzerland and in the department of brain and cognitive sciences at the University of Rochester.

C. Shawn Green is an assistant professor in the department of psychology at the University of Wisconsin–Madison.

IN THE LATE 1990S OUR LABORATORY AT THE UNIVERSITY OF ROCHESTER RAN STUDIES TO EXPLORE THE then somewhat unorthodox idea that even the adult brain could grow new brain cells or rewire itself in response to new experiences—a biological process called neuroplasticity. As part of this research, one of us (Green), then an 18-year-old undergraduate assistant in the lab, coded a computerized psychological test assessing how well one can search for a particular shape in a busy visual scene.

Green began by testing himself. When finished, he insisted that there was a bug in the programming that he could not track down. Previously published work on this type of testing suggested that his performance should have been well below perfect, yet he consistently racked up perfect scores. Green's adviser (Bavelier) was becoming worried that the issue had not been resolved. "Why don't you stop running yourself and test naive participants?" she asked.

A few days later Green reported that newly recruited participants also registered flawless performances. Determined to crack the problem that same day, Bavelier asked to be run on the task herself. Her performance was nowhere near perfect. Instead her scores matched almost exactly the expected average. When Bavelier asked whom Green had run as naive participants, the assistant replied that he had tested several close friends.

Our team spent some time considering why Green and his buddies had performed so well on the task. Eventually we settled on one key difference. Every member of the group had spent more than 10 hours a week playing a newly released video game called Team Fortress Classic.

The discovery immediately raised an intriguing question: Could "mindless" video-game play—in which the main objective is to overpower zombies, aliens, monsters and villains—really trigger such stunning improvements in a cognitive skill? What had started as a search for a computer bug has led to a new research endeavor to assess the impact of video-game play on both the brain and behavior.

When we began our studies, playing fast-paced "shooter" video games was not high on any scientist's list of brain-enhancing activities. For the past 15 years, however, our investigations, coupled with that of other labs around the world, have established that playing action video games can change some aspects of cognition for the better.

During our research, we and other teams have found that video-game play boosts a variety of cognitive skills. Individuals who regularly play action games demonstrate improved ability to focus on visual details, useful for reading fine print in a legal document or on a prescription bottle. They also display heightened sensitivity to visual contrast, important when driving in thick fog. Action gamers also mentally rotate objects more accurately—and so are able to judge how an oddly shaped couch might best fit in an overpacked moving van. The multitasking required to switch back and forth between reading a menu and holding a conversation with a dinner partner also comes more easily.

Furthermore, a player's ability to react to events that unfold quickly gets better with regular play. Tests of reaction times of action video-game players show that performance improved by more than 10 percent compared with before they took up gaming. The video game as life coach may even provide a leg up in the workplace. Game playing seems to confer the ability to make correct decisions under pressure—the type of skill sought by employers in many professions. One study revealed that laparoscopic surgeons who were also game players were able to complete surgeries more quickly while retaining the necessary precision in the operating room. Game-playing surgeons appeared to work more efficiently, not just faster.

Video games as learning tools might come as a surprise to those who recall a congressional hearing in the early 1990s that considered negative effects on children who played games such as Mortal Kombat. Recent studies have not borne out these fears as far as effects on cognitive function, although concerns persist about whether games foster aggression or addictive play. Now that researchers have begun to figure out how some video games improve cognition in players—by bettering attention and reaction times—they have started to design nonviolent games geared toward people with brain injuries or cognitive deficits. This software may be more effective, in fact, than so-called brain games marketed on television and the Web as cognitive enhancers.

BOOSTING THE BRAIN

THE STEREOTYPE of the avid player of Call of Duty and other action games is of someone who is impulsive and easily distracted. Our

Game Menagerie

Video games belong to a complex and constantly evolving ecosystem, with more than 10 different commonly recognized genres (action, sports simulation, party, among others). Among these genres, hundreds of distinct subgenres exist (real-time strategy, turn-based strategy and 4X all fall under the broader strategy genre). There are, moreover, tens of thousands of distinct titles among the various categories.

As far as examining effects on cognition, most research has focused on one particular game genre—action games, which primarily include first- and third-person shooter games, such as the Call of Duty or Gears of War series, but also games that are often labeled as action-adventure (the Grand Theft Auto series), action (the Burnout series) and action-RPG (the Mass Effect series), to name a few.

Whereas action games are best at improving perception, attention or various aspects of cognition compared with other genres, they are not the only ones to yield benefits beyond serving as a fun pastime, as the list of findings below show. Research on games involving action sports, real-time strategy and action role-playing suggests they may have an impact similar to action games in bettering some aspects of cognition. Furthermore, game genres that do not affect cognition might enhance social behaviors or empathy. Investigators who study social games tend to categorize games differently from those who research cognition, sometimes dividing the game world into violent versus nonviolent kinds.

ACTION: Most research on game play for enhancing cognition has focused on action games, a genre that has subgenres, such as shooter and action-adventure games. Action games have demonstrated a range of cognitive benefits that may carry over into work and other activities.

REAL-TIME STRATEGY: Playing one of these games, called StarCraft—which has a military science-fiction story line that involves war among several galactic species—produced improvements in cognitive flexibility, the ability to switch from one task to another.

3-D PUZZLE GAME: Finding an exit door by using a series of tools—the goal of Portal 2—resulted in players showing a statistically significant advantage in measures of problem solving, spatial skill and persistence over a comparison group that played brain games from the Lumosity software.

PROSOCIAL: A 2009 review of studies in the *Personality and Social Psychology Bulletin* found that young people from various countries who played "prosocial" games that involve characters helping one another later cooperated more when interacting with peers.

studies contradict this outdated preconception. Players who immerse themselves in the fast-paced events of digital fantasy worlds derive significant cognitive benefits.

Much of our research has focused on how action games affect a player's attention—the mental processes that lead to finding relevant information in one's environment. Studies of attention have been carried out ever since psychology emerged as a social science in the 19th century. Call of Duty and Medal of Honor have now become tools in research facilities because of their ability to enhance attention. A player must shift between a state of mental focus while monitoring the game scene for potential enemies, switching purposely between what psychologists call focused and distributed attention.

These studies have shown that fighting off waves of zombies requires game players to suppress distracting information or risk obliteration. Specifically, players detect targets better than nongamers and avoid becoming distracted by any single event that occurs as a fast-paced game progresses. A zombie will always be followed by another and yet another. The player who gets hung up on pursuing any single member of the walking dead risks attack by legions of others.

In one of our studies, we used a well-known psychological test to demonstrate the superiority of an action-game player's attentional skills. The test exposes subjects to a series of letters, interspersed with occasional digits. Each item flashes on the screen at intervals of 100 milliseconds, less than the blink of an eye. Test takers who do not indulge in action video games typically have little difficulty identifying the first digit in the string. But if a second digit follows closely thereafter, they often do not notice it—a psychological phenomenon known as attentional blink. Some experienced action-game players, however, barely blink, catching every target digit as it passes by.

Brain scans provide more evidence of the benefits of action games. Widely dispersed regions of the cerebral cortex regulating attention change their activity more in action-game players than in nonaction gamers. Among them are the dorsolateral prefrontal cortex, which helps to sustain attention; the parietal cortex, which switches focus among different targets; and the cingulate cortex, a locus for monitoring one's own behavior.

FASTER, FASTER

ACTION VIDEO-GAME PLAYERS get more out of Burnout and Grand Theft Auto than just better focus. The greater the skill they acquire, the faster they process information in the quick-moving stream of events that makes up each game scene. For psychologists, information-processing speed is a key measure of the efficiency of cognitive functioning—and action games appear to be excellent tools to make a person's reaction time faster. The player must decide whether a moving object is friend or foe and choose which weapon to use, where to aim and when to fire, all in the space of a second or so.

Greater efficiency in controlling attention has a ripple effect on many forms of neural processing. It can ensure that the brain extracts more visual, auditory and other information about a task being performed—and that it excludes sources of distraction or noise. At the highest levels of cognitive processing, an individual

COURTESY OF ACTIVISION (*Call of Duty: Black Ops III*); COURTESY OF BLIZZARD (*StarCraft III: Heart of the Swarm*); COURTESY OF VALVE CORPORATION (*Portal 2*); COURTESY OF 2K GAMES (*City Crisis*)

may demonstrate a high degree of flexibility in refocusing attention from one task to another. These are not just lab test results. Better control of attention helps in adapting to new situations and aids, in general, in speeding up learning.

To be able to make a clear statement about the effects of these games, we had to provide a firm demonstration that the benefits of action video games are genuine—and that *playing* these games actually *causes* players' superior concentration and quick reaction times. After all, it may be that these games simply attract players with exceptional attention—which, in turn, leads to stellar performance on both games and subsequent tests assessing players' cognitive functioning.

To show a true cause-and-effect relation, scientists recruit a group of individuals who rarely play video games. After undergoing a pretest of cognitive skills, this larger group is randomly split into two. One group plays an action game, whereas a control group immerses itself in a social game or another nonaction game. Each group is required to play about one hour a day, five days a week for a period of several weeks. A few days after this sustained training, participants are again tested on the same psychological tests they took before playing the games. Groups trained on action games show consistently larger gains in cognition than control groups.

Controlled studies allow researchers to discard factors that might otherwise account for the benefits shown by either group—the possibility, for instance, that someone taking a psychological test tends to perform better when retested. These studies also demonstrate that not all video games have the same effects. Action games that emphasize attention, cognitive flexibility and speed produce clear gains. Nonaction games—which do not recruit these cognitive processes—garner few. Despite the purported benefits of action-game play, the various studies do not provide a license for video-game bingeing. Obsessive hour-after-hour indulgence is not needed. Players achieved cognitive advantages in our study after short, daily intervals of play.

Some other video-game genres—such as action role-playing games (Mass Effect) and real-time strategy games (StarCraft)—also produce similar beneficial effects on cognition. Ironically, few, if any, of the games marketed explicitly as "brain games" live up to their claims to help people with cognitive deficits or those who wish to improve mental functioning to above-average levels. Early generations of brain games consisted largely of sterile psychological lab tasks "dressed up" with game graphics or engaging sounds that did not actually demonstrate any generalizable cognitive benefit. Indeed, becoming ever better on a specific psychology exercise is unlikely to help the player plan an efficient route at the supermarket or remember where he or she left the car keys.

Even though action video games were never designed as teaching tools, they nonetheless embody many pivotal learning principles. For one, they are fun—a cardinal pedagogical prerequisite that is often given short shrift.

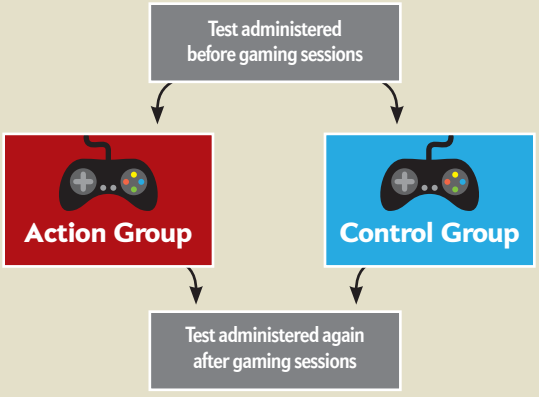
The games' programming also incorporates careful pacing and structuring of the level of play. The number of attackers increases as the game progresses. Players remain absorbed while receiving the right amount of practice to master a game skill. Critically, these games require players to switch between focused and divided attention tasks as the games progress, demanding a high level of attentional control.

The games create a rich environment in which new challenges keep arising, always pushing the players out of their comfort zone. Finally, the games also reward players on many different timescales: seconds (defeating a single enemy), minutes (finishing a single mission), hours (finishing a chapter or campaign), days (completing a full game)—all of which promote planning across different time horizons. The games make for a rewarding experience that promotes learning that can be applied to real-life situations: better mental rotation in science or math classes or quick braking of a car if a child runs into the street to fetch a ball.

TESTS OF SKILL

Brain Training or Not?

To determine whether action-game play improves perception and other aspects of cognition—ensuring that gains result from the game itself and not some other factor—researchers compare performance on cognitive tests (*shown at right*) for a group that plays an action game for a few weeks and for a control group that trains on a nonaction game. Players of action games show greater improvements from pre- to post-testing compared with the control group—and the benefits persist five months later.



A TRUE BRAIN GAME

RESEARCHERS HAVE BEGUN to take lessons from studying commercially available video games and apply them to a new generation of therapeutic games that bears little resemblance to drab psychological tests. Posit Science, Pear Therapeutics and Akili Interactive (disclosure: Bavelier is a co-founding adviser for Akili) are a few names among a growing number of companies looking into using video games as clinical tools, whether for assessment or for actual therapies. Akili, for example, is developing a therapeutic game—derived from a research-based game called NeuroRacer—to enhance attention and diminish distraction. This and other games target clinical populations such as children with attention-deficit disorders or older adults experiencing early symptoms of cognitive decline. It will take time to gain acceptance for these games. Ultimately, to be incorporated as clinical tools, therapeutic games and their health claims will have to be evaluated by independent bodies such as regulatory agencies or the broader scientific community.

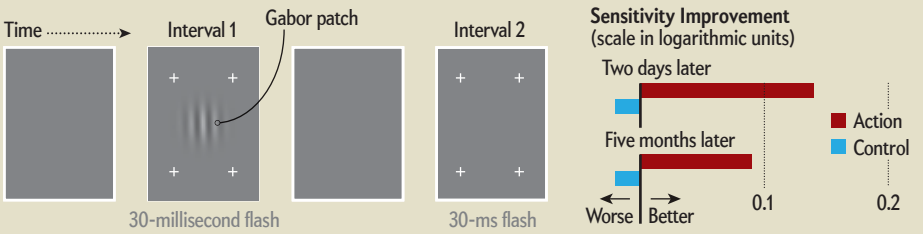
SOURCE: "BRAIN PLASTICITY THROUGH THE LIFE SPAN: LEARNING TO LEARN AND ACTION VIDEO GAMES," BY DAPHNE BAVELIER ET AL., IN *ANNUAL REVIEW OF NEUROSCIENCE*, VOL. 35, JULY 2012

SCIENTIFIC AMERICAN ONLINE Watch Bavelier give a talk at ScientificAmerican.com/jul2016/video

Illustration by Jen Christiansen

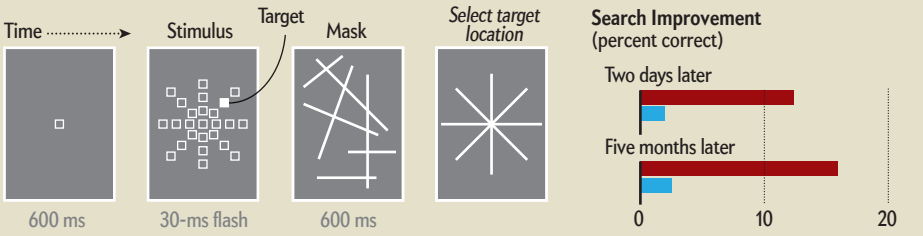
Can You See It Now?

A contrast-sensitivity task measures the ability to detect slight differences in light versus dark on a computer screen. Participants observe a screen at two time intervals and must indicate when a Gabor patch, consisting of alternating dark and light lines, appears. Patches with varying degrees of contrast are used to determine the minimum contrast the participant can see.



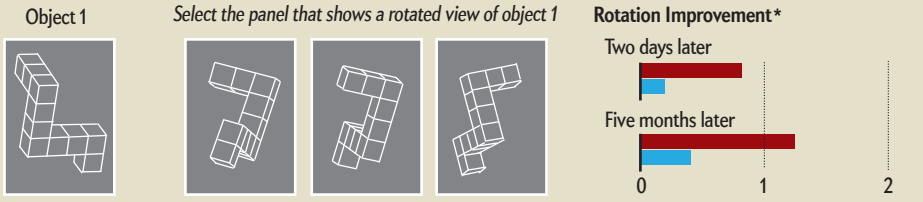
Find It Fast

The useful field of view task, as it is called, measures spatial attention, or the ability to find a target quickly while ignoring distractions in a briefly presented, cluttered scene. Participants in the test must find the solid square (the target) and indicate where it is located.



Turn It Over in Your Mind

A mental rotation test examines the spatial-visualization abilities of players by asking them to determine which rotated object of the three on the right corresponds to "Object 1" (*far left*).



**Scale expressed as the square root of items correct.*

Although action games provide a foundation for developing therapeutic games, a number of weaknesses must be addressed. First, a game needs to be tailored to the needs of the patient. Many individuals with attention deficits show little improvement from playing run-of-the-mill action games, despite the fact that these games enhance attention in healthy individuals. Most players approach the games by using a mental model of how events unfold, which allows them to anticipate what will happen next. People with attention deficits, however, display a more reactive style of play and so run into difficulty visualizing what lies ahead. Developers are now trying to find ways to restructure the traditional action-game format to prod players with attention deficits to take a more active role in strategizing future moves.

A similar revamping will be key for games aimed at increasing the reaction time of older people to, say, improve driving skills. Just downloading a copy of Medal of Honor will not be enough. The furious pace of most action games played by young adults can be overwhelming for the elderly—and they often derive little benefit from off-the-shelf commercial products. Games adjusted to their needs will require a more moderate pacing so that they prove challenging but not impossible.

A less demanding level of play will also be needed for games to enhance vision in amblyopia (lazy-eye) patients—another group targeted by game makers. Finally, the violent nature of many video games must also be scaled back in games targeted at clinical interventions. It may be appropriate for a game to come to a halt when a driver veers off the road, but having body parts flying through the air after the crash is superfluous. To go beyond shooting zombies to delivering actual therapeutic benefits, scientists with expertise in learning, psychology and neuroscience will have to team up with graphic artists, game producers and designers to create compelling content.

The initial inspiration that our research team derived from Team Fortress Classic holds still untapped possibilities. Games tailored for dyslexic children or head-trauma patients might be further customized by using sensors to monitor brain waves to adjust the level of play automatically. Just as important as the technology itself will be the care taken to align the content and skills of a game with the particular cognitive strengths and weaknesses of its players. A sensitivity to the needs of diverse groups of players will be an essential requirement for next-generation brain games to succeed. SA

MORE TO EXPLORE

Brain Plasticity through the Life Span: Learning to Learn and Action Video Games. Daphne Bavelier et al. in *Annual Review of Neuroscience,* Vol. 35, pages 391–416; July 2012.

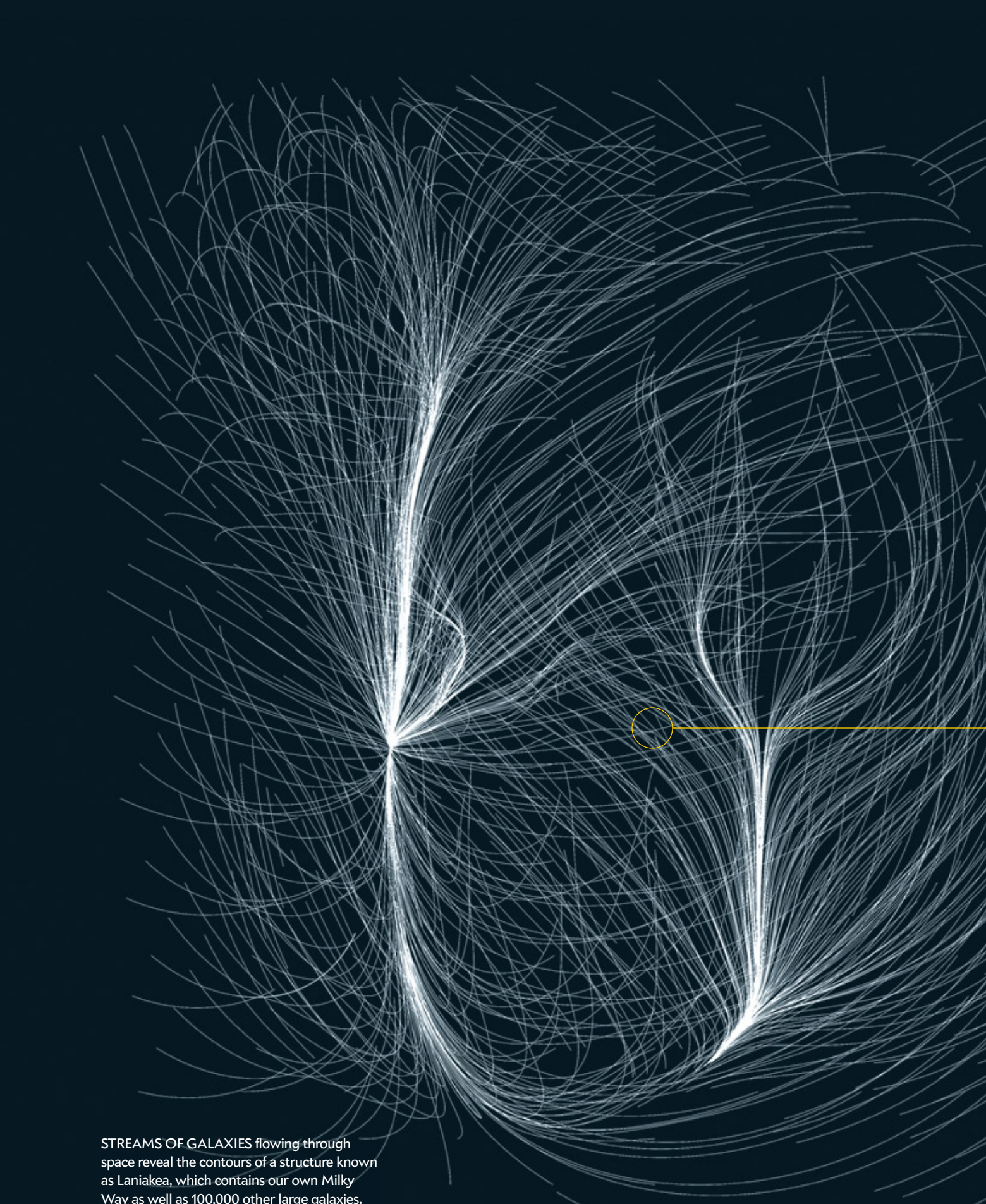
Video Game Training Enhances Cognitive Control in Older Adults. J. A. Anguera et al. in *Nature,* Vol. 501, pages 97–101; September 5, 2013.

C. Shawn Green lectures on video games and learning as part of a massive open online course at the University of Wisconsin–Madison; scroll to bottom of page to view the videos: http://greenlab.psych.wisc.edu

FROM OUR ARCHIVES

Turbocharging the Brain. Gary Stix; October 2009.

scientificamerican.com/magazine/sa



STREAMS OF GALAXIES flowing through space reveal the contours of a structure known as Laniakea, which contains our own Milky Way as well as 100,000 other large galaxies.

ASTRONOMY

Our Place in the Cosmos

The Milky Way turns out to be part of a massive supercluster of galaxies that forms one of the largest known structures in the universe. This discovery is only the beginning of a new effort to map the cosmos

By Noam I. Libeskind and R. Brent Tully

IN BRIEF

Similar to how stars clump together into star clusters and galaxies, galaxies themselves gather into clusters, and galactic clusters group into superclusters.

These galactic superclusters are the building blocks of great filaments, sheets and voids that constitute the largest measurable structures in the universe.

Recent studies of the motions of thousands of nearby galaxies have revealed that the Milky Way's home supercluster is far larger than previously thought. Astronomers call this newfound supersized supercluster "Laniakea."

More detailed mapping of Laniakea and its neighboring superclusters could reveal new details about galaxy formation and help researchers solve the dual cosmological mysteries of dark matter and dark energy.

Noam I. Libeskind is a cosmologist at the Leibniz Institute for Astrophysics Potsdam in Germany. He uses supercomputers to model the evolution of the universe and the formation of galaxies, with a focus on the Milky Way, the Local Group and the small dwarf galaxies that surround us. Follow Libeskind's astrophysics tweets: @satellitegalaxy

R. Brent Tully is an astronomer at the University of Hawaii who, for 40 years, has been measuring the distances to galaxies and mapping their distribution and motions in space. His *Atlas of Nearby Galaxies,* co-written with J. Richard Fisher and published in 1987, is still the most extensive print atlas of the structure of our cosmic neighborhood. Tully takes pride in finding his way without recourse to GPS.

IMAGINE VISITING A FAR DISTANT GALAXY AND ADDRESSING A POSTCARD TO YOUR LOVED ONES BACK HOME. You might begin with your house on your street in your hometown, somewhere on Earth, the third planet from our sun. From there the address could list the sun's location in the Orion Spur, a segment of a spiral arm in the Milky Way's suburbs, followed by the Milky Way's residence in the Local Group, a gathering of more than 50 nearby galaxies spanning some seven million light-years of space. The Local Group in turn exists at the outskirts of the Virgo Cluster, a 50-million-light-year-distant cluster of more than 1,000 galaxies that is itself a small part of the Local Supercluster, a collection of hundreds of galaxy groups sprawled across more than 100 million light-years. Such superclusters are believed to be the biggest components of the universe's largest-scale structures, forming great filaments and sheets of galaxies surrounding voids where scarcely any galaxies exist at all.

Until recently, the Local Supercluster would have marked the end of your cosmic address. Beyond this scale, it was thought, further directions would become meaningless as the boundary between the crisp, supercluster-laced structure of galactic sheets and voids gave way to a homogeneous realm of the universe with no larger discernible features. But in 2014 one of us (Tully) led a team that discovered we are part of a structure so immense that it shattered this view. The Local Supercluster, it turns out, is but one lobe of a much larger supercluster, a collection of 100,000 large galaxies stretching across 400 million light-years. The team that discovered this gargantuan supercluster named it Laniakea—Hawaiian for "immeasurable heaven"—in honor of the early Polynesians who navigated the great expanse of the Pacific Ocean by the stars. The Milky Way sits far from Laniakea's center, in its outermost hinterlands.

Laniakea is more than just a new line on our cosmic address. By studying the architecture and dynamics of this immense structure, we can learn more about the universe's past and future. Charting its constituent galaxies and how they behave can help us better understand how galaxies form and grow while telling us more about the nature of dark matter—the invisible substance that astronomers believe accounts for about 80 percent of the stuff in the universe.

Laniakea could also help demystify dark energy, a powerful force only discovered in 1998 that is somehow driving the accelerating expansion of the universe and thus shaping the cosmos's ultimate fate. And the supercluster may not actually be the final line of our cosmic address—it could, in fact, be part of an even bigger structure yet to be discovered.

PROBING MYSTERIES WITH GALACTIC FLOWS

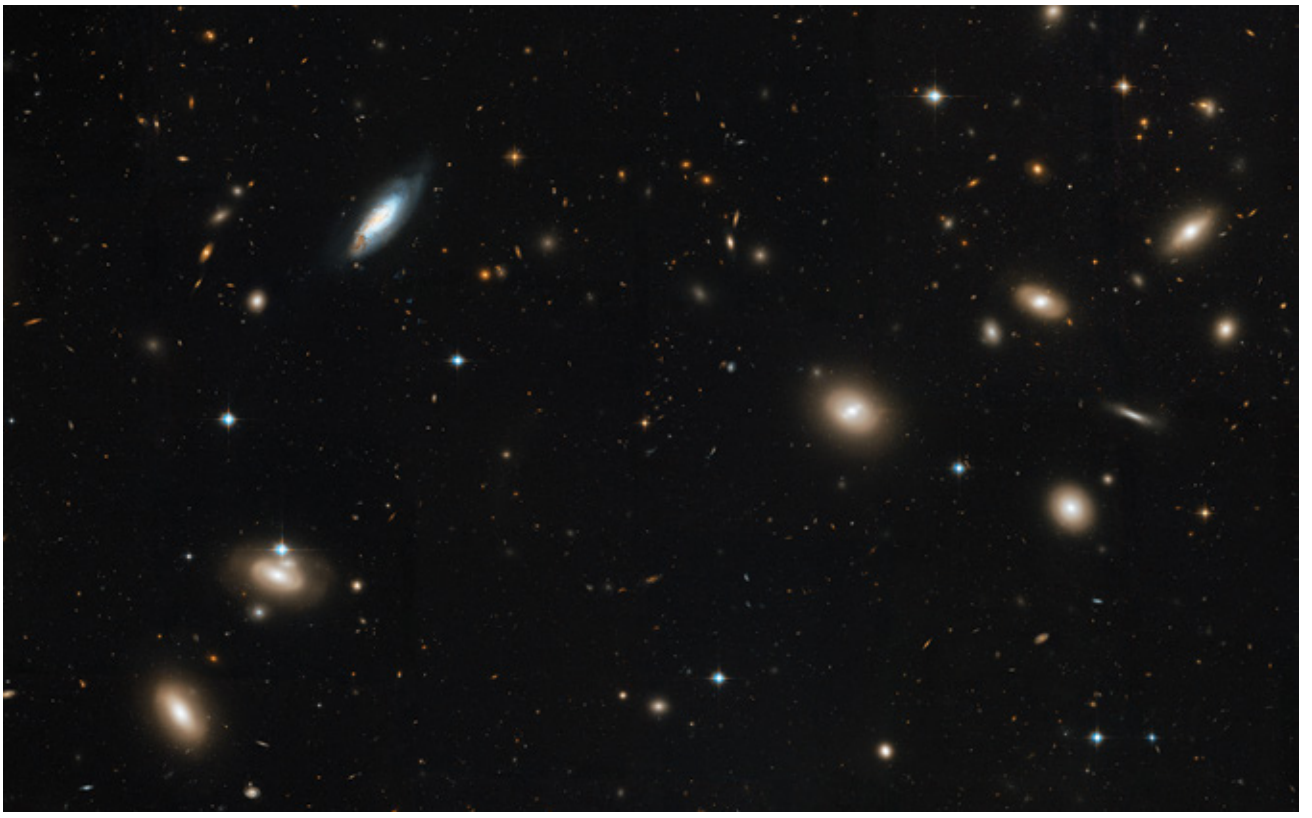
THE TEAM that discovered Laniakea did not exactly set out to find it. Instead Laniakea emerged from efforts to answer lingering fundamental questions about the nature of the universe.

Scientists have known for nearly a century that the cosmos is expanding, pulling galaxies away from one another like dots moving apart on the surface of an inflating balloon. Yet in recent decades it has become clear that most galaxies are not separating as fast as would be expected if expansion were the only force acting on them. Another, more local force is at work, too—the gravitational tugs from other nearby accumulations of matter, which can offset a galaxy's flow in the expansion of the cosmos. The difference between a galaxy's motion from cosmic expansion and the motion from its local environment is called peculiar velocity.

If we take all the stars in all the galaxies that we see and add all the gas and other ordinary matter that we know about, we fall short of explaining the gravitational sources of observed peculiar velocities by an order of magnitude. In our ignorance we astronomers call what is missing "dark matter." We presume this dark matter consists of particles that interact almost exclusively with the rest of the universe through gravity rather than through other forces such as electromagnetism and that the dark matter exerts the "missing" gravitational force needed to account for the observed velocities. Scientists think that galaxies sit within deep pools of dark matter—dark matter being the invisible scaffolding around which galaxies coalesce.

Tully's group and others realized that creating maps of galactic flows and peculiar velocities could reveal dark matter's hidden cosmic distribution, uncovering the mysterious substance's great-

PRECEDING PAGES: COURTESY OF DANIEL POMARÈDE, CEA SACLAY/IRFU



GALAXY CLUSTERS such as this one, the Coma Cluster, are building blocks for the largest structures in the universe. Located more than 300 million light-years away and containing about 1,000 large galaxies, the Coma Cluster is part of an even bigger structure—the Coma Supercluster—which lies beyond Laniakea's boundaries.

COURTESY OF NASA, ESA AND HUBBLE HERITAGE TEAM STScI/AURA

est concentrations by their gravitational influence on galaxies' motions. If, say, streams of galaxies are all flowing toward a particular point, one can assume that the galaxies are being gravitationally drawn to that point by a highly dense region of matter.

They also realized that pinning down the density and distribution of all forms of matter in the universe could help solve another, even deeper mystery: the fact that the cosmos is not only expanding but is doing so at an accelerating rate. This behavior is as counterintuitive as a rock tossed up in the air rushing onward into the heavens rather than falling back to Earth. Whatever powers this bizarre phenomenon is dubbed "dark energy" and has profound implications for the future of the universe. The accelerated expansion suggests the cosmos will ultimately experience a cold death, with most galaxies racing away from one another at accelerating speeds until a final darkness descends on the universe as every star in every galaxy dies and all matter cools to absolute zero. But knowing for sure how it all will end requires not only determining what exactly dark energy is but also how much matter is in the universe: Given a sufficiently high density of matter, in the far future our universe could reverse its expansion to collapse in on itself as a consequence of the self-gravity of its cumulative mass. Or it could instead possess a balanced density of matter that would lead to an infinite but ever slowing expansion.

It was this charting of galactic flows to map the cosmic density of ordinary and dark matter that ultimately led to the unveiling of Laniakea.

FINDING LANIAKEA

MAPPING GALACTIC FLOWS requires knowing both a galaxy's motion stemming from cosmic expansion and its motion stemming from nearby matter. As a first step, astronomers measure a galaxy's redshift—the stretching out of the galaxy's emitted light as it recedes away from us through the expanding universe. A whistle or siren moving toward us has a higher pitch than if moving away because its sound waves are compressed to higher frequencies and shorter wavelengths. Similarly, light waves from a galaxy moving away from us are shifted to lower frequencies and longer, redder wavelengths—the faster they are receding, the more redshifted they become. Thus, a galaxy's redshift gives astronomers a measure of its overall velocity and a rough estimate of its distance.

Astronomers can infer how much of a galaxy's velocity is the result of local gravitational tugging by measuring its distance through other techniques besides redshift. For instance, based on rigorous estimates of the universe's expansion rate, a galaxy measured to be 3.25 million light-years away should have a velocity of about 70 kilometers per second. If instead the galaxy's redshift yields a velocity of 60 kilometers per second, astronomers could infer that matter concentrations near that galaxy are giving it a peculiar velocity of 10 kilometers per second. The techniques used to provide redshift-independent distance measurements mostly rely on the fact that light's intensity decreases by the inverse square of the distance from its source. That is, if you see two identical lighthouses but one appears a quarter as

Cosmic Landscape

Although they contain hundreds of billions of stars, galaxies are not the largest structures in the universe. Bound together by gravity, hundreds of galaxies can group together as a galaxy cluster. Gravity can concentrate galaxy clusters together, too, forming superclusters composed of hundreds of thousands of galaxies. In this hierarchy, our solar system's cosmic address has traditionally been: the Milky Way galaxy, the Local Group, the Virgo Cluster and, finally, the Local Supercluster. Now, however, new research is revealing that our Local Supercluster is only part of another supercluster more than 100 times larger. This larger supercluster is Laniakea, which in Hawaiian means "immeasurable heaven."

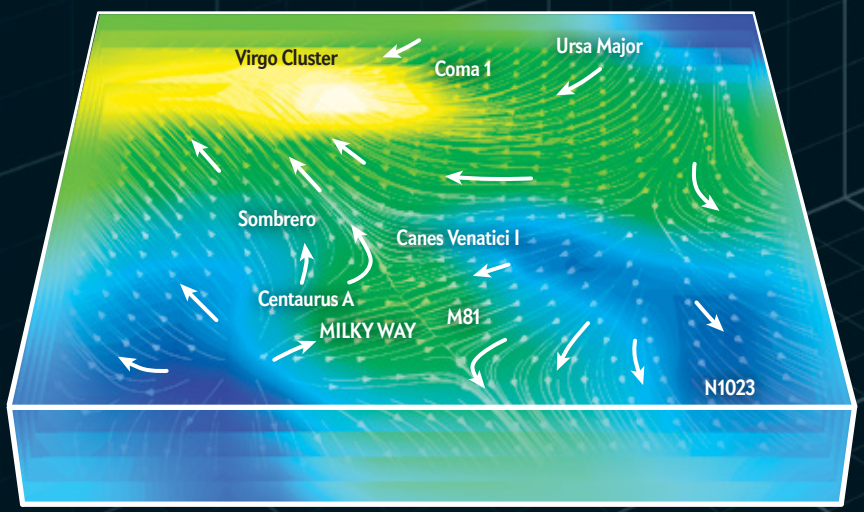
MAPPING THE LANIAKEA SUPERCLUSTER

Considered collectively, the positions and motions of galaxies can either diverge as the universe expands or converge in response to gravity. Supercluster boundaries can be drawn wherever the convergent force of gravity begins to significantly impede the expansion-caused divergent motion of galaxies. Here the positions of more than 8,000 galaxies are mapped and colored according to their relative motions (their velocity and trajectory when both convergent and divergent motion are taken into account). Contours with warmer colors (*yellows* and *pinks*) represent galaxy clusters rapidly converging together. Laniakea's outline appears in cooler blue, delineating where clusters are converging at their slowest. Spanning nearly half a billion light-years, Laniakea encompasses a volume of galaxy clusters that, in the absence of cosmic expansion, would converge to become a single gravitationally bound structure. Beyond Laniakea's boundaries, Shapley, Hercules, Perseus-Pisces and other neighboring superclusters can be seen.

LANIAKEA

GOING WITH THE FLOW

Zooming in on Laniakea's finer details can yield new insights into the distribution of dark matter and the process of galactic evolution. For instance, consider a three-dimensional slice of Laniakea containing the Milky Way and its enclosing Local Group of galaxies (*detail below*). The arrows track the motions of galaxies, which flow like water toward areas where matter is dense and gravity is strong (*depicted in warmer colors*) and away from regions of low density (*cooler colors*). The bulk flows of galaxies reveal cosmic concentrations of matter (be it normal or dark). Flow measurements by Libeskind have shown that the Local Group is falling along a 50-million-light-year-long filament of dark matter toward the Virgo Cluster (*yellow*), a gathering of more than 1,000 galaxies squeezed into a volume of 13 million light-years. Such filaments are thought to play important roles in the formation and evolution of galaxies.



SOURCES: "PLANES OF SATELLITE GALAXIES AND THE COSMIC WEB," BY NOAM I. LIBESKIND ET AL., IN *MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY*, VOL. 452, NO. 1; SEPTEMBER 1, 2015 (*inset slab*); DANIEL POMARÈDE, HÉLÈNE M. COURTOIS, YEHUDA HOFFMAN AND BRENT TULLY (*data for Laniakea illustration*)

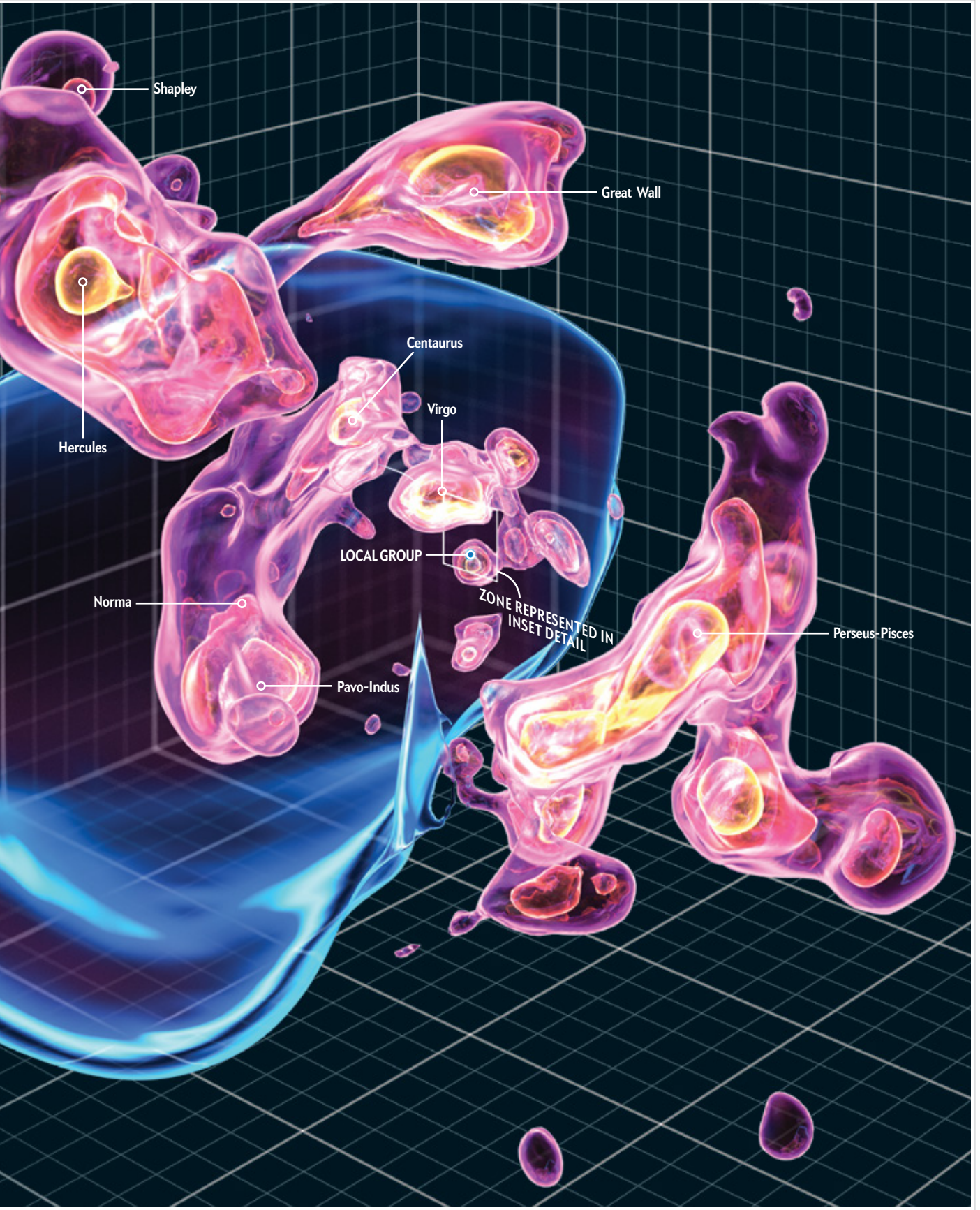


Illustration by Bryan Christie

bright, then you know the fainter one is two times farther away. In astronomy, such identical lighthouses are called standard candles, astrophysical objects that always shine with the same brightness no matter where they are in the universe. Examples include certain types of exploding or pulsating stars—or even massive galaxies as first proposed by Tully and astronomer J. Richard Fisher in 1977. This Tully-Fisher relation draws on the fact that massive galaxies are both more luminous and rapidly rotating than small galaxies—they have more stars and must spin faster to maintain stability in their stronger gravitational fields. Measure the galaxy's rotation rate, and you learn its intrinsic luminosity; compare that with its apparent luminosity, and you learn its distance.

Each distinct standard candle has a different range where it works best. The pulsating stars called Cepheid variables can only be well observed if the galaxies are close to the Milky Way, and so they are unsuitable for large-scale distance measurements. The Tully-Fisher relation can be used with many spiral galaxies, but the distance estimates they yield have uncertainties of up to 20 percent. Exploding stars called type Ia supernovae yield measurements with half as much uncertainty and shine across vast cosmic distances, but they are rare, only occurring once a century in a good-size galaxy.

If peculiar velocities for a large sample of galaxies in the universe can be obtained, astronomers can then map the largest-scale galactic flows. On these immense scales, the flow of galaxies can be compared with rivers winding through what we call cosmic watersheds, with motions defined by gravitational forces from nearby structures rather than topography. In these "cosmographic" maps, galaxies flow in currents, swirl in eddies and collect in pools to indirectly reveal the structure, dynamics, origins and futures of the largest accumulations of matter in the universe [*see box on two preceding pages*].

Mapping on the scale needed to address our questions about dark matter and dark energy required cataloguing all the best available data from a large number of observational programs. In 2008 Tully, Hélène M. Courtois, now at the Institute of Nuclear Physics of Lyon in France, and their colleagues published the Cosmicflows catalog, which collated multiple data sets to detail the dynamics of 1,800 galaxies within 130 million light-years of the Milky Way. The team expanded its efforts in 2013 with the Cosmicflows-2 catalog, mapping the motions of about 8,000 galaxies within a volume of about 650 million light-years. One member of the team, Yehuda Hoffman of the Hebrew University of Jerusalem, developed methods to precisely derive the distribution of dark matter from the peculiar velocities of the Cosmicflows data.

As the catalog expanded, we were amazed to find an unexpected pattern hidden in the mass of data: the outlines of a new, previously unseen cosmic structure. Clusters of galaxies across a span of more than 400 million light-years all moved together within a local "basin of attraction," akin to water pooling at the lowest point of a landscape's topography. Were it not for the universe's incessant expansion, these galaxies would eventually coalesce into one compact, gravitationally bound structure. All together, this vast swarm of galaxies constituted the Laniakea supercluster.

So far studies of the motions of Laniakea's galaxies show them behaving exactly as would be expected from leading models of dark matter's cosmic distribution—although we cannot see it, we can predict with reasonable accuracy where the universe's invisible stuff accumulates. Furthermore, for better or worse, the total density of visible and dark matter within Laniakea suggests that, just as dark energy theorists thought, the universe is destined for a cold death of ever accelerating expansion.

Galaxies flow in currents, swirl in eddies and collect in pools to reveal the structure, dynamics, origins and futures of the largest accumulations of matter in the universe.

These conclusions remain provisional. The daunting task of mapping galactic flows still has a long way to go. Currently only 20 percent of galaxies within 400 million light-years also have peculiar velocity determinations, and many standard-candle distance measurements still have large uncertainties. Even so, the emerging map of our galactic neighborhood is giving us a new appreciation of our perch in the cosmographic basins and ranges of the universe.

OUR COSMOGRAPHIC CONTEXT

LET'S TAKE A TOUR of the flowing, rushing components of our newly discovered home, Laniakea, starting with its most familiar part—you. No matter how slow or fast you are traveling on Earth as you read this, you are spinning around the sun along with the rest of our planet at about 30 kilometers per second. The sun in turn orbits the galactic center at roughly 200 kilometers per second, and the entire Local Group, including the Milky Way, is hurtling toward a mysterious concentration of mass in the direction of Centaurus at more than 600 kilometers per second (more on this later). You probably never realized you could move so fast simply by reading a magazine article—or doing nothing at all.

Zooming out from the Milky Way, our journey through Laniakea's expanse begins with two dwarf galaxies, the Small and Large Magellanic Clouds a "mere" 180,000 to 220,000 light-years away. You can glimpse the Magellanics from Earth's Southern Hemisphere, but for the best views you must travel all the way to Antarctica, during the winter. The only other galaxy visible with the naked eye is the giant spiral of Andromeda, although it appears just as a fuzzy patch in a very dark sky.

Andromeda is two and a half million light-years away and is speeding toward us at a peculiar velocity of some 110 kilometers per second. In roughly four billion years it will slam into the Milky Way in a head-on collision and transform both galax-

SCIENTIFIC AMERICAN ONLINE Watch a video of Laniakea in motion at ScientificAmerican.com/jul2016/laniakea

ies into a single, featureless ellipsoid of old red stars. It is unlikely that our solar system will be affected during this cosmic car crash—the distance between stars is so large that no two stars are likely to get close enough to collide. The Milky Way, Andromeda and four dozen other galaxies are members of the Local Group, a region where gravity has won the battle against cosmic expansion and is undergoing collapse. Like the Milky Way itself, with its Magellanic Clouds, all these large galaxies have their own entourages of dwarfs.

Just beyond the Local Group, within a volume of about 25 million light-years, three distinctive features appear in our maps. Most of the galaxies here, including our own, live in the unimaginatively named Local Sheet. As "sheet" would imply, it is very thin—most of its galaxies are within three million light-years of this structure, itself the equatorial plane of what is referred to as the supergalactic coordinate system. Below this plane, after a gap, is a filament of galaxies—the Leo Spur—as well as galaxies in the so-called Antlia and Doradus Clouds. Above the plane there is mostly nothing nearby. This emptiness is the domain of the Local Void.

If only the galaxies within the Local Sheet are considered, the situation seems very tranquil. These galaxies are flying apart at the rate of the cosmic expansion, with only small peculiar velocities caused by local interactions. Below the Local Sheet, the galaxies of the Antlia and Doradus Clouds and the Leo Spur have small peculiar velocities, too. They are, however, approaching the Local Sheet at high speed. The Local Void is the probable culprit. Voids expand like inflating balloons, and matter moves from underdense to overdense regions to pile up at their boundaries. We now appreciate that the Local Sheet is a wall of the Local Void and that this void is expanding to push us down toward Antlia, Doradus and Leo.

Zooming farther out, we encounter the Virgo Cluster, which is 300 Local Groups' worth of galaxies squeezed into a volume with a diameter of 13 million light-years. These galaxies whiz around at typical speeds of 700 kilometers per second, and any galaxies within 25 million light-years of the cluster's exterior are falling inward to become part of it within 10 billion years. The full extent of Virgo's domain, the region it will eventually capture, extends to a current radius of 35 million light-years. Interestingly, our Milky Way, at 50 million light-years distant, lies just outside this capture zone.

THE GREAT GALACTIC FLOW

THE GREATER REGION around the Virgo Cluster that extends to our location is called the Local Supercluster. Almost 30 years ago a group of astronomers who became identified by the convivial moniker "the Seven Samurai" discovered that it is not just the Milky Way moving hundreds of kilometers per second in the direction of Centaurus but rather the entire Local Supercluster. They called the mysterious mass pulling all these galaxies together the Great Attractor. In many ways, the Great Attractor is not so mysterious—the density of matter in that direction of the cosmos is obviously high because it contains seven clusters comparable to the Virgo Cluster lying within a sphere 100 million light-years wide. Three of the largest clusters are called Norma, Centaurus and Hydra.

According to our conception of superclusters as cosmic watersheds, which draws their boundaries based on the divergent movements of galaxies, the so-called Local Supercluster is misnamed. It is only part of something bigger—namely, Laniakea, which encompasses other large structures such as the Pavo-Indus filament and the Ophiuchus Cluster. Imagining Laniakea as a city, our traffic-heavy downtown would be the Great Attractor region. As with most urban cores, it is hard to specify a precise center, but an approximation would place it somewhere between the Norma and Centaurus clusters. This positioning puts our Milky Way far out in the suburbs, near the borders of an adjacent supercluster called Perseus-Pisces. This border is so relatively close in cosmic terms that we can study it in detail to define Laniakea's blobby, roughly round, half-billion-light-year-wide boundary. In total, Laniakea's boundaries encompass a mass from both normal and dark matter equivalent to some 100 million billion suns.

Astronomers have been glimpsing the outlines of what may lie beyond Laniakea for decades. Soon after the discovery of the Great Attractor by the Seven Samurai, something even larger emerged from the intergalactic murk. Directly behind the Great Attractor region, but three times farther away, is a monstrous accumulation of clusters—the densest known within the local universe. Because astronomer Harlow Shapley first spied evidence for its existence in the 1930s, this distant, huge structure became known as the Shapley Supercluster. (Incidentally, just like the Local Sheet, the Virgo Cluster and the main band of the Local Supercluster, as well as the Great Attractor and Shapley Supercluster, all lie on the supergalactic equator. Imagine an immense pancake of galactic superclusters, and you have a good picture of our large-scale local environs.)

So what is causing our Local Supercluster's peculiar velocity of 600 kilometers per second? To some degree, the culprit must be the Great Attractor complex. But we must also consider the gravitational pull of the Shapley Supercluster, which is three times farther away but bears four times the number of rich clusters. Now, according to the Cosmicflows-2 compendium—the same catalog that revealed Laniakea—there is even more to the story. The peculiar velocities of the 8,000 galaxies within this catalog demonstrate a coherent flow toward the Shapley Supercluster. This flow encompasses the entire volume of the Cosmicflows-2 catalog, 1.4 billion light-years from end to end. Does it stop there? We do not yet know. Only even bigger surveys mapping even larger swaths of the universe can reveal the ultimate source—and ultimate structure—behind the epic flow of galaxies in our local universe.

MORE TO EXPLORE

Cosmography of the Local Universe. Hélène M. Courtois et al. in *Astronomical Journal,* Vol. 146, No. 3, Article No. 69; September 2013.

The Laniakea Supercluster of Galaxies. R. Brent Tully et al. in *Nature,* Vol. 513, pages 71–73; September 4, 2014.

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FROM OUR ARCHIVES

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Dwarf Galaxies and the Dark Web. Noam I. Libeskind; March 2014.

scientificamerican.com/magazine/sa

PUBLIC HEALTH

EBOLA'S SECOND COMING

Brain deficits and more torment many virus survivors in Liberia. The top suspects are hidden viral remnants and immune system overreactions

By Seema Yasmin

Illustration by Edel Rodriguez

Seema Yasmin, a writer and medical doctor, reported for *Scientific American* from Liberia. Travel was supported by the Pulitzer Center on Crisis Reporting.

JOSEPHINE KARWAH STEPPED OUT OF THE EBOLA TREATMENT UNIT AND CRADLED HER pregnant belly. She had hobbled into the white tent in Monrovia, Liberia, two weeks earlier, during August of 2014, her knees burning with pain and threatening to buckle every fourth step.

Josephine's mother had died in this unit. Her body had been carried away in a white body bag that nurses had prepared with her name written neatly on the side. Her father, too, had died from Ebola, as did her aunt and uncle. But Josephine, though she got sick from the virus, lived. She and her unborn child were survivors, unlike 40 percent of the patients in the 2014–2016 African Ebola epidemic. Josephine decided she would name the baby Miracle.

Then the nightmares began. Back at home in her village, Smell No Taste, an hour's drive east of the Liberian capital, Josephine dreamed of the family members she had lost to Ebola and the horrors of the treatment unit. Throbbing headaches interrupted her dreams, and her hips and knees ached as she tried to fall back asleep. During the day she helped her older sister make soap to sell at the market. But her right eye burned, and her left eye made the world appear cloudy, as if drops of dew had settled on a camera lens. At the money changer's booth, she walked away with the wrong change, unable to recall how many Liberian dollars were in her purse when she left the house.

Josephine is one of 1,500 Ebola survivors in Liberia. Like Josephine, many today suffer memory loss, joint pains, muscle aches and eye problems. These are not isolated anecdotes and vague reports. In February, reporting findings from the largest-ever study of Ebola survivors at a conference in Boston, Mosoka Fallah, an epidemiologist from Liberia, said more than half of the patients who lived through an acute attack later reported muscle and joint problems. Two thirds had neurological difficulties, and 60 percent reported eye problems approximately one year after Ebola infection. Although the World Health Organization declared the public emergency was over this past March, now people are living with what doctors call post-Ebola syndrome.

Post-Ebola syndrome has been spotted before. After small virus outbreaks in East and Central Africa in the past 20 years, survivors suffered joint pains, muscle aches and eye problems serious enough to prevent many from working.

But these were limited episodes of the disease and small groups of survivors. The 2014–2016 West African Ebola epidemic has left 17,000 survivors at risk of post-Ebola syndrome. Like Josephine, they stepped out of treatment units into an uncertain future. There is one thing that experts and patients do know: Ebola is not over.

EBOLA'S GHOST

FALLAH'S OFFICE sits at one end of a long corridor in the John F. Kennedy Medical Center in Monrovia. A Harvard University–trained epidemiologist who grew up in one of Liberia's largest slums, he was part of the team testing treatments and vaccines as part of the initial Ebola response. His survivor research grew out of that work.

The National Institutes of Health in the U.S. and the Liberian Ministry of Health and Social Welfare had formed a coalition in 2014 called the Partnership for Research on Ebola Vaccines in Liberia (PREVAIL). By the time the initial vaccine safety tests were completed, however, Liberia's epidemic was slowing down. The number of people becoming infected with Ebola was far fewer than expected, so the first study, PREVAIL I, was scaled back to test only for vaccine safety and immune response and not the vaccine's ability to prevent Ebola. Instead PREVAIL scientists shifted resources to Ebola's aftereffects. Reports were coming in from across West Africa of patients who survived the disease but suffered physical and psychological problems. Fallah was appointed principal investigator for the study in Liberia and switched his focus from the Ebola response to Ebola survivors.

On a Wednesday afternoon, two days before Christmas, Fallah flicked through a patient file at the Kennedy Medical Cen-

IN BRIEF

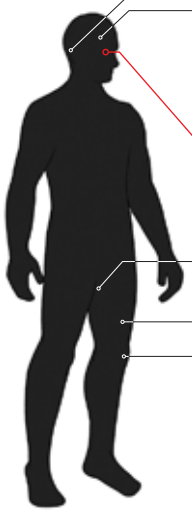
With West Africa's Ebola epidemic declared over, about 17,000 people are at risk for symptoms called post-Ebola syndrome.

In a Liberian study, 60 percent of survivors reported eye problems, 53 percent had muscle aches and joint pain, and 68 percent had neurological problems.

Supposedly virus-free people are frequently shunned by others and must wonder if the disease will afflict them again.

Suspected Hideouts

More than half of the people who live through Ebola have serious symptoms after the disease is supposedly gone, according to a study of more than 1,000 of Liberia's confirmed 1,500 virus survivors. Ailments include neurological problems and muscle pain. Physicians suspect the virus may still be hiding in parts of the body not rigorously patrolled by immune system cells, such as the eye. Or perhaps the initial immune reaction to the virus causes inflammation that damages organs. Here are commonly afflicted body parts and symptoms. The eye is a particular focus because about 60 percent of patients report troubles there.



Ears: Full or partial loss of hearing or a ringing sensation called tinnitus

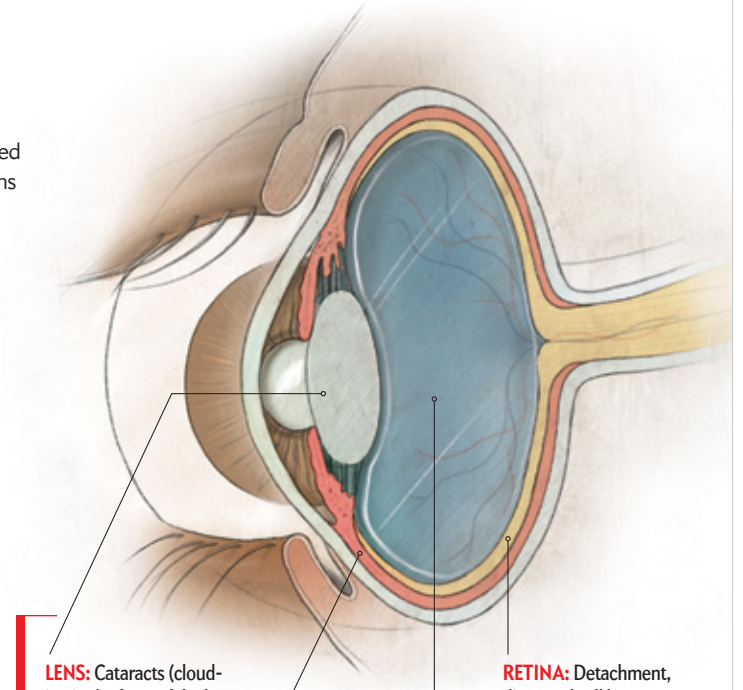
Brain: Headaches, movement-control issues resembling Parkinson's disease, memory problems, cognitive disorders, fatigue, anxiety, depression and sleep disorders
Suspected virus hiding place

Eyes:
Suspected virus hiding place

Testes:
Suspected virus hiding place

Muscles: Pain

Joints and joint cartilage: Pain
Suspected virus hiding place



LENS: Cataracts (clouding in the front of the lens instead of more typical obstructions in the middle or back), leading to blurred or lost vision, difficulty seeing in dim light, and halos around light sources

VITREOUS HUMOR: Protein clumping and particulate matter floating around, causing blurred vision

UVEA: Swelling of the middle layer, producing eye redness, pain, light sensitivity, blurred or decreased vision, and floating spots

RETINA: Detachment, disrupted cell layers, changes in pigment patterns and an inflamed area in the middle of the retina, possibly resulting in blindness or partial vision loss, inability to see in dim light, sensitivity to bright light, and seeing flashes or spots

ter. He had overseen the refurbishment of the building's second floor to include the space and equipment needed to study Ebola survivors. Outside his office and stretching up the corridor, men and women sat in chairs that lined the walls, waiting to be seen by medical staff.

Since the survivor study was launched in Liberia in June 2015, more than 1,000 of the country's confirmed 1,500 Ebola survivors have agreed to take part. Their health will be monitored at semiannual checkups for five years. Each survivor is asked to bring four friends or relatives to one of the study's three sites. These are people with whom the patients have close contact but who were not infected with Ebola. Fallah says he hopes to enroll 6,000 close contacts who will serve as controls, helping researchers separate the health problems that are part of post-Ebola syndrome from those experienced by the general population in Liberia.

When Fallah presented the first findings from the study in February, he had grim numbers: 60 percent of the approximately 1,000 virus survivors in the study reported eye problems, 53 percent said they suffered muscle aches and joint pain, and 68 percent reported neurological problems. His team dug deeper to learn what kind of damage the virus can inflict on the nervous system. At a meeting of neurologists in April, they reported that nearly three quarters of Ebola survivors suffered headaches, 72 percent had depression, and more than half suffered memory loss and difficulty walking.

One in every four or five survivors had changes to the eye affecting vision. When Fallah's team looked more closely at those survivors, they found 10 percent had uveitis, a swelling of the middle layer of tissue in the eye wall.

The vision problems drew his attention early in the research. "We saw as the war went on—I mean, as the epidemic went on—that there were different manifestations among survivors, and that would drive us to do more in-depth substudies," he says. "And it was clear that the first target should be the eye."

Fallah looked to previous studies of Ebola survivors dating back to the 1990s and found that many described eye problems in the convalescent phase. After an outbreak in the Democratic Republic of the Congo in 1995, doctors examined 20 survivors,

Illustration by Shizuka Aoki

some of them more than two months postinfection. Four were found to have eye pain, sensitivity to light, loss of visual acuity and uveitis. After another outbreak, this one in Uganda in 2007, 49 survivors were followed for more than two years. Along with memory loss, joint pain, sleep disorders and hearing loss, these people reported blurred vision and pain behind the eyes.

More recently, a study of eight patients who were treated for Ebola in U.S. hospitals found that all suffered various symptoms of post-Ebola syndrome up to four months after leaving the hospital. Six had psychological problems, including depression, anxiety and memory loss, and five suffered eye problems, including blurred vision and pain. There was no doubt the syndrome was real. But the existing data offered little explanation for how the virus can cause these problems.

AFTERSHOCK: Josephine Karwah, who survived Ebola infection only to be afflicted by other symptoms, stands outside a store in her village of Smell No Taste, Liberia.

UNDERSTANDING THE DAMAGE

THIS KIND OF CONFUSION has happened before, with another virus: HIV. Back in the 1980s when researchers were puzzled by this new viral threat, they tried to understand its effects by applying what they knew about other diseases. The same process is happening with Ebola, says Avindra Nath, a neurologist and scientist at the NIH who works closely with Fallah.

Nath has spent the better part of three decades studying infections of the brain. Although Ebola is not a retrovirus like HIV, Nath believes that years of research invested in studying HIV and the body's response to the infection have jump-started our understanding of how Ebola affects the nervous system. "Ebola has benefited from HIV research. A lot of us involved with Ebola made our careers with HIV, so we are quickly adapting our knowledge and techniques to studying these patients," he says.

Nath wonders if the neurological symptoms in Ebola survivors are a direct result of the virus or, instead, are triggered by the immune system's response to the infection. HIV, for instance, infects immune cells called macrophages in the brain, prompting the release of cytokines, small proteins that are toxic to nerve cells. Studies in monkeys have shown that Ebola infects macrophages and can set off a massive "cytokine storm." (Cytokines, chemical messengers between cells, trigger inflammation.) That can bring on hemorrhaging throughout the body, including the brain, which could explain the memory problems, headaches and movement disorders Nath has seen in Ebola survivors.

As the neurologist looks to HIV for clues to how Ebola affects the brain, others turn to different viruses to understand another symptom: the extreme fatigue reported by Ebola survivors. Studies have shown that up to a quarter of patients with dengue fever and close to 40 percent of Epstein-Barr patients suffer fatigue after the acute illness. Inflammatory cytokines may be to blame. They can act on receptors in the brain to induce postinfection fatigue and loss of appetite.

Painful joints seem to be one of the more common symptoms of post-Ebola syndrome. In a study of survivors of the 1995 Congo outbreak, almost two thirds experienced joint pain two years after infection, and one third of a Ugandan outbreak's survivors suffered from joint pain two years later.

Lumps of immune system proteins that sit inside a joint like the hip or shoulder could cause irritation and swelling. Other components of the immune system, including antibodies, could explain or even act as a surrogate marker for joint pain. After the Congo outbreak, survivors who complained of painful joints were found to have higher antibody levels as compared with survivors who did not report joint pain. Another protein might be at work in causing joint pain, too: D-dimers, small chunks of protein that break off from blood clots, have been linked to joint pain in people recovering from other infections. Patients suffering joint pain after infection with the bacterium *Neisseria meningitidis* had high levels of D-dimers in their blood. Studies looking for D-dimer-level changes have not been done on Ebola survivors.

HIDING PLACES

AS FOR THE EYE DISEASE seen in many Ebola survivors, experts say it, too, could be a result of the immune response to the virus. Or, more ominously, the virus could be replicating in the eye long after it has been cleared from the blood. The eyeball offers a safe place for the virus to hide out, away from detection and interference by the immune system. In one survivor the eyeball was found teeming with Ebola. In September 2014 an American physician, Ian Crozier, fell sick with Ebola while working in Sierra Leone. Less than two months after he was discharged from a U.S. hospital, he felt pain in his left eye and noticed that its color had changed from blue to green. When doctors inserted a needle into Crozier's eye, they found more copies of the virus in his eyeball than had been in his blood when he was close to death weeks earlier.

The eyeball is not the only hiding place for Ebola. The testes, central nervous system and joint cartilage can act as sanctuary sites for a number of pathogens, including HIV. These vital structures are at risk of collateral damage when the immune system wages war on foreign invaders. So to protect themselves from the inflammatory response, they have adopted such clever mechanisms as immune-suppressing molecules and physical

SCIENTIFIC AMERICAN ONLINE Listen to Josephine Karwah talk about life after Ebola at ScientificAmerican.com/jul2016/josephine

Photograph by Seema Yasmin

barriers. These protective measures make them great hiding spots for viruses. Hidden reservoirs could explain how Pauline Cafferkey, a Scottish nurse who recovered from Ebola, fell sick nine months after her blood tested negative for the virus and again a year after she was first infected.

If the testes harbors Ebola, that could explain why the virus persists in the semen of some survivors for months, even after they are free of symptoms. At the beginning of the West African outbreak, the World Health Organization cautioned people to practice safe sex for at least three months after their blood tested negative for Ebola. That advice was based on the 1995 Congo episode where the virus was found in the semen of survivors 82 days after the onset of symptoms.

But during the West African epidemic, Ebola virus lived in the semen of some survivors for a much longer time, more than a year after acute infection. At the conference in Boston, Fallah reinforced these findings, saying the virus was found in the semen of Liberian Ebola survivors 18 months after infection. In some men, the virus disappeared from the semen and then reappeared over the course of the year. (The WHO now advises male Ebola patients to practice safe sex for a year and to get their semen tested repeatedly.)

In his Monrovia office, Fallah has a patient file that belongs to a woman whose son died of Ebola in November 2015. The family reported no contact with anyone sick with Ebola or any survivors, but Fallah believes otherwise. He thinks the mother may have had sex with a survivor, not realized that she was sick with Ebola and passed the infection to her son.

Fallah had previously investigated a case of Ebola that was most likely transmitted via sex. In March 2015 a woman who died from Ebola was found to have had sex with a man who had been discharged from an Ebola treatment unit six months earlier. Blood samples from the man tested negative for Ebola, but a semen sample tested positive.

Fallah furrows his brow when talking about the woman who contracted Ebola from a survivor. That the virus can persist after many symptoms stop—even after a patient's blood appears clear—makes him anxious for two reasons: if Ebola hides out in people who seem healthy, only to reappear from compartments deep within the body to make them sick and potentially contagious, it could spark more outbreaks.

But finding the viral genome or bits of viral RNA in the bodily fluids of survivors does not prove they are contagious, he adds. What really worries Fallah is the stigma that these new findings place on survivors. "It's bad enough with post-Ebola syndrome that they have these symptoms we can't explain—and for who knows how long," he says. "Survivors are going through enough. Now imagine people are scared of them for fear of catching the virus."

TRAGEDY IN THE WOMB

A FEW DAYS AFTER Josephine left the Ebola treatment unit in Monrovia, while she was sleeping in her bed in Smell No Taste, she woke just after midnight. This time it was not nightmares or headaches; it was cramping in her abdomen. She rose to use the bathroom, and when she wiped herself she saw blood on the tissue. Then her water broke. "Ophelia!" she called for her older sister. They phoned for an ambulance but were told none were available. So they called a radio station in Monrovia for help. No one came.

Josephine paced up and down her bedroom, stopping to press her palms against the wall when it felt like her stomach was tearing. At 5 A.M., she wrapped herself in a maroon lapa, a traditional Liberian saronglike fabric, and staggered out of the house. If help would not come to her, she would find help on the streets. The village was asleep, sunrise still an hour away. Josephine walked alongside her house, clutching the walls to steady herself. As she screamed, women came out of their houses. "Help me, please help me," she cried. But no one would come near her, fearful of touching the woman who had left the Ebola treatment unit only a few days ago. When she reached the house at the corner of the dirt road, Josephine could no longer walk. She fell to the ground, her back against the wall and felt the baby between her legs.

Five women approached, unwrapping their lapas as they walked. They formed a semicircle around her so the male onlookers could not watch her give birth. Josephine pushed and screamed, and Miracle was born. What a chubby boy, she thought, lifting the silent child to her chest. But Miracle was not breathing.

No one would touch Josephine. The women stared as she rocked her baby and sobbed into her chest. Only her brother came close to her. He took Miracle from her arms and wrapped the baby and placenta in a yellow towel, ready for burial.

Josephine's mother had been a midwife before she died of Ebola. "Why isn't she here to help me now?" Josephine lamented. In the weeks that followed, there were more questions: Did Ebola kill Miracle, or was it because nobody would help? Would the baby have lived if an ambulance had come? Was the virus still lurking in her body, and would it harm any future pregnancies?

On visits to the Kennedy Medical Center for her survivor study appointments, Josephine asks Fallah these same questions. One afternoon she sits in his office wearing a leopard-print shirt and matching head wrap, waiting for his response.

Fallah worries the uterus may be another sanctuary site for Ebola, offering the virus a safe place to hide and still affect the body. Perhaps it could reappear and infect others. Then he wonders if the stress of being an Ebola survivor can cause a woman to give birth to a stillborn baby in the street with people watching but no one helping. He thinks, "When you can no longer sell soap in the market, when you have to wrap your money in tissue to buy vegetables, when your boyfriend stops loving you because you are an Ebola survivor—what impact does that have on a person's body? What could that do to the unborn child?"

This is what goes through his mind, but when Josephine asks, he says: "I don't know, Josephine. We are trying to find out." SA

MORE TO EXPLORE

Possible Sexual Transmission of Ebola Virus—Liberia, 2015. A. Christie et al. in *Morbidity and Mortality Weekly Report,* Vol. 64, No. 17, pages 479–481; May 8, 2015.

Persistence of Ebola Virus in Ocular Fluid during Convalescence. Jay B. Varkey et al. in *New England Journal of Medicine,* Vol. 372, pages 2423–2427; June 18, 2015.

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FROM OUR ARCHIVES

Ebola War. Helen Branswell; March 2015.

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DRILLING FOR EARTHQUAKES

ENVIRONMENT

Scientists are increasingly confident about the link between earthquakes and oil and gas production, yet regulators are slow to react

By Anna Kuchment

TO CATHY WALLACE, the earthquakes that have been rattling her tidy suburban home in Dallas feel like underground thunderstorms. First comes a distant roar, then a boom and a jolt. Her house shakes, and the windows shudder. Framed prints on the walls clatter and tilt. A heavy glass vase tips over with a crash.

The worst moments are the ones between the rumble and the impact. "Every time it happens you know it's going to hit, but you don't know how severe it's going to be," she says. "Is this going to be a bigger one? Is this the part where my house falls down? It's scary. It's very scary."

Until 2008 not a single earthquake had ever

IN BRIEF

Earthquake rates in Oklahoma and Texas have skyrocketed since 2008. The cause, scientists say, is injecting wastewater from oil and gas operations into deep underground wells. **The injections** can alter stresses that hold geologic faults together, letting them slip, unleashing an earthquake. **Slow to react,** regulators in certain states have begun to limit the amount of wastewater sent underground. **Quakes** could continue even if injections were stopped because pressure changes already induced in deep rock can migrate for years, possibly encountering faults.

THE VOORHES

been recorded by the U.S. Geological Survey from the Dallas–Fort Worth (DFW) area, where Wallace has lived for more than 20 years. Since then, close to 200 have shaken the cities and their immediate suburbs. Statewide, Texas is experiencing a sixfold increase in earthquakes over historical levels. Oklahoma has seen a 160-fold spike in quakes, some of which have sent people to hospitals and damaged buildings and highways. In 2014 the state's earthquake rate surpassed California's.

The rise in quakes coincides with an increase in drilling activity. Wallace's house, for instance, sits above the Barnett Shale Formation, a layer of hard black rock that holds the U.S.'s second-largest deposit of natural gas. Between 1998 and 2002 companies started drilling this deposit using hydraulic fracturing, or fracking, which involves pumping millions of gallons of water, plus sand and chemicals, into the ground at high pressure to crack the rock and release the gas. As the gas comes up the well so does the fracking fluid, along with volumes of brine so salty it is hazardous. The fluids are pumped back down a different hole drilled far below the shale into porous rock for permanent disposal. As more and more fluid is injected into these wastewater wells, pressure can start to build up on deep geologic faults. Eventually one can slip, causing an earthquake.

Researchers at the USGS and other institutions have tied earthquake surges in eight states, including Texas, Oklahoma, Ohio, Kansas and Arkansas, to oil and gas operations. Some state regulators have been slow to accept scientists' findings. Residents have become increasingly angry, and environmental groups have sued. "This is a public safety issue, and there's been a lot of denial and ignoring of the problem," says Wallace, who has joined neighbors to push for the shutdown of nearby wastewater wells.

As scientists continue to study the phenomenon, they have found more reason for concern. Evidence suggests that earthquake risks can spread for miles beyond the original disposal sites and can persist for a decade or more after drilling stops. And although the biggest earthquake from wastewater injection was a 5.6 on the Richter scale, near Oklahoma City in 2011, scientists think that temblors as powerful as 7.0—enough to cause fatalities and damage buildings across a wide area—are possible, though unlikely.

THE FIRST SIGNS OF A LINK

GEOLOGISTS HAVE KNOWN since the 1960s that pushing fluids into the ground can set off quakes. In 1961 crews drilled a deep well at a chemical weapons plant outside Denver, known as the Rocky Mountain Arsenal. Within months after workers started pumping hazardous waste into the well, residents felt tremors. More than 700 small to modest-size quakes shook the ground between 1962 and 1966.

A local geologist, David Evans, noticed that the volume and pressure of the injections corresponded with earthquake rates. In a 1966 paper he concluded that the well was likely to blame for the quakes. "It is believed that a stable situation," he wrote, "is being made unstable by the application of fluid pressure."

The U.S. Army shut down the disposal well that same year. Yet the earthquakes continued and even grew stronger as pressure from the injections propagated belowground, encountering new faults and disturbing them. Matthew Hornbach, a geophysicist at Southern Methodist University (S.M.U.) in Dallas, compares the phenomenon with spilling a cup of water on a paper towel. "Even if you stop pouring, the water is still there spreading out, and it's very difficult to stop it," he says. The largest quakes, including one that reached magnitude 4.8—strong enough to knock objects off shelves but generally not damage buildings—struck in 1967 and then gradually petered out. Residents continued to feel smaller tremors until 1981.

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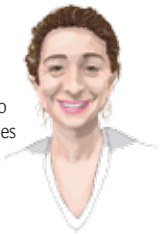


The case intrigued seismologists, and the USGS set up an experiment based on it a few years later. In 1969 Chevron Oil allowed the USGS to use one of its wells to more closely study the effects of fluid pressure on faults. The well was in a seismically active zone of the Rangely oil reservoir in Colorado, and Chevron had been injecting water into the well to stimulate petroleum production. USGS scientists turned the injections on and off and followed the fluid pressure as it migrated through deep rocks. They came up with the exact injection pressure required to trigger quakes. When the pressure exceeded that level, earthquakes rumbled; when the pressure fell below the level, they quieted down.

The experiment showed that human-triggered earthquakes could be controlled by adjusting wastewater-injection pressure. Unfortunately, the lessons of Rangely and the Rocky Mountain Arsenal were apparently forgotten by the early 2000s, when fossil-fuel companies embarked on the shale-gas boom. "Scores of papers on injection-induced earthquakes were published in the geophysical literature in the following 40-plus years, and the problem was well understood and appreciated by seismologists," says Bill Ellsworth, a Stanford University geophysicist who launched his career at the USGS while the Rangely experiment was under way. He believes professional skepticism slowed the formation of a consensus. "There were a lot of doubts expressed by very good petroleum engineers that [earthquakes caused by injection wells] were even possible," he says. "Knowledge of the whole physical process was either lost or had not been effectively communicated to a broad community."

IT STARTED IN TEXAS

SOON AFTER more aggressive drilling began in Texas and Oklahoma shales, reports of quakes started coming in. On October 30, 2008, Dallas–Fort Worth residents called 911 to report loud booming noises accompanied by shaking walls and furniture. Many wondered if something had blown up.

Seismologists Cliff Frohlich of the University of Texas at Austin and Brian Stump of S.M.U. investigated. They put out numerous seismometers and recorded more than 180 small earthquakes between October 30 and May 31, 2009. They then found that a major gas producer had recently drilled a wastewater well at Dallas–Fort Worth International Airport, less than half a mile from the center of the quake cluster. "On the basis of time and spatial correlations, we conclude the DFW sequence may be the result

WELLHEAD in Coyle, Okla., pumps wastewater into a deep, underground rock formation for permanent disposal. Thousands of disposal wells operate across the state.

of fluid injection at the SWD [saltwater-disposal] well," they wrote in a paper published in March 2010 in *The Leading Edge*.

The paper, Frohlich says, might have been ignored were it not for several other events. In June 2009 another set of quakes had rustled a small industrial city south of Fort Worth. A few months later stronger quakes shook the towns of Guy and Greenbrier in Arkansas. In March 2011 the typically steady ground of Ohio started shifting as 12 quakes rattled the Youngstown area.

From their offices in Menlo Park, Calif., USGS scientists noticed that something unusual was happening. "On a daily basis, we could see there were earthquakes occurring in places where they didn't belong," says Ellsworth, who worked at the USGS until 2015. He began to look broadly at earthquake rates in the U.S. and discovered an unsettling pattern: Between 1967 and 2000 the average rate of earthquakes east of the Rocky Mountains was 21 per year. Between 2010 and 2012 the rate had jumped to 100. He plotted the data and presented them at a scientific conference. "It generated a lot of interest," he says, from the general public as well as from scientists in industry and academia.

DRILLING SIDEWAYS

BEHIND THE RISE of earthquakes is the rise of wastewater injection wells. And behind those wells is a technological breakthrough known as horizontal drilling. The technique allows operators to drill wells vertically and then bend them 90 degrees like flexible straws. Instead of drilling right through a gas deposit that is 300 feet thick but miles across, these wells can turn when they are inside the deposit and run for thousands of feet, collecting significantly more gas and oil.

With that gas and oil, however, come vast quantities of very salty water. "The oil and gas business is really a water-handling business," says Scott Tinker, Texas's state geologist and director of the University of Texas at Austin's Bureau of Economic Geology. The water comes from the same rocks as the oil and gas. All three are remnants of ancient seas that heat, pressure and time transformed. "The pore spaces, or tiny holes, in the rock remain filled with these ancient oceans, so when we drill wells today that water is produced to the surface," Tinker says. Although the water is natural, it can be several orders of magnitude more saline than seawater and is often laced with naturally occurring radioactive material. It is toxic to plants and animals, so operators bury it deep underground to protect drinking-water supplies closer to the surface.

A legendary Texas natural gas baron named George Mitchell, who died in 2013, was the first to tap the Barnett shale using hydraulic fracturing. Oklahoma's Devon Energy combined horizontal drilling with hydraulic fracturing to extract even more gas. The technique soon caught on across Texas, Oklahoma and other petroleum-producing states.

As drilling proliferated, U.S. shale-gas production rose steeply, from 1.3 trillion cubic feet in 2007 to 5.3 trillion in 2010 and 13.4 trillion in 2014. The volume of wastewater that was brought to the surface and had to be disposed of soared, too.

In Texas the amount of water pumped into wastewater wells grew from 33.8 million barrels per month in 2007 to 81.1 million in 2014. In Oklahoma it nearly doubled from 849 million barrels per month in 2009 to 1.54 billion in 2014. Soon regular injection wells were not large enough, and operators turned to so-called

J PAT CARTER *Getty Images*

high-volume injection wells with names like "Deep Throat." Many absorbed more than 300,000 barrels of water per month.

OKLAHOMA LIGHTS UP

AS THE QUAKES MOUNTED, scientists moved from loosely associating them with wastewater injection to deducing a more direct link. In 2011 University of Oklahoma seismologist Katie Keranen returned from a field study in Alaska with half a dozen seismometers in tow. As they stood in storage in her basement lab, a magnitude 4.8 earthquake jolted the town of Prague, about 60 miles east of Oklahoma City. No sooner had she and her students put out the instruments than a 5.6 quake rocked the same town. To date, that November earthquake is the largest event related to wastewater injection, according to the USGS. It injured two people, destroyed 14 homes, buckled parts of a highway and was felt in at least 17 states.

Keranen and her students recorded that temblor, and hundreds of aftershocks, and used the data to publish papers in *Geology* and *Science*. For the *Geology* paper, published in March 2013, Keranen and her colleagues created a geophysical model to estimate how quickly fluid pressure could build up underground and how far it could spread. It showed that the pressure was likely strong enough to have caused the first earthquake, which then set off a domino effect; stress changes from the first rupture caused nearby faults to slip. The *Science* paper, released in July 2014, tied four high-volume injection wells to a cluster of earthquakes in Jones, just west of Prague.

Keranen compares the movement of fluid and pressure through the earth's subsurface to water filling a vase that someone broke and glued back together. "If you have high enough pressure, the fluid could just force its way down the fractured pathways," she says. The pressure counteracts the friction that holds faults together and allows them to slip apart—a phenomenon known as an induced earthquake.

Unconvinced, the Oklahoma Geological Survey (OGS) issued a statement disputing Keranen's findings in the *Geology* paper. "Our point was just that it looked like a natural earthquake, and there was no reason to call it induced," says Randy Keller, who was director of the survey until he retired at the end of 2014. The statement, signed by Keller and Oklahoma's state seismologist at the time, Austin Holland, pointed to evidence of historical natural earthquakes in the area.

Keranen was surprised by the response but now thinks her reaction was naive. "I have more appreciation for the fact that they wouldn't necessarily believe one report," she says. "They wanted to see the bulk of the scientists and multiple studies point in that direction." Still, she felt frustrated that Oklahoma did not quickly slow down or stop injections in some wells, a step the state did not take on a wide scale until early 2015. She says she also received pushback from administrators at her university who were not convinced that a link between disposal wells and quakes could be demonstrated. In mid-2013 Keranen left the University of Oklahoma for Cornell University.

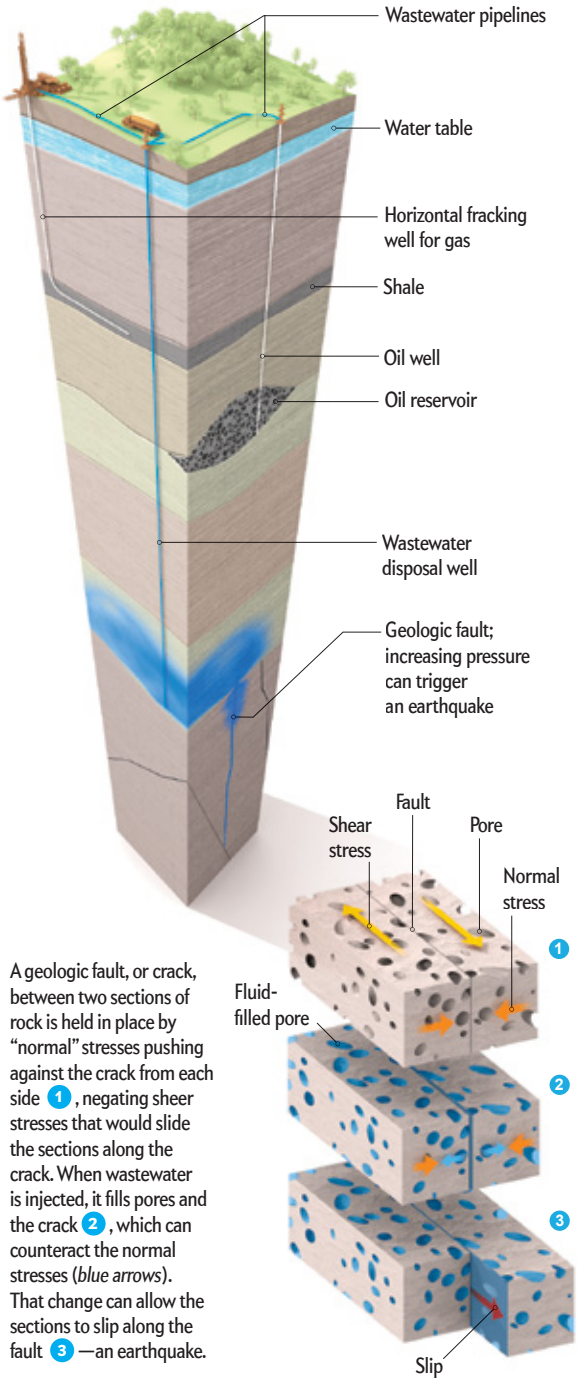
RUMBLES NEAR FORT WORTH

A FEW MONTHS AFTER Keranen's paper came out, Texas started shaking again. This time quakes struck two rural towns northwest of Fort Worth—Azle and Reno, in one of the densest areas of oil and gas development.

THE CAUSE

Injection Triggers an Earthquake

Large volumes of extremely salty brine, and chemicals, come back up gas and oil wells (*left* and *right*, respectively). Companies often inject this wastewater down a shaft (*blue*) into a deep layer of porous rock for permanent disposal, which can trigger an earthquake (*inset diagrams below*).



A geologic fault, or crack, between two sections of rock is held in place by "normal" stresses pushing against the crack from each side 1, negating sheer stresses that would slide the sections along the crack. When wastewater is injected, it fills pores and the crack 2, which can counteract the normal stresses (*blue arrows*). That change can allow the sections to slip along the fault 3—an earthquake.

Illustration by Bryan Christie

1

2

3

IN 2011 a magnitude 5.6 quake shook homes in Prague, Okla., knocking down Sandra and Gary Landra's chimney, which struck Sandra (*1*). It also cracked their basement floor. More quakes in the state since then have prompted residents to protest against disposal wells, linked to the Prague temblor and others (*2*). Scientists are installing additional seismographs to increase their data, in some cases powered by solar panels (*3*).

LINDA DAVIDSON *Getty Images (1 and 3);* PAT CARTER *Getty Images (2)*

By this time S.M.U. had hired several new geophysicists, who joined Frohlich and Stump's investigation. Heather DeShon, a seismologist, deployed seismic stations and began mapping faults underneath the towns. Hornbach, along with Stanford's Ellsworth, began studying lake, river and aquifer levels to see if North Texas's drought could have altered stresses on faults. The team also collected data on nearby saltwater-disposal wells and built a 3-D model to simulate pressure from injection wells and estimate how it would move through underground rock. Their conclusion: wastewater injection from two nearby wells was the most likely cause of the earthquakes.

Even before the study was published in April 2015, state regulators began questioning its findings. After I sent an embargoed version of the S.M.U. paper to Craig Pearson, a seismologist who works for the Railroad Commission of Texas (RRC)—the state agency that regulates oil and gas—he responded with a statement saying the research raised "many questions with regard to its methodology, the information used and conclusions it reaches." But he declined to elaborate before meeting with the paper's authors.

The RRC (its name is a historical artifact) is overseen by three commissioners. One received campaign contributions from an oil-company political-action committee, and the two others received contributions from the CEO of EnerVest, one of the two operators implicated in the S.M.U. study. Nevertheless, "regulatory decisions are made based on science, data and best practices to ensure protection of public safety and our natural resources," wrote Gaye McElwain, an RRC spokesperson, in a statement to *Scientific American*.

The RRC did eventually summon both well operators to full-day hearings in Austin to demonstrate why their wells should not be shut down. "As a result of those highly technical hearings, based on scientific data and evidence presented, it was determined the operators were not contributing to seismic activity," McElwain wrote. By September 2015, when the commission issued its ruling, the volumes of wastewater being injected in the vicinity of the earthquakes had been reduced, the earthquakes had died down and the well operators were officially allowed to continue business as usual.

OHIO SAYS STOP

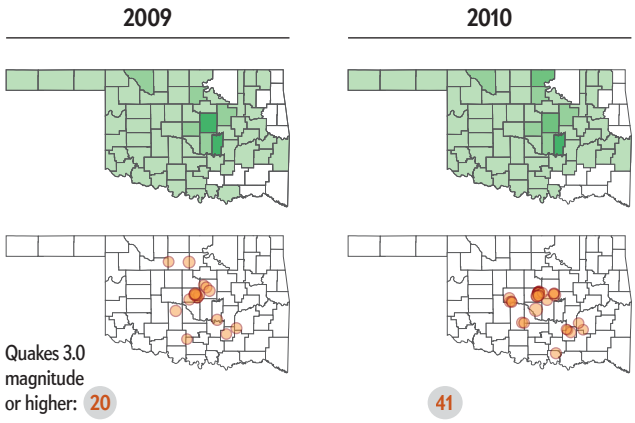
OTHER STATES have reacted differently. After a series of tremors disturbed the residents of Youngstown, Ohio, in 2011, the state shut down nearby injection wells and installed additional seismic stations to detect earthquakes too tiny to be felt. It established new rules dictating that a quake as small as magnitude 2.0, about 10 times too weak to create noticeable shaking, would trigger well shutdowns and investigations. Ohio's earthquakes peaked at 11 in 2011 before decreasing to four in 2015, according to USGS data.

Kansas also responded relatively quickly. Rex Buchanan, interim director of the Kansas Geological Survey, was watching a Kansas City Royals game in September 2014 when his cell phone started buzzing with alerts from the USGS. Tremors were shaking south-central Kansas near the state's border with Oklahoma. This was not a surprise, because more than 100 earthquakes had visited Kansas during that year, up from an average of one every two years. But the tremors were growing stronger and soon reached magnitude 4.2. Kansas governor Sam Brownback convened an induced-seismicity task force to evaluate the quakes. The task force, chaired by Buchanan, recommended restricting injection volumes within five seismic zones across two counties.

How were Kansas officials able to reach a consensus? "I don't think we could come up with any other explanation," Buchanan says. "You see a level of activity like we saw: a dramatic, dramatic increase, and in almost exactly the place where the really

More Wastewater, More Earthquakes

The number of wells injecting wastewater deep underground from oil and gas production in Oklahoma has increased in the past six years. But the overall volume of wastewater sent underground has risen much more, from 849 million barrels in 2009 to 1,538 million barrels in 2014 (*green shading*). Earthquakes of magnitude 3.0 (felt by some people, low chance of damage) or higher have multiplied in similar fashion, up from 20 in 2009 to 581 in 2014 (*orange circles*).



large-volume wells are going in—and where you see the same correlation in Oklahoma. It's pretty hard to come to any other conclusion." He adds that he and his colleagues had the benefit of watching science and regulations develop in Ohio, Texas and Oklahoma. So far the measures Kansas took seem to have had an impact. "Certainly our activity has been down lately," he says, in terms of both earthquake rates and size. "But I have pressed people real hard not to take the approach that this is some sort of problem solved, because it's not."

The reduced activity is at least partly related to the currently low price of oil, which has prompted some operators to drill less and therefore to produce less wastewater. But prices will eventually rise again, Buchanan says, and he wants to be ready "so we don't have to go through this again."

HOW BIG CAN QUAKES GET?

ENGINEERS WHO SET building codes and officers at insurance companies need to know where the next induced earthquakes will strike and how big they will be. To find out, geologists at the USGS's Earthquake Hazards Program are analyzing the rates of the induced quakes that have been multiplying across the U.S. and how induced earthquakes shake the ground differently from natural ones.

USGS scientists have found that ground movements from induced quakes are stronger just above the epicenter but less so away from the immediate area, possibly because they tend to be shallower than natural ones. Because the uppermost layers of the earth's crust east of the Rocky Mountains are denser than those in California, however, they transmit energy efficiently, and induced quakes can still be felt at great distances.

Next, the group had to come up with a maximum magnitude for these temblors: How strong could they get? After comparing central U.S. earthquakes with tremors in geologically similar parts of the world—and noting that induced quakes, so far, tended to rupture either smaller faults or smaller sections of faults than West Coast quakes—they settled on an upper limit of magnitude 6, which can damage even well-built structures. "But we can't rule out quakes of magnitude 7 and above," says Mark Petersen, chief of the National Seismic Hazard Mapping Project. Because scientists have evidence in the prehistoric record of quakes that large in the Texas-Oklahoma region, the USGS's new maps include a low-probability chance for that possibility.

Finally, the geologists had to work out the time period over which to make a reasonable earthquake forecast. They settled on a one-year forecast based on the previous year's earthquake rate and put that information in a series of maps. "It's kind of like the weather," Petersen says. "If it rained today, it's more likely that it will rain tomorrow."

The USGS issued the maps on March 28 of this year. The computer models used to generate the maps also estimate where, how often and how strongly ground shaking from an earthquake could occur, so that residents, engineers and city planners can see the likelihood that their community will experience a damaging earthquake over the next year.

CURBING THE THREAT

TO MANY OKLAHOMANS, it is clear that that risk has risen sharply. Data back up their experiences. The earthquake rate in the state has grown at an astounding pace. In 2013 the state recorded 109 quakes of magnitude 3 and greater. The following year the number jumped to 585, and in 2015 it reached 890.

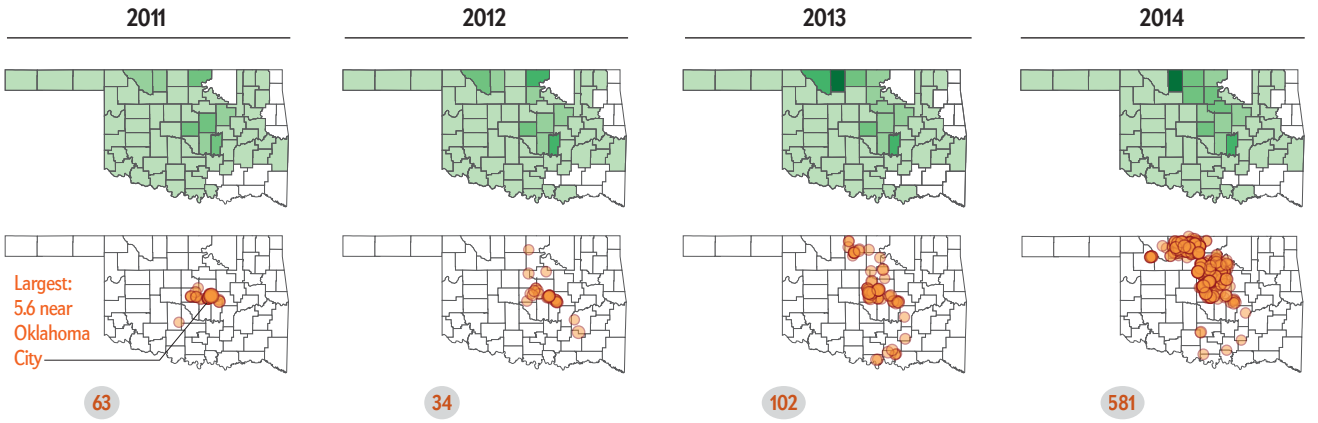
The escalation prompted two unusual warnings jointly issued by the USGS and the OGS in October 2013 and May 2014. Seismologists stated that Oklahoma had a significantly increased chance of seeing a damaging magnitude 5.5 temblor. "It was the first time I think we'd ever issued an earthquake advisory east of the Rockies," says Robert Williams, the USGS central and eastern U.S. coordinator for earthquake hazards.

Scientists such as Keranen and Mark Zoback, a geophysicist at Stanford, are producing even more detailed analyses of why quakes happen so frequently in some places but less—or not at all—in others. For example, North Dakota, the second-largest crude oil–producing state after Texas, has logged only one earthquake in the past five years. One possibility is that fluid pressure has not yet built up strongly enough to cause quakes. And only a fraction of faults may have the necessary orientation, relative to natural stresses in the earth's crust, that is conducive to a slip.

As the science has advanced, so have regulations. The OGS formally declared in April 2015 that disposal wells were trig-

SOURCES: *CLASS I / SALTWATER DISPOSAL FOR 2009–2014 AT THE ANNUAL-, STATE-, AND COUNTY-SCALES BY GEOLOGIC ZONES OF COMPLETION, OKLAHOMA.* BY KYLE E. MURRAY; OKLAHOMA GEOLOGICAL SURVEY, DECEMBER 31, 2015 *(wastewater injection data)*; USGS EARTHQUAKE MAPS *(earthquake data)*

SCIENTIFIC AMERICAN ONLINE To see the USGS earthquake-prediction map, go to ScientificAmerican.com/jul2016/kuchment



gering its quakes. "The OGS considers it very likely that the majority of recent earthquakes, particularly those in central and north-central Oklahoma, are triggered by the injection of produced water in disposal wells," it wrote in a statement.

Since then, the state has asked that more than 600 disposal wells operating in quake-prone areas cut injection volume by 40 percent below 2014 levels. Although it is too early to know if the actions will have a lasting effect, Jeremy Boak, director of the OGS, says he is starting to see declines in earthquake rates in the areas where injections have been reduced. Overall, the state saw an uptick in stronger quakes at the beginning of 2016, however. Stanford's Ellsworth does not offer policy prescriptions but wonders if the volume reductions in Oklahoma will be sufficient. "If you pump less, you're still pumping," he says, "and it doesn't guarantee you won't encounter a fault and cause an earthquake."

Many wonder why Oklahoma waited until 2015, after the state had experienced more than 750 earthquakes over seven years, to take significant action.

Matt Skinner, a spokesperson for the Oklahoma Corporation Commission, which regulates oil and gas in the state, says the agency had been shutting down individual wells and taking other steps to manage earthquake risk since 2013. The agency did not take wider action until last year, he says, because by that time researchers had published more scientific studies showing how far fluid pressure could travel from a wastewater well. "The issue changed from which well do we take action on to what group of wells do we need to take action on to reduce potential risk?" Skinner says.

Keller, the retired OGS director, says he was also aware of the state's economic dependence on oil and gas. "We were absolutely slower than those that were quick to pull the trigger," he says. "We were sitting there trying to balance the economic impact and trying to not push the panic button and at the same time trying to be responsible. It was not an easy task to figure out what to do." For well operators, a volume reduction means a loss of income and the possibility of having to truck wastewater over long distances to other facilities.

Texas has introduced new measures to monitor earthquakes. Last year the state allocated nearly $4.5 million for the installation of a seismic network and additional earthquake research. Over the past two years the Railroad Commission has also given itself new powers to shut down wells and ask operators to perform tests in areas of new seismic activity. Although the agency has expressed concern about the quakes, it has not yet formally concluded that any have been triggered by energy production.

Other mitigation strategies that states and oil and gas companies are exploring include recycling the wastewater or injecting it into layers of rock that are farther removed or isolated from deep faults. They may also space injection wells farther apart.

To the oil and gas industry, a moratorium on injections—even in a single broad area—is unacceptable. "A ban on injection is a ban on oil and gas production," says Steve Everley, a spokesperson for Energy InDepth, which is part of the Independent Petroleum Association of America. That is because there are not yet any cost-effective alternatives to injection, and many come with their own environmental costs, such as trucking water over longer distances, he says.

Even if Oklahoma shut down all its wells today, many experts say the quakes would continue. "We're trying to calculate how much energy is in the system right now and how long it may continue on—and at the current earthquake rate the numbers are very big," says Daniel McNamara, a seismologist at the USGS Geologic Hazards Science Center in Golden, Colo.

Pressed for details, he paused. Then he added: "It's hundreds of years." SA

MORE TO EXPLORE

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FROM OUR ARCHIVES

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Maps by Amanda Montañez

EVERY TIGER has a unique pattern of stripes, which makes it possible to identify individuals from photographs and thus count them.

CONSERVATION

TRACKING TIGERS

The science of surveying these elusive cats has advanced dramatically, but conservation agencies lag behind

By K. Ullas Karanth

COURTESY OF KALYAN VARMA

As a schoolboy growing up in the spectacular wilderness of southwestern India's hill country, known as Malenad, I was enchanted by tigers. The many tiger-themed rituals in our Hindu culture fueled my fascination. During the autumn Dasara festival celebrating the triumph of good over evil, for example, muscular *Huli Vesha* men, their bodies painted in patterns of ochre, white and black, mimicked the cat's graceful movements as the dancers moved to the crescendo of drumbeats. It was an electrifying spectacle. But the unfolding reality around me was grim: livestock farmers and sport hunters were killing off the last wild tigers, and loggers were relentlessly felling the rich forests for timber. By the time I was a teenager in the early 1960s, I had given up dreams of ever seeing a tiger in the wild.

K. Ullas Karanth is a senior scientist at the Wildlife Conservation Society, headquartered in New York City. Originally trained as an engineer, he later became a conservation biologist. Karanth has studied tigers for more than 30 years.

A few years later, however, an apparent miracle intervened. Responding to the rising clamor from conservationists, India's then prime minister Indira Gandhi implemented strict conservation laws and established several protected wildlife reserves. Tiger conservation gained global momentum in the decades that followed. Many countries banned legal tiger hunting and attempted to reconcile the deep contradictions between the tiger's need for forests and human demands on its habitat. India did better than most tiger nations: although it harbors only 20 percent of the remaining tiger habitat today, India shelters 70 percent of the world's tigers—no mean feat, given pressures from its 1.2 billion humans, persistent poverty and the growing industrial economy.

Despite those conservation initiatives, however, tiger populations have continued to blink out across Asia. Just two centuries ago wild tigers roamed across 30 Asian countries, from the reed beds of the Caspian Sea to the conifers of Russia, from India's woodlands to Indonesia's rain forests. That once vast range has collapsed by 93 percent, confined to a handful of countries. And populations with reasonable chances of recovery occupy an even smaller area—less than 0.5 percent of the historical tiger range.

The fate of these 40 to 50 tiger clusters, known as source populations because only they are large enough to sustain reproduction, hangs in precarious balance. Most are isolated and surrounded by hostile human landscapes. Like patients under intensive care, these source populations need close monitoring. Yet even after long-running conservation efforts, such focused tiger monitoring is the exception rather than the rule. As a result, scientists have a poor understanding of how wild tigers are actually faring. The traditional methods for surveying tigers are at best sufficient for determining where in Asia they still roam; they cannot reliably estimate how many individuals remain. Indeed, many of the tiger numbers bandied around by conservationists in the media have little solid evidence to back them up.

In recent years my colleagues and I have made significant inroads into the problem of how to count these elusive felines. By combining camera-trap technology that snaps shots of animals as they pass by with software that identifies specific individuals and sophisticated statistical analyses that can estimate full population sizes from samples of tiger photographs, we have painted a far more accurate picture of several tiger populations. The challenge going forward is getting conservation agencies to apply these improved surveillance methods to track the fate of the source populations across their range.

AN ELUSIVE SUBJECT

DETERMINING HOW MANY TIGERS EXIST, and where, is a formidable task because the cats are scarce, secretive, far-ranging and distributed across an immense geographical area. For decades these traits rendered useless attempts begun by officials in India, Nepal, Bangladesh and Russia in the 1960s to census tigers by counting tracks. The officials assumed that just as human fingerprints are unique, so, too, are tiger paw prints. Thus, they thought, they could count every tiger by counting tracks. But in truth, these methods fail because tracks can be difficult to differentiate and can go undiscovered. In India, clouds of unreliable data generated using this flawed census approach gave the impression that tiger numbers were rising and bred a deep complacency about conservation, even as risks to tigers rose. But while the officials were engaged in their misguided paw-print counting, rapid scientific progress in the fields of ecology, photography, computer programming and statistics were giving rise to new methods capable of accurately tallying tigers.

As a graduate student at University of Florida in the 1980s, I busied myself learning these novel approaches. I was determined to enter the secret world of tigers so that I could learn about their behavior and better understand how they were faring in the wild, particularly those in Nagarahole National Park, one of the reserves in Malenad where tigers had staged a come-

IN BRIEF

Wild tigers have declined to the point where the species now occupies just 7 percent of its former geographical range.
The fate of the species turns on the 40 to 50 populations that have a reasonable chance of recovery. These populations need careful monitoring.
But many conservation agencies use outdated methods to track tigers, generating unreliable and misleading counts of the elusive cats.
Fresh insights into the pressures that tigers face and new techniques that better estimate where the cats live and how many exist are key to saving the felines from extinction.

SPYING ON TIGERS: The author sets up a camera trap in a forest in India to automatically photograph the creatures that pass by (*1*). Tigers may become curious or wary of the traps after the first shot, influencing the probability of subsequent detection (*2*).

back following Gandhi's conservation mandates. In 1990 I got my chance, working with the Wildlife Conservation Society to carry out the first ever radiotelemetry study of tigers in India. By keeping close tabs on a few individuals, I would be able to glean insights into tiger behavior that would inform efforts to count as well as conserve them.

I recall the cool, bright morning of January 29 when I sat five meters up in a *Randia* tree with a dart gun, waiting for a 220-kilogram tiger that other team members were chasing my way using a cloth funnel. From my perch I spotted a flicker of sunlit gold 50 meters away in the dense brush. The tiger was calmly padding toward me. As his shoulder, and then flanks, came into my crosshairs, I squeezed the trigger. The red-tailed dart flew through the air to sting his thigh, eliciting a mild growl. We soon found him lying sedated under a shady tree and outfitted him with a special collar containing a fist-size transmitter that would broadcast radio signals that I could pick up using a handheld antenna, allowing me to locate him at any time. A couple of hours later the tiger—now labeled T-04—wandered off to join three other tigers I had collared earlier in the 645-square-kilometer reserve.

Over the next six years radiotelemetry revealed the nuances of tiger behavior by enabling me to spend less time searching blindly for tigers and more time observing them. More important, this approach exposed where the cats wandered. The resident tigers I tracked in Nagarahole had home ranges of about 18 square kilometers for adult females and 50 square kilometers for adult males. Tigers are territorial, and adults steer clear of one another unless they are mating. These small range sizes suggested that tiger population density in protected parks such as Nagarahole might be higher than previously thought.

The telemetry work also revealed in greater detail than ever before what the Malenad tigers eat by leading me to the stinking carcasses of the prey they killed. Together with the even smellier scats I collected, these data showed that tigers typically kill one large prey animal a week, consuming two thirds of it over a period of three to four days before moving on. Ultimately the diet findings implied that depletion of wild prey by human hunters was a decisive factor in driving historical tiger decline and suggested ideas for how best to recover the species now.

By 1993 I had also figured out how to estimate numbers of the tiger's chief prey—deer, wild pigs and wild cattle—in a given area. I started with a sampling method, developed by American wildlife biologists, that involves two surveyors walking stealthily along transects—straight, narrow, 3.2-kilometer-long trails that I cut through the forest. The surveyors count all the prey animals they see on their walk and measure a given animal's distance from the transect line using a range finder. From these counts and distance measurements, one can estimate the total number of prey animals, accounting even for animals that were missed during the count.

Looking at my results—the first such data from Asia—I was astonished by the abundance of prey in the protected reserves of Malenad. These forests now harbored 16 to 68 wild ungulates (the mammal group that includes deer, pigs and cows) per square kilometer, densities higher than those in the richest East African savannas. This was good news for tigers: India's reserves, though relatively small compared with the parks of North America or Africa, could still support a lot of big cats. From such estimates of prey availability, biologists could begin to guess how many tigers any forest in Asia could potentially support.

But by the mid-1990s tigers in India's reserves came under intensified poaching pressure from organized criminals catering to burgeoning demand for tiger body parts from newly rich Chinese consumers. Conservationists needed to assess the scope of their impact by getting accurate counts of tigers in key populations. How many tigers actually remained? How many were

COURTESY OF KALYAN VARMA (*left*); COURTESY OF K. ULLAS KARANTH AND WILDLIFE CONSERVATION SOCIETY (*right*)

being lost or gained every year? Did tiger numbers naturally fluctuate? Did their densities vary from region to region?

READY FOR THEIR CLOSE-UPS

TO ANSWER THESE QUESTIONS, I hoped to identify and count tigers in what was a new way at the time, using photographs shot automatically by camera traps placed along trails. The traps were electronically triggered by tigers (and other animals) walking past them. I would identify each tiger based on the unique stripe pattern on its flanks. The camera traps would allow me to spy on many more tigers than the radiotelemetry permitted. Still, I realized that my traps would photograph only a subset of the tigers in the populations I was studying. To correct for this shortcoming, known as imperfect detection, I needed to be able to estimate the size of the full population by extrapolating from the number of animals I managed to photograph.

My search for the appropriate statistical method for this situation led me to James D. Nichols of the U.S. Geological Survey's Patuxent Wildlife Research Center in Maryland. Nichols is an expert in what are known as capture-recapture models, which rely on numbers of identifiable individuals caught in repeated surveys to address the problem of imperfect detection. Imagine a jar of marbles of equal size. You grab a few, label them, then dump them back into the jar. Then you take another handful. Some are labeled; some are not. From the frequency of recaptures of labeled individuals, the models can estimate the average probability of detecting any given individual and then the total population size.

I had to fine-tune this generic model to solve the particular problems that tiger biology and field logistics posed. Whereas each marble is just as likely to get caught as any other, the same does not hold true for tigers. Because tigers have different home ranges and preferred paths, camera traps located in any area differ in their chances of capturing each individual. Tiger movement can vary by season and by the age and sex of the animals, thereby affecting capture rates. Some tigers may get spooked by the camera flash and avoid the trap next time. And unlike marbles in a jar, tiger populations experience births, deaths, and movement of individuals in and out of the area. I had to sample the population repeatedly but do so within a short period of 30 to 45 days to ensure that the numbers did not vary too greatly. Unfortunately, many expensive tiger surveys still ignore this precaution and produce inflated numbers as a result.

My camera-trap studies showed that population densities could range from 0.5 tiger per 100 square kilometers to 15 tigers per 100 square kilometers. Why, I wondered, did they vary so widely across habitats? In 1967 wildlife biologist George Schaller surmised from his observations of tigers in India's Kanha National Park that a tiger annually takes 10 percent of all prey animals available in its territory. If, as my early telemetry studies indicated, a tiger kills roughly 50 prey animals a year, then it needs some 500 ungulates in its territory to produce sufficient prey for it to consume. I speculated that prey densities might explain the huge variations in tiger densities.

To test this idea, between 1994 and 2003 I ventured beyond Malenad to estimate tiger and prey densities in reserves across India with diverse habitats ranging from mangrove swamps to evergreen forests. My results, published in 2004, confirmed the predicted ratio of one tiger to 500 prey animals. They also supported my hunch that overhunting of prey animals by local hunters, not tiger poaching for international markets, was the primary driver behind the historical collapse of the tiger range over the past 200 years. Determining the main cause of the decline was essential because it suggested that the key to combating the decline was preventing villagers from hunting the tigers' preferred prey through effective local patrolling, as opposed to catching tiger traders in faraway places.

Building on those density data, I expanded the annual monitoring of tiger populations from Nagarahole to other important reserves in Malenad in 2004. When camera-trap surveys are repeated year after year, they can capture population increases or decreases as well as numbers of individuals lost (from deaths and dispersal) and gained (from births or immigration). Such comprehensive, real-time understanding of tiger population changes offers the only means of providing a rigorous audit of successes or failures of efforts to secure and recover tiger populations.

The overall number of wild tigers, if we could even get an accurate count, may not matter.

Manually comparing each new tiger photograph with thousands of previous ones to identify individuals was tedious and slow. But pattern-matching software called ExtractCompare, developed by mathematician Lex Hiby of Conservation Research in England, enabled me to automate and speed up the identification process starting in 2000. (This versatile software identifies not only live tigers but also tiger skins seized from poachers, which greatly helps to secure criminal convictions.)

Twenty-five years of camera trapping in Malenad has created one of the largest systematic photographic databases of wild tigers, with 8,843 images of 888 individuals on record. Every season I document about 250 individual tigers concentrated in reserves that together span some 4,000 square kilometers. Some individual tigers appear year after year in the surveys, whereas most are detected in only one or two seasons, indicating high rates of turnover in the tiger population. The population of 400 to 450 tigers in the Malenad landscape is possibly the largest in the world now. My observations suggest that there are five times more tigers here than there were 50 years ago—a tribute to the efforts of local governments and conservationists.

Results from these long-term studies demonstrate for the first time how healthy tiger populations function in the wild. Well-protected tiger populations, such as the one in Nagarahole, are not static. Their densities naturally fluctuate from a low of seven tigers per 100 square kilometers to a high of 15 tigers per 100 square kilometer over longer periods. Even such a high-density tiger population loses an average of 20 percent of its members annually. Natural violence—killing of cubs by males, injuries sustained while fighting or hunting, followed by starvation—inflicts

SCIENTIFIC AMERICAN ONLINE See more camera-trap images of tigers at ScientificAmerican.com/jul2016/tigers

substantial losses. Killings by farmers who are defending their livestock and poachers who are supplying the black market for tiger parts—activities that occur even around protected reserves—also contribute to mortality rates. But because prey is abundant on these reserves, the number of new tigers born more than compensates for these losses. The surplus animals try to disperse and settle in new areas. These findings mean that instead of fretting over deaths of individual tigers, as conservationists often do, our goal ought to be to focus on populations as a whole. Rather than using our limited resources to try to eliminate all the threats tigers face everywhere across their range, we should target our efforts on sustaining those source populations with the greatest potential to recover and expand.

LANDSCAPE VIEW

THROUGH THE 1990S AND EARLY 2000S I focused on understanding how tiger source populations function and are affected by human pressures. Yet these relatively secure populations are themselves embedded in wider landscapes that are less tiger-friendly. What is happening to tigers that live not in the reserves that house the source populations but in these surrounding "sink landscapes," so named because they absorb the surplus tigers produced by the breeding source populations?

My camera trapping in Malenad revealed long-range dispersals of newly grown up tigers: male tiger BDT-130 migrated more than 180 kilometers from Bhadra to reach Anshi-Dandeli in 2008; another male, BPT-241, moved more than 280 kilometers from Bandipur to the forests in the Shimoga district in 2011. Many other tigers traveled between adjacent reserves. These data suggested that sink landscapes allow animals from different source populations to mate, which helps to maintain healthy levels of genetic diversity. Thus, an important aspect of sustaining the source populations is maintaining habitat connectivity through sink landscapes to permit tigers to disperse.

To obtain a fuller picture of where tigers live, I decided to expand my assessment to monitor landscapes beyond 4,000 square kilometers. But the camera-trap surveys that worked well in smaller reserves were impractical and expensive to use over such large areas. Landscape-scale tiger surveys must necessarily use methods that involve searching for less direct signs that are more readily encountered than the animals themselves, namely tiger spoor—tracks and scats—data that can establish where tigers are present but not how many there are.

In 2006 I initiated a habitat-occupancy survey of tiger signs across the entire Malenad landscape of 38,350 square kilometers. The results showed that tigers inhabited about 14,076 square kilometers, or 66 percent, of the 21,167 square kilometers of suitable habitat available to them, which means that tiger populations do have plenty of room to expand. My findings additionally revealed that those areas with the highest tiger densities also had higher prey densities and restricted levels of human access, bolstering the notion that a key to saving tigers is ensuring that human hunters do not compete with them for prey animals.

In an ongoing collaboration between the Wildlife Conservation Society–India Program and the Indian Statistical Institute, my colleagues and I are exploring how tiger abundance measured at reserves using intensive and expensive methods such as camera trapping can be integrated with extensive and cheaper scat and track data from wider landscapes to yield better estimates of tiger numbers across even wider regions and countries. We hope the work will provide new insights into how to enhance tiger survival across the species' range.

DANGEROUS SPECULATION

PHOTOGRAPHIC CAPTURE-RECAPTURE and large-scale occupancy modeling are now used to estimate tiger numbers and range in several countries across Asia. (Scientists who study other elusive carnivores with unique body markings, including African wild dogs and wolverines, are also employing these approaches.) Yet on the whole, although the science of tiger population assessment has rapidly progressed, its adoption by governmental and nongovernmental conservation agencies has not, whether because of a lack of understanding of or comfort with the new methods or because the old methods cast a more flattering light on their efforts.

A recent example illustrates just how insidious reliance on outdated tools is. In April the WWF and the Global Tiger Forum announced to great fanfare that the planet's wild tiger population was at last on the rise, numbering 3,890 individuals. These groups aim to increase the number of tigers to 6,000 by 2022. But their tally, based on official estimates, relied on flawed methodologies, including the use of statistically weak extrapolations from tiger photographs and field counts of spoor. And their goal for population growth far exceeds what one would expect to realize on the basis of studies carried out using the rigorous techniques described here. Furthermore, apart from the increases in tigers in a few reserves in India and parts of Thailand, there are no convincing data to show that populations are recovering in the rest of Southeast Asia or Russia. Indeed, countries such as Cambodia, Vietnam and China have lost their viable tiger populations in recent years—losses masked by any single global tiger number.

Speculative tiger numbers for countries and regions undermine efforts to save tigers by distracting conservationists and the public from what should be our top priority: guarding and growing the source populations. In a way, the overall number of wild tigers, if we could even get an accurate count, may not matter. The source populations are the ones we need to monitor vigilantly, using the best science available to track their numbers. Only with reliable counts can we set realistic goals for future growth, develop suitable strategies for meeting those goals and measure the impact of our conservation efforts.

History shows that scientific progress can stall from lack of understanding, institutional inertia and political considerations for decades or even centuries. But as the world enters into the sixth mass extinction of wild species, we simply cannot afford to divorce conservation practices from sound science if we are to have any hope of saving a wildlife icon like the majestic tiger. SA

MORE TO EXPLORE

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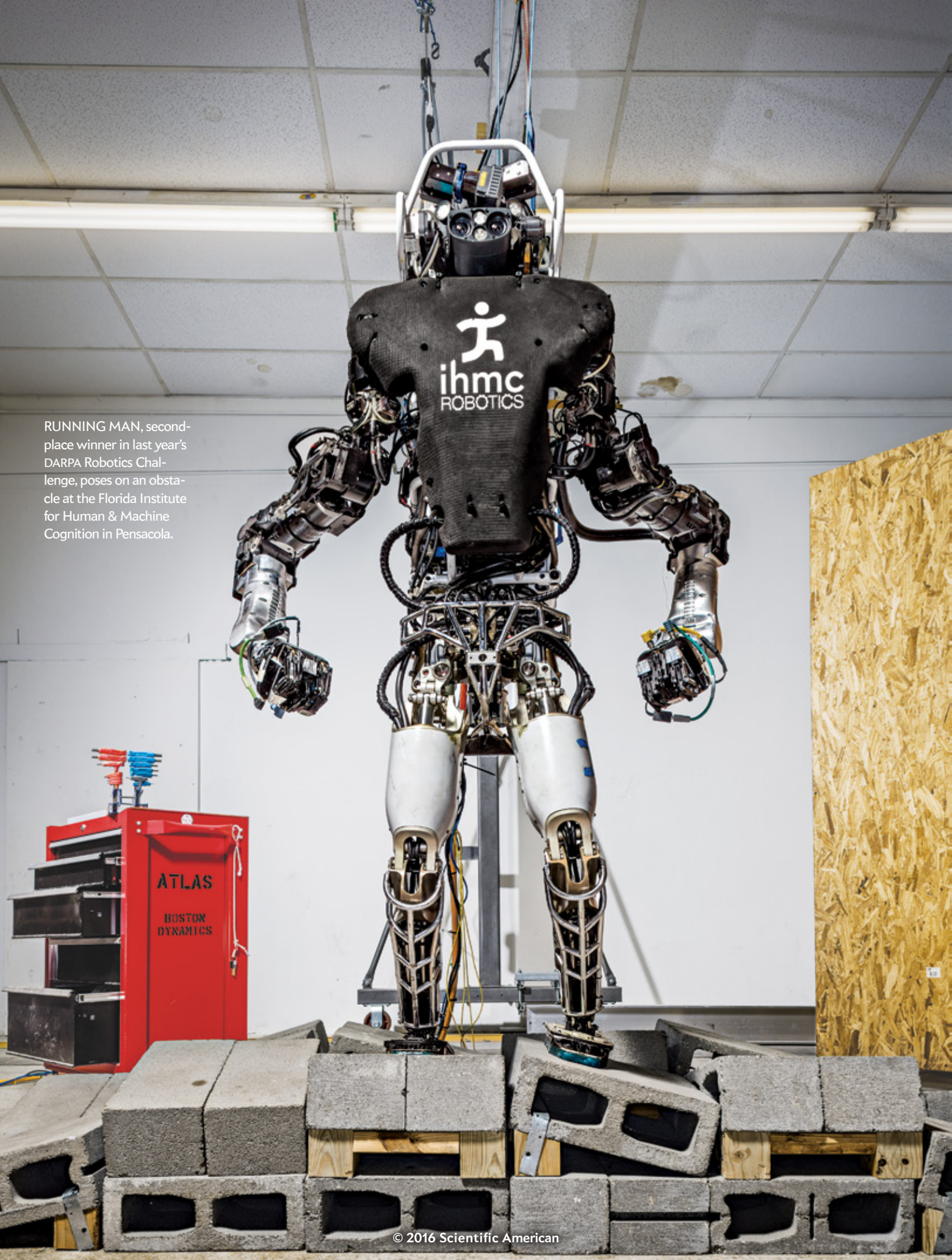


RUNNING MAN, second-place winner in last year's DARPA Robotics Challenge, poses on an obstacle at the Florida Institute for Human & Machine Cognition in Pensacola.

ROBOTICS

BIPEDAL METAL

Why is it so hard to build a walking robot?

By John Pavlus

IN BRIEF

What babies develop naturally remains far out of reach for robots: no one has come close to building a robot that can walk as efficiently and steadily as humans or other legged animals.

Yet engineers keep trying because in many applications—disaster response, for example—robots will have to negotiate stairs, doorways and other features of the human-designed world.

Motivated in part by competitions such as the DARPA Robotics Challenge, researchers pursuing several different approaches are making progress toward robot bipedalism.

Photographs by Jeff Wilson

John Pavlus is a writer and filmmaker focusing on science, technology and design topics. His work has appeared in *Bloomberg Businessweek* and *MIT Technology Review*, among other outlets.

JERRY PRATT SAW SKY ON THE VIDEO MONITOR AND KNEW HE'D FOULED UP. The sky—southern California blue as usual on a June afternoon in Pomona, about 30 miles east of Los Angeles—wasn't the problem. The problem was that there was only one reason to see sky on a monitor connected to a camera connected to the head of a very expensive, very sophisticated humanoid robot. Instead of stepping nimbly onto a small pile of cinder blocks, the robot, nicknamed Running Man, had fallen flat on its back.

Pratt did not see the fall happen, but the crowd of roboticists, journalists and spectators gathered around the course at the 2015 DARPA Robotics Challenge (DRC) did. Pratt and his collaborators from the Florida Institute for Human & Machine Cognition (IHMC) were here competing against 24 other teams to win a $2-million prize. And for the moment, Running Man lay frozen, its right leg stuck skyward like a postpratfall comedy actor waiting to hear the director shout, "Cut!" Then gravity reasserted itself, and the robot's hips and torso lolled to the side, the dead weight of its legs sagging slowly to the pavement. Its long arms lay flat and splayed, snow-angel-style.

This is not what Pratt and his partners were going for. They and the other teams, including competitors from top robotics laboratories such as ones at Carnegie Mellon University and the Massachusetts Institute of Technology, had come to show that their robots could do simple things most able-bodied humans take for granted—like opening doors, driving motor vehicles, manipulating hand tools and walking around on two legs. In 60 minutes or less, DRC contestants had to drive, steer and exit a small Jeep-like vehicle, open a closed door and enter a building, clear debris out of a hallway or traverse a pile of jumbled cinder blocks, pick up a power tool and cut through a panel of drywall with it, turn a large metal valve and ascend a short staircase. Many of the robots managed at least several of these feats, but they also fell down. A lot. The most enduring footage of the event is destined to be a highlight reel of robots toppling over like inebriated college students; on YouTube, it has been viewed 1.8 million times and counting.

Six months after the competition and back in his lab in Pensacola, Fla., Pratt recalled the event and offered assurance to anyone worried about a humanoid-robot uprising. "Walking," he says, "is hard."

BABY STEPS

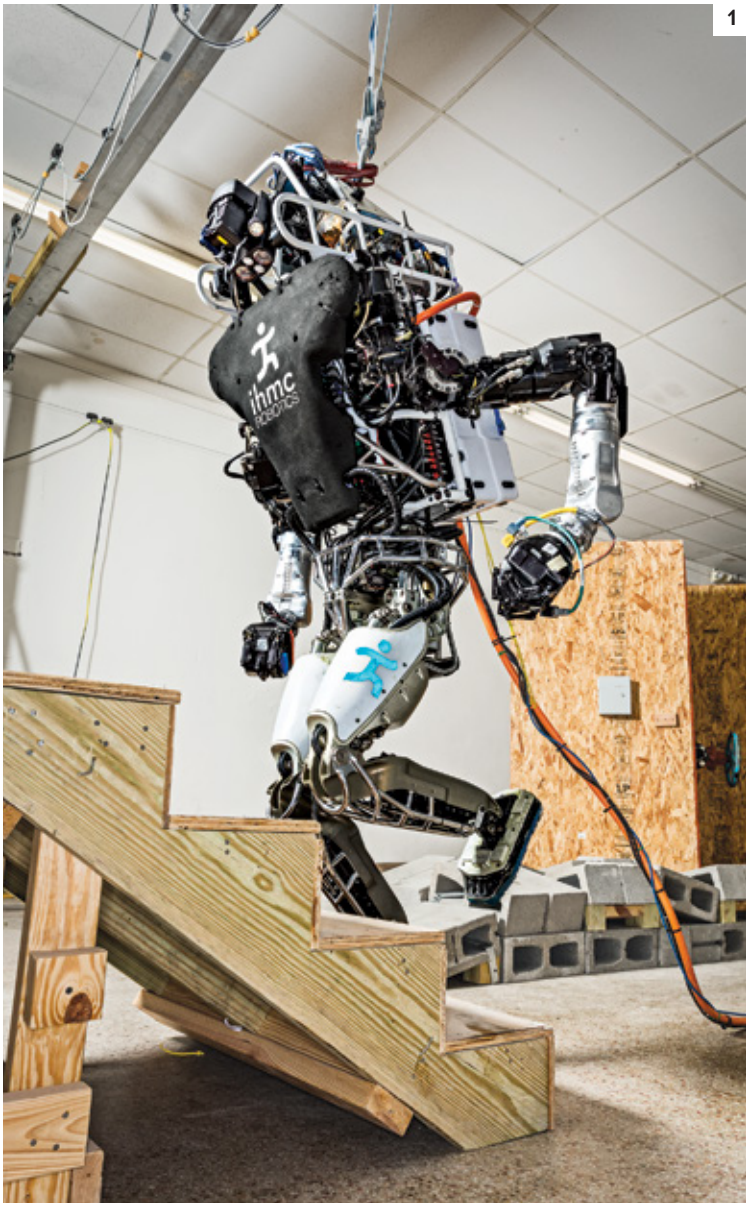
WALKING *IS* HARD—just observe a child under the age of two or talk to anyone undergoing physical therapy to regain the skill after an injury. But *why* is it hard? After all, our species has been bipedal for hundreds of thousands of years; other bipeds such as ostriches have been walking for millions more. "One has an intuition that if babies walk, it must be easy," says Andy Ruina, a professor of mechanical engineering at Cornell University who has been studying legged locomotion and designing walking robots since 1992. "But babies can do all kinds of things that we still don't understand."

What babies struggle to master about walking could be summed up in one word: agility. Stepping, balancing, maintaining momentum, correcting for errors, adapting to terrain—each of these complex behaviors is necessary but insufficient for bipedal locomotion. Degrade any one of them even slightly, and the smoothly integrated act of walking that most healthy adults take for granted quickly becomes clumsy, fragile and enervating.

Biological agility exhibits the opposite characteristics. First, it is controlled: we use our senses to find our footing with confidence and reliability. Second, it is robust: most of the time we can accommodate surprises and recover from errors. Third, walking is efficient: it does not require maladaptive amounts of time, energy or attention to perform routinely. In other words, an organism ought to be able to walk and chew gum at the same time.

Adult humans pull off this trifecta with an ease honed by millions of years of evolution (not to mention several years of continuous practice in the early stages of life). We learn control and balance using sight, touch and proprioception. Our reflexes ensure that we do not pitch into the dirt every time we encounter an unexpected pebble, and strong bones surrounded by flexible tissue protect against most spills. Finally, our every step is a symphony of mechanical and computational efficiency: our muscles and tendons can passively absorb impacts one instant and actively generate propulsion the next, and our spinal cords maintain periodic motor patterns that keep our legs moving in the right direction while our brains tend to more important business.

This, then, is what makes robotic walking "hard": no bipedal robot has yet been engineered to combine control, robustness and efficiency as well as humans—or chickens, for that matter—do. Honda's famous, astronaut-faced ASIMO meticulously calculates the force, trajectory and momentum required for each step: a control-focused approach. Boston Dynamics, whose viral videos show its next-generation Atlas humanoid hiking through a snowy forest and picking itself back up after falling down, emphasizes robustness: speed and balance over planning and precision. (Running Man and several other DRC competitors were modified from Atlas robots.) Aaron D. Ames, a robotics re-



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IN ITS CREATORS' laboratory at the Florida Institute for Human & Machine Cognition (IHMC), Running Man climbs stairs (*1*) and opens a door (*2*), both tasks from the DARPA Robotics Challenge. John Carff of IHMC guided Running Man through the competition; here he works the lab's control console (*3*).

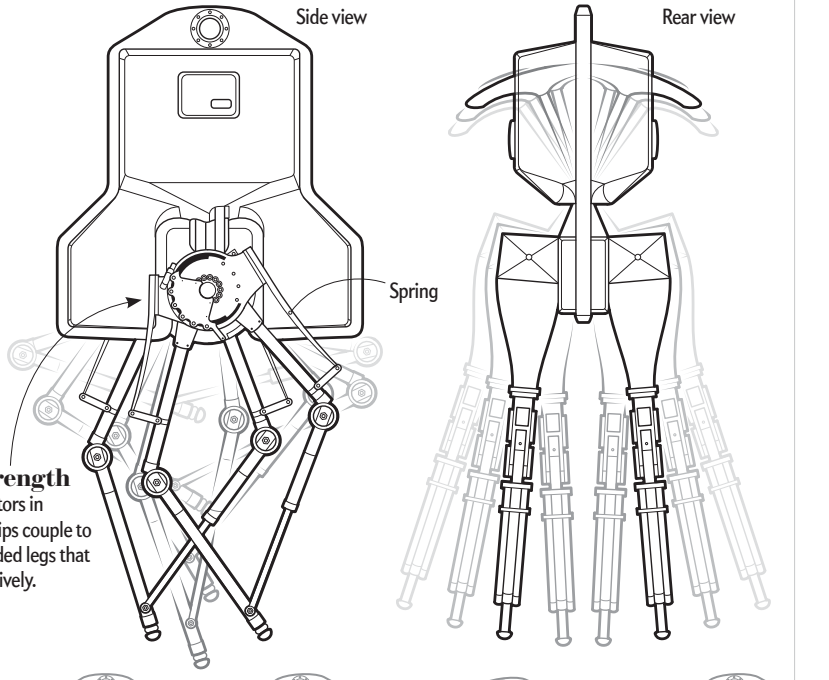
searcher at the Georgia Institute of Technology who is working on a headless, armless biped called DURUS, specifies every possible degree of freedom in the robot's body with dense mathematical equations that would fill hundreds of pages each if written out. Jonathan Hurst, a mechanical engineer at Oregon State University, built a relatively simple robot called ATRIAS based on a generic physics model that also describes the behavior of ground-running birds. Despite their differing approaches, both Ames and Hurst are interested in the same thing: efficiency. Hybrid strategies exist, too. Pratt, whose Running Man won second place in the DRC, used a method called capture point to blend ASIMO-like control with Boston Dynamics–style stability. Each approach has its advantages, yet none can emulate the efficiency, flexibility, speed and precision of an adult human walking.

It is tempting to say that engineers shouldn't bother trying. After all, Jun Ho Oh, a leading roboticist at the Korea Advanced Institute of Science and Technology (KAIST), won the $2-million DRC first prize not by outwalking the competition but by avoiding legged locomotion as much as possible. (The robot was equipped with wheels on its knees and feet, allowing it to roll in a stable kneeling position through much of the course.) And the Wright brothers didn't invent the airplane by slavishly mimicking the way bird wings flap.

Yet there are valid reasons that the desire to build walking robots endures. The most obvious application is as old as the legend of the Golem: a stronger, better version of a human body could accomplish tasks deemed too difficult, dangerous or tedious for people to risk by using their own bodies. The DARPA Robotics Challenge itself was designed to mimic the meltdown at Japan's Fukushima Daiichi nuclear power plant in 2011. That disaster might have been mitigated if robots had been capable of driving into the plant, navigating a few staircases or debris-filled corridors, and

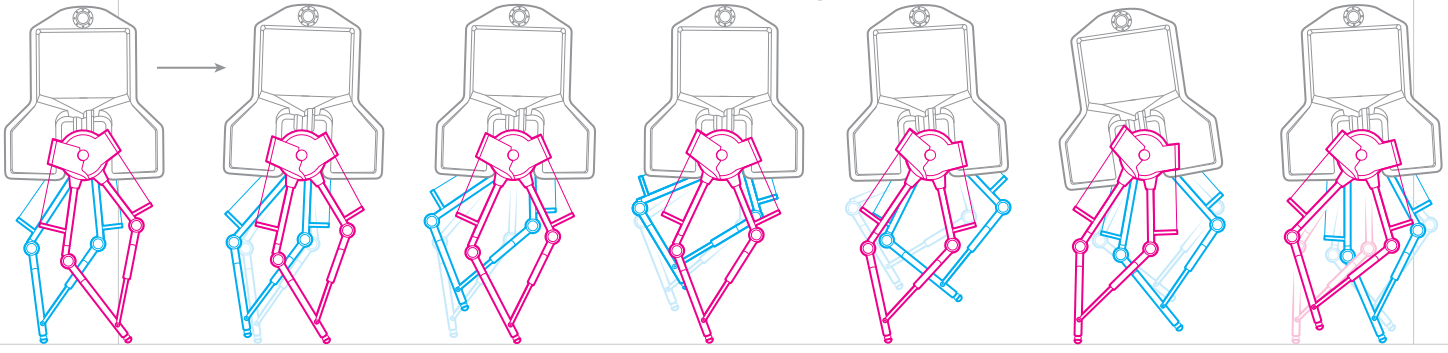
The Pogo Stick Approach

Jonathan Hurst and his graduate students at Oregon State University built ATRIAS—the name stands for "assume the robot is a sphere"—to study the fundamentals of bipedal locomotion. The robot operates using the spring-mass model of locomotion, which treats walking as the action of a massive body attached to a massless, springy leg. The result is surprisingly agile: ATRIAS can walk and run at more than six feet per second and recovers easily when kicked midstride.



Hip Strength
Strong motors in ATRIAS's hips couple to spring-loaded legs that swing passively.

Springy Step
The springs in ATRIAS's legs conserve some of the energy from each foot strike and turn it into work, thus powering the robot's next step. The elastic joints in an animal's legs do much the same thing.



turning some valves or switches. Disaster response would just be one application. Office telepresence and home assistance, package logistics and delivery, security patrols and safety monitoring, and resource exploration and extraction could all conceivably be augmented or automated by humanoid robots. "I know of no existing biological or mechanical form that is better suited for terrestrial locomotion than a humanoid," Pratt says.

The indirect benefits of robotic bipedalism could be significant as well. Ames says that building robotic systems that capture the full range of human locomotion will help us understand walking itself. "If you can make robots walk like people, you can help a lot of people who can't walk," he says.

The promise of a bipedal humanoid mirrors the promise of artificial intelligence: that of unbounded versatility. If an AI is the ultimate thinking machine, a humanoid robot could become the ultimate "doing machine"—a truly general-purpose meta tool, capable of getting to and performing in unpredictable environments while taking advantage of all the useful devices we have already invented. "The only reason to have a humanoid robot is to have a general-purpose robot," Oh says. "Bipedal robots are not necessary everywhere. But somewhere it *will* be necessary. We are preparing for those situations."

COMPLETE CONTROL

PRATT'S IHMC ROBOTICS LABORATORY looks like an indie maker space crossed with a small software start-up. Two young researchers ride caster boards around an open bullpen of standing desks, firing Nerf guns at each other. A cluttered, hangarlike work space houses a replica of the DRC course and a large metal gantry. Dangling from the gantry like a side of beef is Running Man: limbs slack, slab-shaped feet tipped downward, toes just barely touching the concrete floor. John Carff, the lab's most experienced robot operator, launches Running Man's calibration routine. Still dangling, the robot begins raising its arms and legs into a precise pose, like Leonardo da Vinci's *Vitruvian Man*.

Leaning against a pillar next to the gantry is a long length of white pipe with a miniature red Everlast boxing glove taped to one end. It represents a minimum safe distance one should keep from Running Man when the robot is active. "We have an official '10-foot pole,'" Pratt explains, as a motorized pulley lowers Running Man's feet to the floor. A thick electric cable delivers 10 kilowatts of power to the 386-pound humanoid's hydraulic actuators. "That's about the strength of 12 horses coursing through its veins," Pratt says. "If something went wrong and it whacked you in the face, it could kill you."

SOURCE: "DYNAMIC MULTI-DOMAIN BIPEDAL WALKING WITH ATRIAS THROUGH SLIP BASED HUMAN-INSPIRED CONTROL" BY AYONGA HEREID ET AL., IN *PROCEEDINGS OF THE 17TH INTERNATIONAL CONFERENCE ON HYBRID SYSTEMS: COMPUTATION AND CONTROL*; APRIL 2014

Illustration by Brown Bird Design

As Pratt and Carff put Running Man through some of the paces it made at the DRC, though—balancing on one foot, walking a few steps toward a cinder block, stepping onto the block and off—it seems at once imposing and unnervingly fragile. Its hulking torso, encased in a padded metal roll cage, balances over tapered legs bent at the knee, giving the robot a burdened, top-heavy appearance. Its push-recovery software is not installed at the moment, so a decent shove could tip it over (although the safety harness attached to the gantry would catch it). It moves with the deliberate pace and shuffling gait of an elderly person guiding a walker across a traffic intersection. But its steps are sure: the safety harness slackens visibly as Running Man pushes its considerable bulk atop the cinder blocks.

The method Pratt uses to plan Running Man's steps, known as capture point, refers to the position on the ground that a biped's foot must reach to stop its body from falling over. When someone is striding quickly or running, the capture point for each step does not need to be determined as precisely in advance, because the biped spends a relatively short time balancing before taking the next step. When a person is walking slowly or stepping over uneven terrain, however, "the placement of each step is more critical," Pratt explains. "If you're off by a few inches, you're going to be staggering all over the place."

Think of using stones to cross a creek without falling in. One approach would be to quickly "fall forward" step by step in roughly the right places on the stones to maintain your balance and trajectory. The other would be to move slowly and carefully, placing your foot in just the right spot to safely transfer your weight with each step.

According to Pratt, Running Man's real-time ability to sense its own position in space—accomplished via an inertial measurement unit in its pelvis and software that recomputes balance and orientation 1,000 times per second—far outpaces humans. But what humans have that Running Man does not are lightweight, flexible limbs capable of moving quickly enough to correct for errors or disturbances on the fly. Pratt describes a game he plays with his sons that makes this point clear. "We'll be walking down the street, and all of a sudden I'll yell, 'Push recovery!' and give 'em a shove," he chuckles. If Pratt were to pull the same prank on Running Man, there is a decent chance that even with its sophisticated push-recovery programming and 12-horsepower hydraulic joints, the robot would simply crash to the ground.

Another advantage that human bodies have over robots is the ability to get back up after falling—or at the very least, to not shatter into pieces. "You're landing on big pieces of heavy metal, so it's hard to build something that can survive a fall," Pratt says.

So if the bipedal robots at the DRC walked more like tense, frail old people than fearsome, agile Terminators, it is because their bodies forced them to do so. "The bottleneck [to engineering bipedal robots] isn't computational at all. It's the hardware," Pratt says. "If we could build the robot with something that had the same properties as muscle"—a lightweight, energy-efficient actuator capable of behaving like a powerful motor one moment and a passive spring the next—"I think it could be really good."

MEET RUNNING MAN'S MASTERS: Doug Stephen (*left*) is a researcher at IHMC, and Jerry Pratt (*right*) leads the institute's robotics group.

THE SPRING-MASS MODEL

HURST'S WALKING ROBOT, ATRIAS, is blind as a bat and dumb as a rock. It does not even have a head—just a metal pole jutting out of its boxy black thorax, which Hurst and his graduate students use to guide the robot as it struts around Oregon State University's Graf Hall like a decapitated mechanical chicken. Despite these apparent deficiencies, however, ATRIAS can perform a surprisingly humanlike feat that no path-planning, capture-point-calculating biped at the DARPA competition could: it can trip over an unexpected obstacle and keep on walking as if nothing happened. Compared with the plodding footwork of most bipedal humanoids, ATRIAS is Gene Kelly performing "Singin' in the Rain."

"We designed this robot as a scientific tool for one purpose: investigating the fundamental principles behind walking," Hurst says. In other words, don't expect to see ATRIAS ostriching its way into any future disaster sites. But if his understanding of bipedal walking is correct, we may not have to wait for someone to invent artificial muscles before robots can walk with animal-like robustness and efficiency.

ATRIAS stands for "assume the robot is a sphere," a physics in-joke that basically means "keep it simple, stupid." Its behavior is based on a decades-old theory of legged locomotion called the spring-mass model. According to this model, all the variables needed to describe a walker made of bones, muscles and tendons can be abstracted to just two elements: the mass of a body attached at a single point to a massless (in the real world, as lightweight as possible) spring-equipped leg.

The spring-mass model is little more than a computer-controlled pogo stick with a weight on top. But this model has informed the engineering of legged locomotion in robots for decades, most famously at the M.I.T. Leg Lab, where founder and principal investigator Marc Raibert conducted pathbreaking re-

search in the late 1980s and early 1990s on hopping and running robots before leaving academia to found Boston Dynamics. (Hurst and Pratt also spent time at the Leg Lab before starting their own respective legged-robotics labs.)

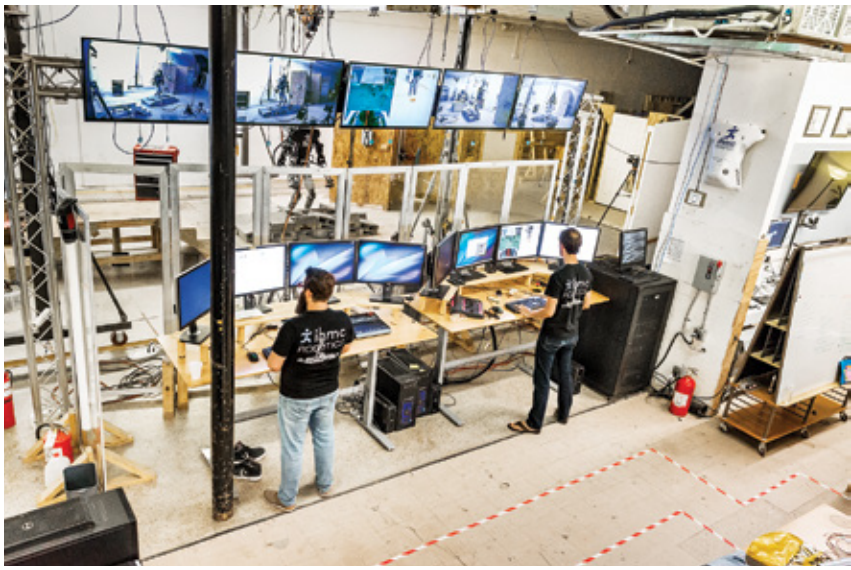
The spring-mass model is important because it provides one of the foundations for an important feature of walking called dynamic stability. A dynamically stable walking robot maintains balance in the same way a human does: by catching itself midfall with each step. If a disturbance or mistake interrupts its stride, and the walker cannot correct its gait in time to support its center of mass, the walker will fall down. "A human's center of mass is about [three feet] off the ground, which means you have to swing your leg into place in less than one third of a second to avoid a significant fall," Pratt explains.

Static stability, meanwhile, takes the opposite approach: rather than maintaining a state of controlled falling, it treats walking "as a perturbation of standing still," Ruina says. The path and momentum of each step must be precisely calculated in advance so that the robot's center of mass stays continuously balanced at every point in its stride. Early bipedal humanoids used statically stable walking to make the robots' rigid limbs easier to control and allow them—in theory, at least—to freeze midstep at any point without falling over. Contemporary humanoid robots, including the ones competing at the DRC, still use a version of this approach called quasi-static stability, which requires similarly deliberate, flat-footed steps to maintain balance.

A quasi-static biped walker needs a lot of energy-guzzling actuators and computational power to control its stiff, bent-kneed gait—and it is still exceedingly sensitive to disturbances. But a dynamically stable biped based on the spring-mass model, like ATRIAS, off-loads much of this business to the naturally occurring physical interactions between its legs and the terrain. "If you're walking on rocky ground, you can swing a leg out, flop it down, and it'll just conform automatically to whatever it hits," explains Pratt, who took advantage of similar dynamics while designing bipeds at the M.I.T. Leg Lab in the late 1990s.

When combined with strong hip motors and legs that can swing passively (without being pushed by motors), the spring-mass model can produce an efficient gait that is surprisingly resilient when disturbed. Hurst uses the phrase "animal-like performance" to describe the combination of energy savings and agility in ATRIAS's walk. Indeed, when he tracked the robot's movements and plotted the data over time, the resulting curve closely matched that of a human and several species of ground-walking birds.

Hurst says this correspondence implies that the physics he used to design ATRIAS's body and behavior might be identical to some of the principles underlying natural bipedalism. "We're not doing any biomimicry with ATRIAS," he asserts. "Its legs look nothing like a chicken's or a human's. But the walking patterns we see are the same underneath. That tells me we're onto something—and it probably doesn't require faster actuators or more computation."



PROVING GROUND: Stephen (*left*) and Carff (*right*) work the IHMC lab's two operator-control units. Carff is steering Running Man while Stephen reviews data displayed on various monitors.

ADAPTING WHILE WALKING

OH'S DRC-HUBO+ MAY HAVE WON the $2-million first prize at the DARPA Robotics Challenge, but a glance around Oh's lab proves that his is not an overnight success. Nestled in a bunkerlike workshop on KAIST's campus in Daejeon, South Korea, Hubo-Lab is festooned with obsolete iterations of the humanoid robot that Oh has spent the past 15 years bootstrapping.

They hang from small gantries like suits that have gone out of style: the original Hubo design, a child-sized ASIMO facsimile that Oh cobbled together in 2004 using leftovers from his colleagues' research budgets after being refused funding by the South Korean government; a version that *did* receive funding following Oh's successful proof of concept, its gray outer shell now stripped away and its metal innards exposed like a robotic Body Worlds exhibit; a black, headless prototype of Hubo that Oh constructed to stress-test his latest designs for the rigors of DARPA's simulated disaster scenario. DRC-Hubo+ itself is more like a life-sized GoBots toy, with gleaming red and blue accents adorning its slim, geometric, brushed-aluminum body. And much like that same toy, Hubo's secret weapon is not brains or strength but an ability to transform its humanoid shape in surprising ways.

Oh carries himself with a jolly, slightly eccentric air. He is comfortable putting on a bit of a show—especially since receiving that $2-million check from DARPA. One day in early February, Oh and his graduate students performed Hubo demos for a visiting delegation of French technocrats, the president of KAIST and a Korean military official. The week before, he had accompanied Hubo to the World Economic Forum meeting in Davos, Switzerland.

Given Hubo's accolades and celebrity, one might assume that Oh has boundless faith in his robot's walking ability. Instead he jovially recounts how often Hubo fell in the run-up to the DRC—"about once a month, but mostly the damage wasn't that serious," he says—and openly admits that his winning strategy depended on avoiding bipedal locomotion wherever possible. "If

SCIENTIFIC AMERICAN ONLINE Watch videos of walking robots at ScientificAmerican.com/jul2016/robots

walking works 99 percent of the time in the lab, the 1 percent in reality is always where the problems are," Oh says.

Oh originally intended Hubo to walk through the DRC course, just like Running Man. But after repeated difficulties during testing, Jungho Lee—a fellow roboticist and co-founder of Rainbow, a spin-off of HuboLab that commercializes the robot and its technology—convinced Oh to take a more conservative tack. Instead of staking their chances on Hubo's imperfect walking, Oh came up with a solution he calls "multimodal mobility." Another phrase that comes to mind is "whatever works."

Essentially Oh turned Hubo into a Transformer. On even ground, the robot folds into a kneeling position and drives around on wheels affixed to its knees and feet. Hubo's torso can also spin independently from its pelvis, which lets the robot twist itself into positions that can maximize its effectiveness in clever ways. For instance, when faced with the DRC's debris-filled hallway, Hubo did not waste time—or risk falling—by removing the obstructions by hand from an upright position. Instead it knelt on its wheels, rotated its upper body 180 degrees and used the flat bottoms of its feet—now facing "forward"—as a ram, pushing the debris out of its way as it rolled swiftly and safely ahead.

Oh's ingenuity produced a legged humanoid robot whose performance combines precision, robustness and efficiency while staying true to the letter of the DRC's rules. But what about its spirit? It depends on which roboticist you ask. "I didn't love that," says Georgia Tech's Ames of Hubo's transformations. (His DURUS humanoid did not compete in the main challenge course, but it did win the Robot Endurance Test, a sideline competition for ultraefficient bipedal walking.)

Tony Stentz of Carnegie Mellon, whose third-place-winning CHIMP robot eschewed walking in favor of rolling on four legs equipped with tank treads, has a different opinion. "You have to look at the problem and come up with the best design to solve it, all factors considered," he says. "If you just come out [to the DRC course] and say the solution must have a bipedal form, then I'd say you're greatly constraining your solution—and it's possible that you no longer have the optimal solution."

Oh agrees, even though he is as bullish on the utility of humanoid bipeds as anyone else at the DRC. "If [humanoid] walking were perfect 100 percent of the time, we wouldn't need multimodal mobility," he says. He shares Pratt's belief that hardware is what is holding humanoids back; he plans to devote the next two years to building up an understanding of actuators "from scratch." Still, Oh adds, "I'm not going to wait for innovative actuators—so we have to rely on electric motors, hydraulics or pneumatics" to refine Hubo's effectiveness. If that means devising clever locomotive hacks to compensate for humanoids' imperfect performance on two legs, so be it.

ALMOST HUMAN

IN FEBRUARY, Boston Dynamics released a video of its new humanoid robot doing almost all of the things that the robots competing in the DRC had struggled or failed to do. The new robot—a redesigned version of the Atlas humanoid that several DRC teams had used—could approach a door, open it and walk through it at a brisk, humanlike pace. It marched down an uneven embankment and regained its balance even as its feet slipped to and fro on the snowy ground. It confidently lowered and raised its body from a squatting position while grasping a 10-pound weight. It fell down on its face—hard—without shattering or spraying fluid from a ruptured hydraulic vein (as one unlucky DRC competitor memorably did in 2015). And perhaps most impressively, it pushed itself onto its feet and stood back up.

The demonstration hit the humanoid robotics community like Deep Blue beating Garry Kasparov at chess. Ruina called it "a game changer." Ames and Hurst, respectively, deemed it "spectacular" and "the real deal." Pratt praised its "phenomenal" range of motion, especially "the way it can squat all the way down." He added, "I can't even do that." Still, none of them consider robust bipedal walking to be "solved" and not just because Boston Dynamics refuses to share the scientific or engineering details behind its creations. "This is the new state of the art," Ames says. "What they presented is a solution, and theirs is better than most others, clearly. But it's not *the* solution." (Boston Dynamics did not respond to repeated interview requests from *Scientific American*.)

For these researchers, the same questions still persist. How can mechanical actuators deliver powerful torque and exploit passive dynamics at the same time? What control algorithms will let a robot manage the difference between tiptoeing carefully up a staircase and striding swiftly up a mound of boulders? How will the engineering of the system scale up in efficiency and down in price? "There's no Moore's law for this," Pratt says.

And so the work to solve bipedal walking continues. Hurst is working on a successor to ATRIAS that can already run, walk, steer itself and pick itself up off the ground in simulation. Ames plans to get DURUS off the treadmill and walking around Georgia Tech's campus sometime in 2017. Ames and Pratt are contributing to NASA's Valkyrie project, aimed at developing a humanoid robot to accompany astronauts to Mars; meanwhile Ruina is developing a biped called Tik-Tok that he claims will demonstrate humanlike efficiency and performance using cheap, off-the-shelf components.

"We had hopes of making a video like [Boston Dynamics's] within a year or two, so they did take that away," Ruina admits. "For a minute I thought, 'Shoot, now what am I going to do for the rest of my life?' But then I thought of the Wright brothers. Their invention wasn't the end—it was the beginning. The theory of airplane dynamics came along afterward. Atlas is by far the most impressive biped anyone's ever made. But does it mean there's nothing left to do? No. This opens up a whole world of thought." SA

MORE TO EXPLORE

Capture Point: A Step toward Humanoid Recovery. Jerry Pratt et al. Presented at the 6th IEEE-RAS International Conference on Humanoid Robots, Genoa, Italy, December 4–6, 2006. www.ihmc.us/users/jpratt/publications/2006_Humanoids_CapturePoint_Pratt.pdf

Bio-inspired Swing Leg Control for Spring-Mass Robots Running on Ground with Unexpected Height Disturbance. H. R. Vejdani et al. in *Bioinspiration & Biomimetics*, Vol. 8, No. 4, Article No. 046006; December 2013.

First Steps toward Formal Controller Synthesis for Bipedal Robots. Aaron D. Ames et al. in *Proceedings of the 18th International Conference on Hybrid Systems: Computation and Control*, pages 209–218; 2015.

Jonathan Hurst's seminar on "Designing Robots to Walk and Run": www.youtube.com/watch?v=2NVFymqa8qY

FROM OUR ARCHIVES

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AGRICULTURE

SALTWATER SOLUTION

Farmland is being ruined by salty water. Rice and fruits, genetically modified to survive salt, could feed millions

By Mark Harris

ERIC REY PULLS A PLASTIC CONTAINER HALF FULL OF COOKED RICE OUT OF HIS BRIEFCASE. THE FAT, brown grains look like normal rice. They smell like normal rice. When I gingerly raise a few grains to my lips, they even taste like normal rice: soft, chewy and a little bland. I have to stop myself from reaching for a bottle of soy sauce here in the kitchen of Arcadia Biosciences' offices in Seattle—Rey is the chief executive of the biotechnology company—to add a little salt.

My desire for extra flavor is a bit odd because this rice was grown in a salty brine that would kill most plants on the earth. The rice plants were genetically engineered to survive the chemical, mimicking unusual plants called halophytes that flourish on ocean bays, inlets and marshy shorelines. I'm surprised the grains in my mouth don't make my tongue curl. I try a blind taste test comparing them with unmodified rice grown in freshwater, and I can't tell the difference.

"Rice is the most valuable crop in the world," measured by the amount produced in 2012, Rey says, but "in parts of China where the salinity has gone up and up, they basically can't grow crops anymore." Rey believes that new understanding of the genes that help halophytes cope with huge doses of salt, combined with modern biotech methods of inserting those genes into rice and other plants, could hold a key to feeding our planet's growing population.

Nearly a quarter of the world's irrigated areas suffer from salty soil caused by poor irrigation practices. Sea-level rises also threaten tens of millions of hectares more farmland with saltwater intrusion. If healthy crops could be grown in such salty regions, they might provide food for tens of millions of people, a vital step toward supporting the extra two billion mouths expected on the earth by midcentury.

This is no pipe dream, says Eduardo Blumwald, a plant biologist at the University of California, Davis, whose work forms the basis of Arcadia's rice. "I believe it's now feasible to grow crops in low-quality, brackish and recycled water, even diluted seawater," he says. About 700 miles south of Seattle, Blumwald's U.C. Davis greenhouses are packed with tall, emerald-green rice plants thrusting up from shallow pools of salty water. He and a few other scientists around the world are transferring genes from naturally salt-tolerant halophytes into everyday crops—not just rice but also wheat, barley and tomatoes. (Cotton, too, is under study.)

For these seeds of salvation to take root, however, they will have to move out of greenhouses and prove they can thrive amid real-world storms, droughts and predatory insects. They will

Photograph by Plamen Petkov

Mark Harris is a science and technology writer based in Seattle. He wrote "Waves of Destruction" in the May 2015 issue of *Scientific American*.

also need to survive a tempest of safety and regulatory questions from politicians, scientists and farmers.

Even if the plants themselves are delicious, genetic engineering can leave a nasty taste in people's mouths. They worry the genes may be transferred to other organisms, with unforeseen effects. Such projects, critics say, expose some of poorest and most vulnerable people in the world to these uncertainties. Furthermore, points out Janet Cotter, an environmental consultant, creating food that can be grown in salty conditions simply encourages more poor irrigation practices. "If you've got bad irrigation, then you're on an unsustainable treadmill," she says.

A SALTY TALE

HALOPHYTES, whose very name means "salt plants," can survive in water ranging in salinity from a stiff Bloody Mary to full-on seawater. Mangroves are halophytes. This plant type is relatively rare and tends to look (and taste) unappetizing, with knobby protuberances, few or ugly leaves, or prominent roots.

Early attempts to popularize halophytes tried to stimulate a market by touting mangroves as a building material, oil-rich succulent halophytes for biofuels or salt-tolerant bushes for animal forage. In 1998 researchers wrote an article in *Scientific American* envisioning large-scale halophyte farms around the world to feed people. But in the absence of any developed markets for the niche crops they offered, such farms were doomed to failure.

By the time Blumwald began work on halophytes in the mid-1990s, they had been largely dismissed as botanical curiosities. "Most agricultural scientists never thought about salinity," he says. "They were thinking about making food bigger, rounder, more colorful, sweeter."

Blumwald, however, became interested in a protein found in these plants that is called an antiporter. It accelerates the exchange of sodium (salt) and hydrogen ions across a plant's cell membranes. When sodium in water is absorbed by the plant, it disrupts enzymes, the transport of water around the plant and, ultimately, photosynthesis itself. Blumwald found that by genetically engineering everyday species to produce large amounts of this antiporter, he was able to breed plants that could grow in water a third as salty as seawater, with few ill effects. The antiporter pushed sodium ions into vacuoles, sealed-off spaces within cells, where they could do no harm. In some natural halophytes, these vacuoles become so big they are called salt bladders. Quinoa, one halophyte that has found its way to tables, has bladders that look like tiny translucent spheres on its leaves.

When Blumwald boosted antiporter levels in some English heirloom tomatoes, the plants grew in water that was "four times as salty as chicken soup," he says. And they produced red, round, sweet, juicy fruit, each weighing several ounces. But while Blumwald's creations thrived in the laboratory, they struggled in the real world. "Everything works in the greenhouse, where you have a relative humidity of 40 percent or more," Blumwald says. As humidity decreases, however, plants lose more moisture from their leaves and defensively close pores. So growing plants is much harder, he notes, "when you go to the field, with a humidity of 5 percent and much less water."

The problem is that an ability to shed salt is not the only requirement for growing well in salty soil. Plants possess thousands of genes, involved in many biological processes, that can help the organism cope with many kinds of stress, such as heat, drought or salinity. To grow in salty conditions, a plant needs to have multiple genes that change their activity to protect the plant when growing conditions become challenging. There is no single magic bullet, says Simon Barak, a senior lecturer in plant sciences at Ben-Gurion University of the Negev in Israel, "but we have developed a computational method to sift through those genes and see which are most likely to be involved in stress tolerance."

Barak constructed a stress gene database, gathering data from published experiments on the plant *Arabidopsis thaliana* (commonly used by agricultural researchers to study botanical processes). Using statistical analyses that allowed him to rank the importance of each gene for plant survival under conditions such as high heat, he identified a number of promising candidate genes.

Then Barak's group ran lab tests on plants with mutated versions of those genes to see how the vegetation coped with harsh conditions. Mutants that showed tolerance to drought, salt or heat were then targeted for further study. "In classical genetic screens for new mutants, you'll screen thousands of plants of which maybe 1 to 3 percent might look interesting," Barak says. "We got a hit rate of 62 percent. We have enough mutants to last us our whole scientific lifetimes."

Other researchers have also homed in on salt survival by blending biology with statistics and computer science. A few years ago, for example, while working at the Central Salt & Marine Chemicals Research Institute in Gujarat, India, geneticist Narendra Singh Yadav found a number of genes associated with salt tolerance in another halophyte, salicornia. He did not know exactly what the genes did, only that his analysis suggested they played an important role. To test his theory, Yadav inserted two of these genes into tobacco, a plant usually quite vulnerable to salt. When grown in water about a third as salty as seawater, the transgenic plants germinated better, had longer roots and shoots, and were larger and leafier than unmodified plants. Although they did not develop visible salt bladders, the plants had lower levels of harmful molecules called reactive oxygen species that accumulate under salt stress. Yadav is now based in Israel with Barak, and his former research group is working on a salt-tolerant version of cotton in Gujarat. "And I think there are still a lot more genes to discover," he says.

IN BRIEF

Nearly a quarter of the world's farmland suffers from increasingly salty soil, which is killing plants.

Geneticists have figured out ways to modify rice and tomatoes with genes that increase salt tolerance.

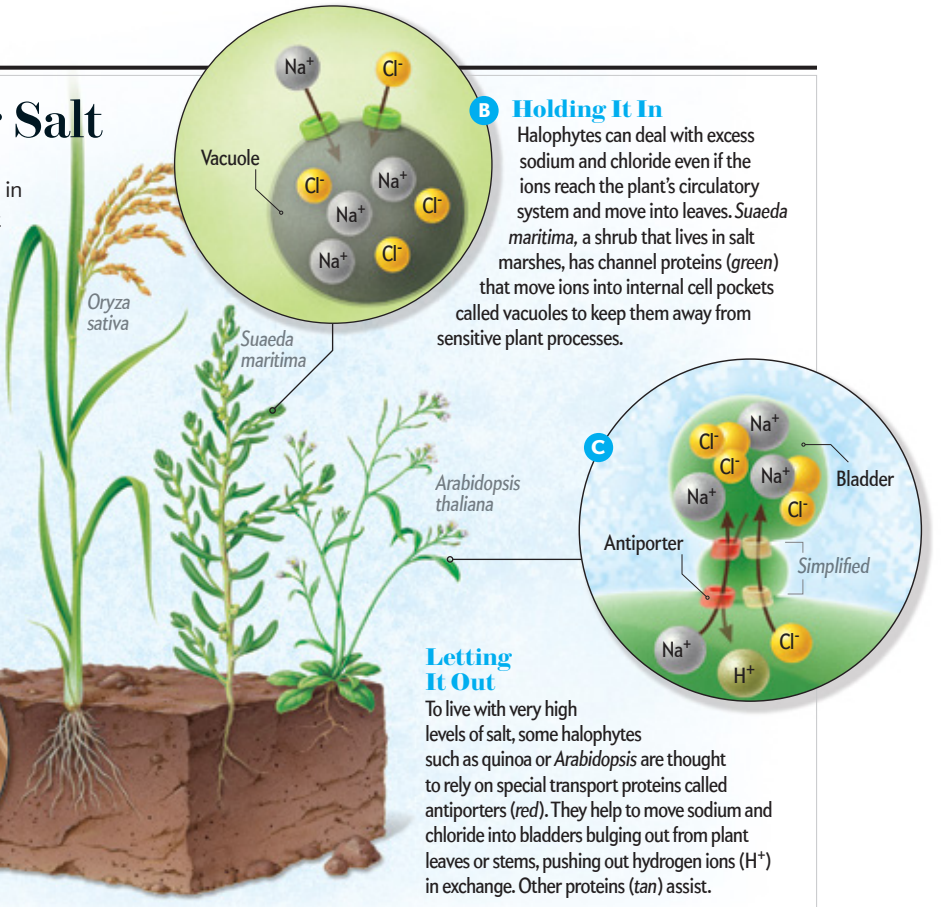
Such plants could feed millions and save farms, but critics worry about unplanned effects of gene modifications.

PAGE 68: TOMATO PLANT PROVIDED BY JAN HICKCOX, MARILYN HOCK AND MARCH FARMS OF BETHLEHEM, CONN.

SCIENTIFIC AMERICAN ONLINE Watch a talk about genetically engineering more salt-tolerant crops at ScientificAmerican/jul2016/salt-crops

Three Strategies for Salt

All plants can tolerate some salt (sodium chloride) in the soil. Sodium and chloride ions move into plant cells and between various tissues. But high levels can damage vital biochemical processes. Most plants have physical or chemical barriers at their roots to keep these ions out A. One plant type, halophytes, gets additional help. Halophytes have proteins to move large quantities of sodium and chloride ions into a plant cell's internal B or external C storage spaces. These spaces are sealed off from delicate cellular mechanisms of growth and photosynthesis. Scientists are trying to add these transporter proteins to plants such as rice to improve salt tolerance.



Barrier Method

Most plants have physical and biochemical barriers at their roots to keep out sodium ions (Na^+) and chloride ions (Cl^-) and to let water in. Rice such as *Oryza sativa* is an example. The barriers can handle only relatively low salt levels, though.

B Holding It In

Halophytes can deal with excess sodium and chloride even if the ions reach the plant's circulatory system and move into leaves. *Suaeda maritima*, a shrub that lives in salt marshes, has channel proteins (*green*) that move ions into internal cell pockets called vacuoles to keep them away from sensitive plant processes.

Letting It Out

To live with very high levels of salt, some halophytes such as quinoa or *Arabidopsis* are thought to rely on special transport proteins called antiporters (*red*). They help to move sodium and chloride into bladders bulging out from plant leaves or stems, pushing out hydrogen ions (H^+) in exchange. Other proteins (*tan*) assist.

The important thing, Blumwald says, is "to be intelligent without being stupidly optimistic." His group at U.C. Davis has a dozen greenhouses running experiments on thousands of different transgenic plants, from alfalfa and pearl millet to peanuts and rice. Most are modifications of successful commercial crops, and each experiment tries to replicate natural, stressful conditions. Massive fans simulate erratic winds, water is delivered at irregular intervals or in pulses like storms, and salt and heat are applied. "I'm tired of taking our plants to fields and watching them die," he says. "Is it feasible to get crops to grow in seawater? I don't think so. They might grow, but their nutritional value will be really small. But in diluted seawater or recycled water? Surely."

NATURAL FEARS

GENETIC MODIFICATION (GM), however, remains controversial in many parts of the world. Cotter says: "We're never quite sure what else may be affected in the plant and whether that has any implications for food or environmental safety." She prefers a breeding system called marker-assisted selection that uses genomic tools to identify genes for salt tolerance in wild versions of crop plants, then naturally breeds those plants with domesticated ones to reintroduce the gene into plants grown on farms.

Timothy Russell, who is an agronomist working in Bangladesh for the International Rice Research Institute, is also skeptical. "There's not a huge problem with GM in my mind, but it is a lot easier to get a conventionally bred variety into the market," he says. "We think that we can get reasonably good tolerance to salinity using conventional techniques. Why go down a more complicated way when it's not really necessary?"

One good reason to use GM, advocates say, is that it is faster. Breeding, selecting and rebreeding take time. Genetically engineered salt-tolerant crops will likely beat conventionally bred plants to market, probably within the next four years. The salt-tolerant rice I tasted from Arcadia Biosciences is already halfway through its final field trials in India and is headed for regulatory approval there. The plant produces 40 percent more grain than today's rice in water a tenth as salty as the sea, and Rey expects a subsequent strain to be twice as tolerant again. "Better yields for farmers mean that they make money, we make money, and we reduce the load on freshwater resources," he says.

It's a small start, Blumwald feels: "It's a step in the right direction. Feeding billions more people in the future will require not one success like this but dozens or hundreds." SA

MORE TO EXPLORE

Engineering Salt Tolerance in Plants. Maris P. Apse and Eduardo Blumwald in *Current Opinion in Biotechnology*, Vol. 13, No. 2, pages 146–150; April 1, 2002.

The Development of Halophyte-Based Agriculture: Past and Present. Yvonne Ventura et al. in *Annals of Botany*, Vol. 115, No. 3, pages 529–540; February 2015.

Plant Salt Tolerance: Adaptations in Halophytes. Timothy J. Flowers and Timothy D. Colmer in *Annals of Botany*, Vol. 115, No. 3, pages 327–331; February 2015.

FROM OUR ARCHIVES

Irrigating Crops with Seawater. Edward P. Glenn, J. Jed Brown and James W. O'Leary; August 1998.

scientificamerican.com/magazine/sa

Illustration by Cherie Sinnen

By Clara Moskowitz

MORE TO EXPLORE
FOR AN INTERVIEW WITH AUTHOR ADA PALMER, VISIT
SCIENTIFICAMERICAN.COM/JUL2016/RECOMMENDED

Future Tense

Five scientifically satisfying visions of what is to come

Quarantine Zone

by Daniel H. Wilson.
Illustrated by Fernando Pasarin.
DC Comics, 2016 ($22.99)

The capacity for violence is an illness with a cure in this graphic novel. Society restricts the few "incurables" to a lawless region called the Quarantine Zone, patrolled by enforcers who keep the incurables out and the disease contained. When an enforcer is exposed to the virus that allows aggression, he ends up on the run in the zone and discovers that having an ability for evil does not necessarily mean people will choose to act on it. *Quarantine Zone* is a beautifully illustrated, fast-paced look into a future where society must decide if "curing" human behavior can ever be justified. *—Jennifer Hackett*

Too Like the Lightning

by Ada Palmer. Tor Books, 2016 ($26.99)

It is 2454, and technology has enabled a semi-Utopian society to form: geographical nations have been replaced by ideological "hives" that unite the like-minded, religion is banned because of its tendency to incite conflict and even acknowledging a person's gender is considered offensive. The rules seem to ensure harmony and prosperity, but below the surface political tensions simmer. Against this backdrop, a convicted criminal, bound to travel the world serving others to atone for his deeds, gets caught up in a global power struggle as factions and fortunes shift in the wake of a mysterious theft. This imaginative tale ponders whether any human society can sustain peace over the long term.

Join

by Steve Toutonghi.
Soho Press, 2016 ($27)

In a near-future society, digital networks link individuals' brains to make "joins": collective minds controlling multiple bodies called drives. As Chance, a join of five, and Leap, a join of four, try to understand a puzzling illness affecting joins, they learn unsettling truths about the miracle technology that created them and come to question whether people can be both individuals and collectives without losing something in the process. *—J.H.*

Sleeping Giants

by Sylvain Neuvel. Del Rey, 2016 ($26)

A giant metal hand discovered in present-day South Dakota defies scientific explanation. Carbon dating suggests it is ancient, yet its construction is beyond the capabilities of modern technology. Soon more body parts show up, and a physicist, a linguist, a geneticist and two military pilots team up to crack the puzzle: Is the discovery a futuristic tool for learning about the universe or a massively destructive weapon? This page-turner probes the intellectual and political fallout of an astonishing find.

Dark Matter

by Blake Crouch. Crown, 2016 ($26.99)

This quantum-mechanics-inspired thriller follows physicist Jason Dessen, who suddenly finds himself in an alternative universe where his life has played out very differently. Instead of living an unremarkable existence with his wife and son, the Dessen in this new reality has devoted himself to his career and achieved world-changing breakthroughs. As he faces the future in his parallel life, Dessen yearns for his lost family and struggles with the repercussions of glimpsing the road not taken.

Illustration by Paulo Campos

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

Tiger Blood and Goat Milk

Charlie Sheen's misadventure with a false cure for HIV/AIDS

By Michael Shermer

When basketball legend Magic Johnson announced in 1991 that he had tested positive for HIV, it was a death sentence, and he promptly retired from the Los Angeles Lakers. Fans mourned his coming demise, but to everyone's astonishment, Magic's life continued in relative normalcy. A quarter of a century later he is an active entrepreneur, business leader, philanthropist and advocate for HIV/AIDS prevention.

Magic's story is emblematic of one of the great medical achievements of our time. Although there is still no cure or vaccine for HIV, teams of medical researchers have developed a highly active antiretroviral therapy (the HAART "cocktail") that significantly slows the progression of the disease by reducing the viral load to an undetectable level. If treatment is started promptly after early detection in young adults, for example, life expectancy returns close to normal.

Perhaps this is why there was far less media frenzy and social mourning after the November 2015 announcement by actor Charlie Sheen that he was HIV-positive. Most assumed HAART would save Sheen's life, not his "tiger blood" and "Adonis DNA" that he boasted about during his highly publicized 2011 meltdown following his dismissal from the hit TV series *Two and a Half Men*.

What a surprise, then, to see featured on the popular HBO series *Real Time with Bill Maher* on January 29, 2016, one Dr. Samir Chachoua, who told Maher and his more than four million viewers that he cured Sheen of HIV through his own drug cocktail of milk from arthritic goats. The treatment is based on Chachoua's "nemesis theory" that "for every disease there is an antidisease organism capable of destroying it and restoring health." Goat milk infected with caprine arthritis encephalitis virus, Chachoua says, is HIV's nemesis. When Sheen went to see him in Mexico (Chachoua is not licensed to practice medicine in the U.S.), very soon after treatment Sheen's liver tests allegedly returned to normal levels.

Chachoua also boasted that he had eradicated HIV from the small African island nation of Comoros, and when Maher asked him why he wasn't better known, he said that his cure was buried by the Cedars-Sinai Medical Center in Los Angeles after he sent clinicians there his vaccine for testing.

Not likely. According to Sheen's doctor, University of California, Los Angeles, professor Robert Huizenga, Sheen went on the HAART cocktail in July 2011 after his diagnosis, and by December of that year his viral load was undetectable. ("Undetectable" does not mean cured; the virus can be hiding in the body.) Four years later, in search of a permanent cure, Sheen visited Chachoua, who credited his goat-milk nemesis for Sheen's undetectable HIV load. Sheen went off the antiretroviral medications, and his HIV levels shot back up. Fortunately for him, Sheen came to his senses and started taking his antiretroviral medications.

As for the Cedars-Sinai "cover-up," in a lawsuit against the medical center Chachoua claimed that it reverse engineered his vaccine and destroyed his samples, but a court document states that he failed "adequately to identify the alleged trade secrets; and has not shown that such secrets are deserving of protection" and that "Chauchoua has failed to introduce admissible evidence supporting an inference that Cedars improperly acquired or revealed any alleged trade secrets." Further, Cedars-Sinai told the court that once it learned in July 1996 that Chachoua had "improperly used his collaboration with Cedars to promote his products for treating HIV infection" it terminated testing of his virus and "returned all remaining samples ... for delivery to Chachoua on September 25, 1996." Finally, according to the U.C.S.F. Medical Center, of the nearly 800,000 people of Comoros, about 7,900 of them have HIV/AIDS. Some cure.

After the HBO show, Sheen and his physician appeared on *The Dr. Oz Show* to denounce Chachoua as, in Sheen's words, a "grand work of fiction," for whom "I'm not going to be trading my meds for arthritic goat milk," because "guys like this are dangerous." The real nemeses of many potentially deadly diseases for which we do not as yet have cures are those who would capitalize on our fears. SA

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Illustration by Izhar Cohen

Steve Mirsky has been writing the Anti Gravity column since shortly before Bob Dole won the Iowa Caucus on his way to the GOP presidential nomination. He also hosts the *Scientific American* podcast Science Talk.

Clever Creatures

The world is brimming with brainy beings

By Steve Mirsky

Twenty years ago I wrote a profile of primatologist and author Frans de Waal for another magazine. As a placeholder for the title until we could think of a better one, I came up with "The Writing on de Waal." I'm both delighted and appalled to say that either by an act of editorial commission or by one of omission, the piece was published with that title. Now I have the chance to write on de Waal again, in the context of the arrival of his latest book, *Are We Smart Enough to Know How Smart Animals Are?* The answer: sometimes, with great effort.

Imagine judging Michael Jordan's basketball skills by watching him hit .202 when he played Minor League Baseball. Gauging an animal's brightness poses similar issues: "We need to familiarize ourselves with all facets of the animal and its natural history before trying to figure out its mental level," de Waal writes. "And instead of testing animals on abilities that *we* are particularly good at … why not test them on *their* specialized skills?" De Waal thus prefers the term "evolutionary cognition" to "animal intelligence" for this field of study. "It seems highly unfair to ask if a squirrel can count to ten," de Waal writes, "if counting is not really what a squirrel's life is about." You could even say it's nuts.

Consider the story in the book about a test administered to gibbons, pretty good apes. (Not great apes. They're technically lesser or smaller apes.) The tree dwellers were asked to reach out with a thin stick to move a banana close enough to their enclosure to pick it up. Chimpanzees and some monkeys could get their bananas lickety-split. But gibbons flopped and were thus considered intellectually backward. Until a researcher named Benjamin Beck realized that their hooklike hands, excellent for traveling among the tree limbs, were miserable at the kind of manipulations the task required. When Beck redesigned the experiment so that the provided tools were in the subjects' anatomical wheelhouse, well, blue ribbons for the gibbons.

De Waal reviews numerous studies involving crows, dolphins, whales, bats, sheep and other fauna showing off their brainpower. But as a longtime chimp researcher—he is director of the Living Links Center at Emory University's Yerkes National Primate Research Center—he devotes the lion's share of his time to our close cousins. One anecdote involves a colony of 25 chimps at Burgers' Zoo in Arnhem, Netherlands, which de Waal studied for six years, starting in 1975. The chimps spent nights inside but were let out onto an adjoining island all day. One morning he and some colleagues carried a crate overflowing with grapefruits past the watchful chimps and out to the island—the first time either group of primates had ever engaged in this behavior. "We thought we would get a reaction from them, but they sort of ignored the grapefruits," de Waal told me when he visited New York City in April.

The researchers then hid the grapefruits on the island to study how the chimps would search for them later. "And then we came back with an empty crate," he said. "And *that's* when they reacted. They saw an empty crate, and they started jumping around and hollering and slapping one another on the back. And I've never seen animals so excited for no fruit.… They must have deduced that we cannot go out with a crate of grapefruits and come back with it empty without these things staying" on the island, where they would soon be able to party hearty on the citrus snacks.

But there's more. When the troop got to the island, some went right past the site of a few grapefruits buried not quite completely in the sand. The human observers assumed all the chimps had overlooked the cache. But later, when his *Pan* pals were taking a siesta, a low-ranking male nonchalantly returned to the buried fruit. "He knew exactly where they were," de Waal said to me, "but he had decided not to react at the moment that he saw them." Presumably because if he had, higher-ranking individuals would have pilfered his produce. That's some quick, strategic thinking that shows off impressive evolutionary cognition.

So when somebody says they don't believe that humans evolved from ape ancestors, I tell myself I'm better off talking to de Waal. SA

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Illustration by Matt Collins

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Daniel C. Schlenoff

JULY

1966 Soft Landing on the Moon

"Six hundred miles from the site where the Russian spacecraft Luna 9 made the first controlled landing on the moon in February, the U.S. spacecraft Surveyor 1 touched down in the Sea of Storms and began sending back thousands of pictures. The pictures from Surveyor 1 show an area having the appearance of a 'freshly turned field' with rocks and pebbles protruding through a thin layer of dust. The landing pads of the spacecraft made circular footprints about an inch deep and threw out miniature 'rays' resembling those that might have been produced by a small meteorite. All the evidence indicated that the surface can easily support astronauts as well as spacecraft."

Food Economics

"The small poultry farm cannot compete in efficiency with a modern mechanized ranch. The poultry industry today requires large capital, high technical skill, business acumen and fewer workers. The new role of poultry in the U.S. diet represents no less pronounced a change than the position of poultry in agriculture. Turkey or chicken was once a special item reserved for Sunday dinner or holiday feasts; today it is an everyday staple. Poultry is now competitive in price with red meat and fish and is offered in inviting new forms. The aged, noble hen that used to require several hours of boiling to be made edible has been relegated to canned dog food and is replaced in the market by young fryers or broilers or by the chicken 'TV dinner.'"

1916 Zeppelin Docking

"To hold a big Zeppelin at the entrance to its shed, immovable against the wind which so vastly surpasses in velocity the currents of the sea, requires almost as many men as would suffice to hold a steamer against the tide. With galley slaves no longer available, and with modern prices for manual labor prevailing, it becomes necessary to find a way of docking the Zeppelin more in accord with the spirit of the present age. This is accomplished by laying rails on either side running into the shed, with wheeled clamps rolling easily along the rails and made fast to her sides with lines [*see illustration*]."

View images from the leading edge of aviation technology in 1916 at www.ScientificAmerican.com/jul2016/aviation

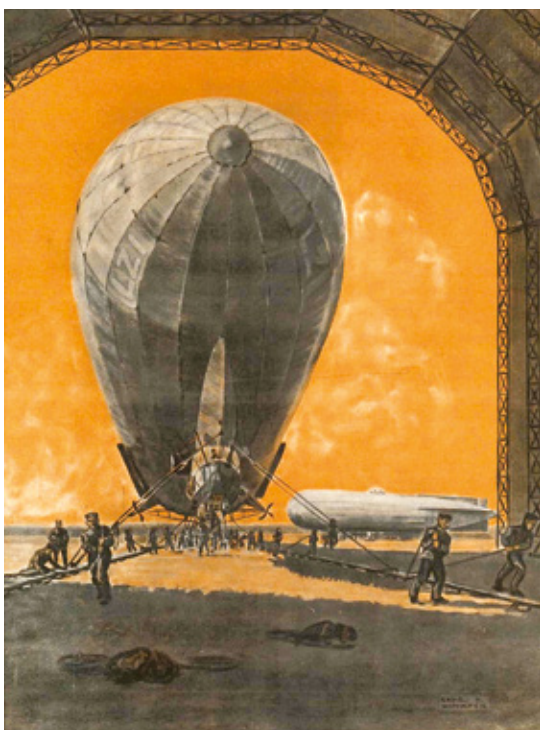
1966

1916

1866

Lubricating Time

"In this hastening age of ours when even seconds count in business life, it may sound paradoxical to say that we owe our punctuality and time-saving to the playful porpoise. And yet such, indeed, is the fact, for watches, clocks, and the still more dignified chronometer would not run month in and month out with regularity, but for the lubricant obtained from his jaws. This oil has the unique property of being able to retain its fluidity summer and winter. Neither should the oil oxidize, evaporate, or grow rancid. These exacting requirements are met in their entirety only by porpoise-jaw oil, and it is no wonder that the stuff when refined sells wholesale in the neighborhood of $25 a gallon."



1916: Zeppelin, large and fragile, is protected from the weather in its cavernous shed.

1866 Helicopter Thoughts

"Mr. F. H. Wenham lately read a paper before the Aeronautical Society of Great Britain, entitled 'Some Observations on Aerial Locomotion, and the Laws by which Heavy Bodies Impelled through the Air Are Sustained.' In the paper some experiments are quoted, which show that a force of from three to four horse-power is required for each 100 lbs. raised in the atmosphere by means of a screw or windmill, rotating with its axis set vertically, and the author concludes from these experiments that any machine constructed on this principle, for raising or transporting heavy bodies, must end in failure, as we have no continuous motive power sufficiently light even to support its own weight."

Hotter Than July

"It is probable, if not certain, that never in the history of this country, has a summer of such severity of heat as this been experienced. In our school-boy geography, we were told that the climate of the temperate zones consisted of 'extremes of heat and cold.' It is literally true. It is not an exaggeration to say that the temperature of the thermometer here [in New York] during the first two weeks of July equals anything of the sort under the equator. Existence has resolved itself into the simple effort to follow the oft quoted advice, 'keep cool.'"

SCIENTIFIC AMERICAN, VOL. CXV, NO. 3; JULY 15, 1916

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Cyberspace

Speaker: Paul Rosenzweig, Esq.

Introduction to the Cyber Domain

Virtually every aspect of global civilization now depends on cyberspace—telecommunications, commercial and financial systems, government operations, food production. This ubiquity makes keeping these systems safe from threat one of the most pressing problems we face. We'll examine how cyberspace works and what makes the Internet so vulnerable.

Big Data—"They" Know Everything About You

In the new age of "Big Data" your Internet searches can be tracked, your cellphone can broadcast your geographical location instantly, and your online purchases can be catalogued. We'll ponder the consequences of these developments in this discussion of personal data tracking and privacy.

Government Regulation of Cyberspace

Join the debate about government regulation of cyberspace in this discussion of both sides of the issue. By looking at the debate over government oversight of cybersecurity and whether we need it, you'll be better informed about a topic that has serious ramifications for how you use the Internet.

Listening In and Going Dark: The Encryption Debate

Learn how encryption and wiretapping work in cyberspace, and how both methods are becoming increasingly frustrating for law enforcement and national security officials. This "going dark" phenomenon, as you'll find in this discussion, brings benefits and causes problems—and the solutions seem to spur issues of their own.

Physics

Speaker: Pauline Gagnon, Ph.D.

The Incredible Higgs Boson

Much has been said about the Higgs boson, but why is it so important? We'll demystify this little particle. Learn how the theory called the Standard Model describes the basic constituents of the universe and how these particles interact to form all visible matter around us.

The Dark Side of the Universe

Everything on Earth and in all stars and galaxies accounts for only five percent of the universe. The rest, called dark matter and

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dark energy, remains completely mysterious. We'll discuss this great challenge and the various efforts on Earth and in space to understand this dark side of the cosmos.

Gigantic Tools to Explore the Smallest Particles

The Large Hadron Collider (LHC) is 27 kilometers long and has four huge detectors weighing up to 14,000 tons each. Why is everything so big? Learn how the LHC team designed and built such behemoths and what hopes they have for new discoveries with the recent restart of the collider.

The Tragic Destiny of Mileva Marić Einstein

How did Albert Einstein's first wife aid his extraordinary productivity in the first years of his career? The story of Mileva Marić has been largely unknown, but recent sources have shed more light on her life, allowing us to finally get a better idea of her contributions.

Physics (cont.)

Speaker: Clara Moskowitz

Hubble's Universe

We'll examine some of the most famous photographs from the Hubble Space Telescope. Learn how these images were created and how scientists turned the raw data into the colorful works of art we see. Finally, we'll discuss the future outlook for Hubble and its successor, the James Webb Space Telescope.

The Particle Zoo

We'll take a tour through nature's fundamental particles, from the familiar ingredients of the atoms that make up you and me, to the more exotic species such as neutrinos. Hear the story of how we discovered some of these particles and the outlook for finding new species.

Behind the Scenes

The Evolution of Antievolution

Speaker: Steve Mirsky, M.Sc.

Evolution has been a subject of waxing and waning controversy since the day that Darwin published *The Origin of Species*. We'll look at some of the history of the anti-evolution movement, with special attention to the "creationist science" and "intelligent design" efforts of the past three decades, as well as famous court trials.

What Do Scientific American Editors Read?

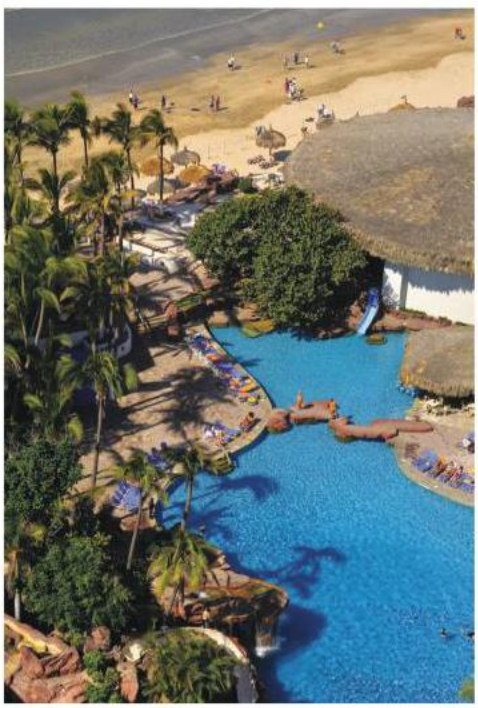
Speakers: Steve Mirsky, M.Sc. and Robin Lloyd, Ph.D.

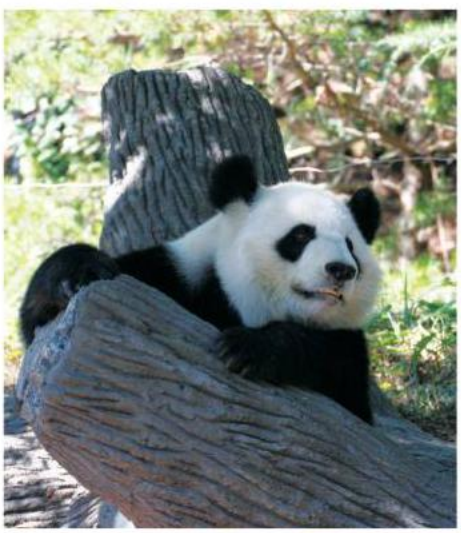
Which newspapers, journals, feeds, and websites do *Scientific American* editors read? How do we filter the fire hose of news and information every day to get the most valuable drops on the latest breakthroughs and innovations? We'll discuss a recent survey of our staff on cutting-edge sources of information.

How the Science Sausage Gets Made

Speakers: Steve Mirsky, M.Sc. and Robin Lloyd, Ph.D.

What's it like to be a science journalist? Hear the inside story from writers Steve Mirsky and Robin Lloyd, who have been at *Scientific American* for 11 and four years, respectively. They'll talk about how science gets turned into articles and some of the more amazing moments that have occurred during that process.





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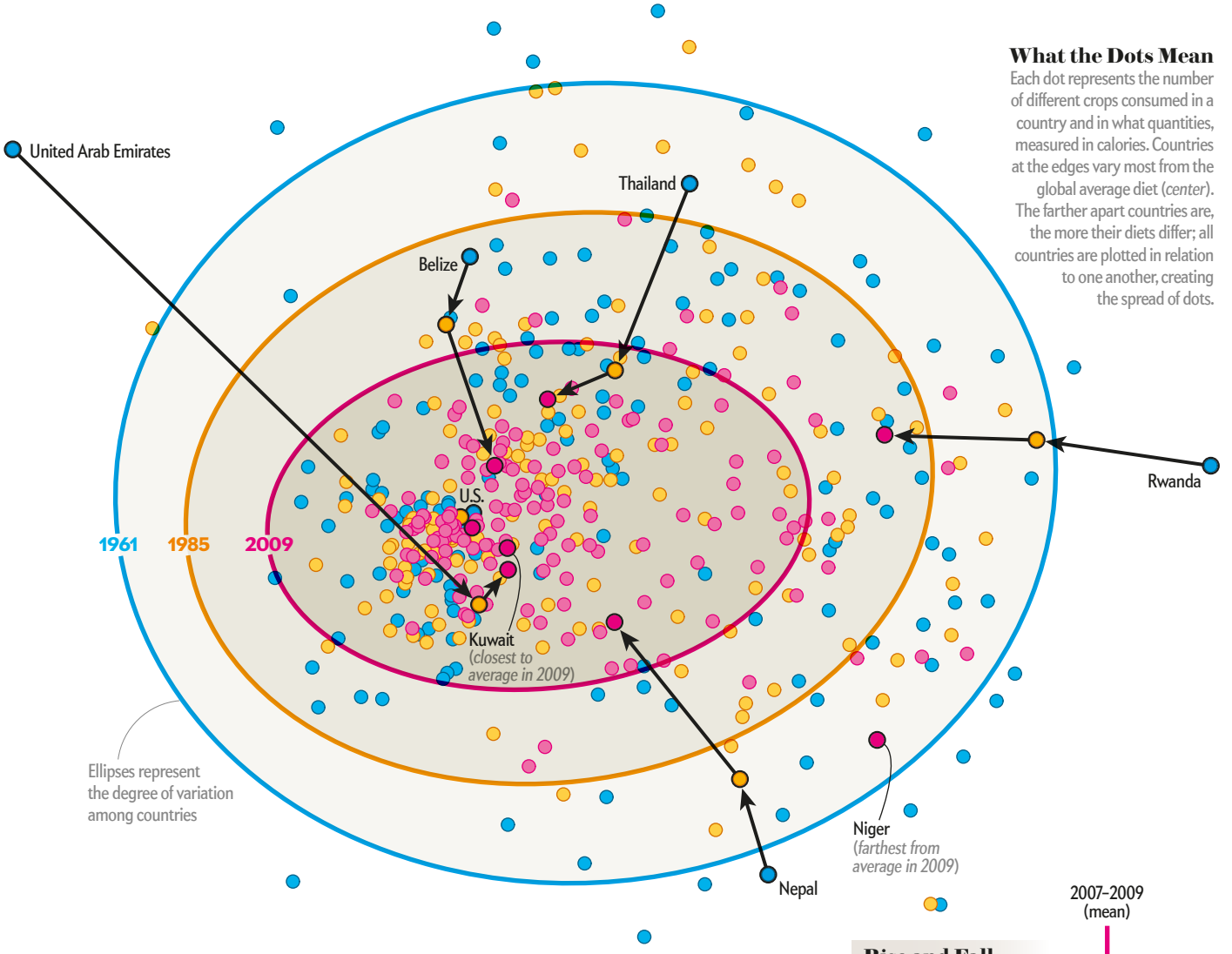
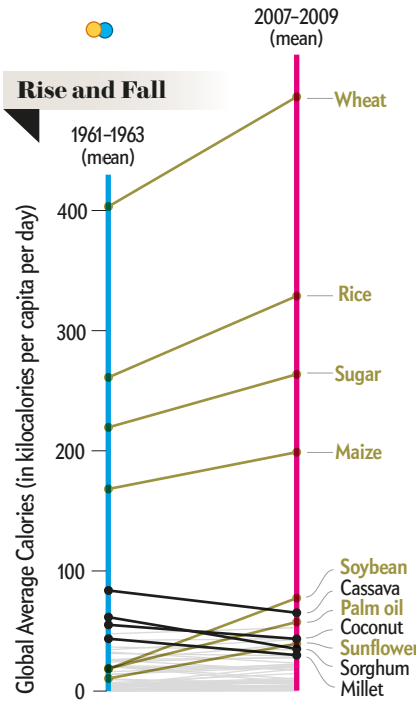
FOR INSIGHT INTO HOW CLIMATE CHANGE MAY AFFECT CROPS, GO TO SCIENTIFICAMERICAN.COM/JUL2016/GRAPHIC-SCIENCE



One-World Menu

Diets around the globe are more similar than they used to be

Back in 1961, residents of far-flung countries ate very different mixes of crops (*blue, above*). By 1985 the disparities worldwide had shrunk (*orange*), and daily fare became even more homogeneous by 2009 (*magenta*). In nearly 50 years the differences in foods eaten narrowed by 68 percent. Prevalent staples such as wheat have become even more dominant, and oil crops such as soybean, palm and sunflower have risen sharply (*right*). The convergence comes at the expense of many minor crops, says Colin Khoury of the International Center for Tropical Agriculture. People are consuming more processed foods made from a small number of ingredients and are frying with oils instead of steaming. Although the resultant increase in calories has been needed in certain regions, scientists say obesity, diabetes and heart disease are rising globally. They are also concerned that if one crop falters because of disease or drought, food prices could soar and supplies across continents could crumble. *—Mark Fischetti*



SOURCE: "INCREASING HOMOGENEITY IN GLOBAL FOOD SUPPLIES AND THE IMPLICATIONS FOR FOOD SECURITY," BY COLIN K. KHOURY ET AL., IN *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES USA* VOL. 111, NO. 11; MARCH 18, 2014

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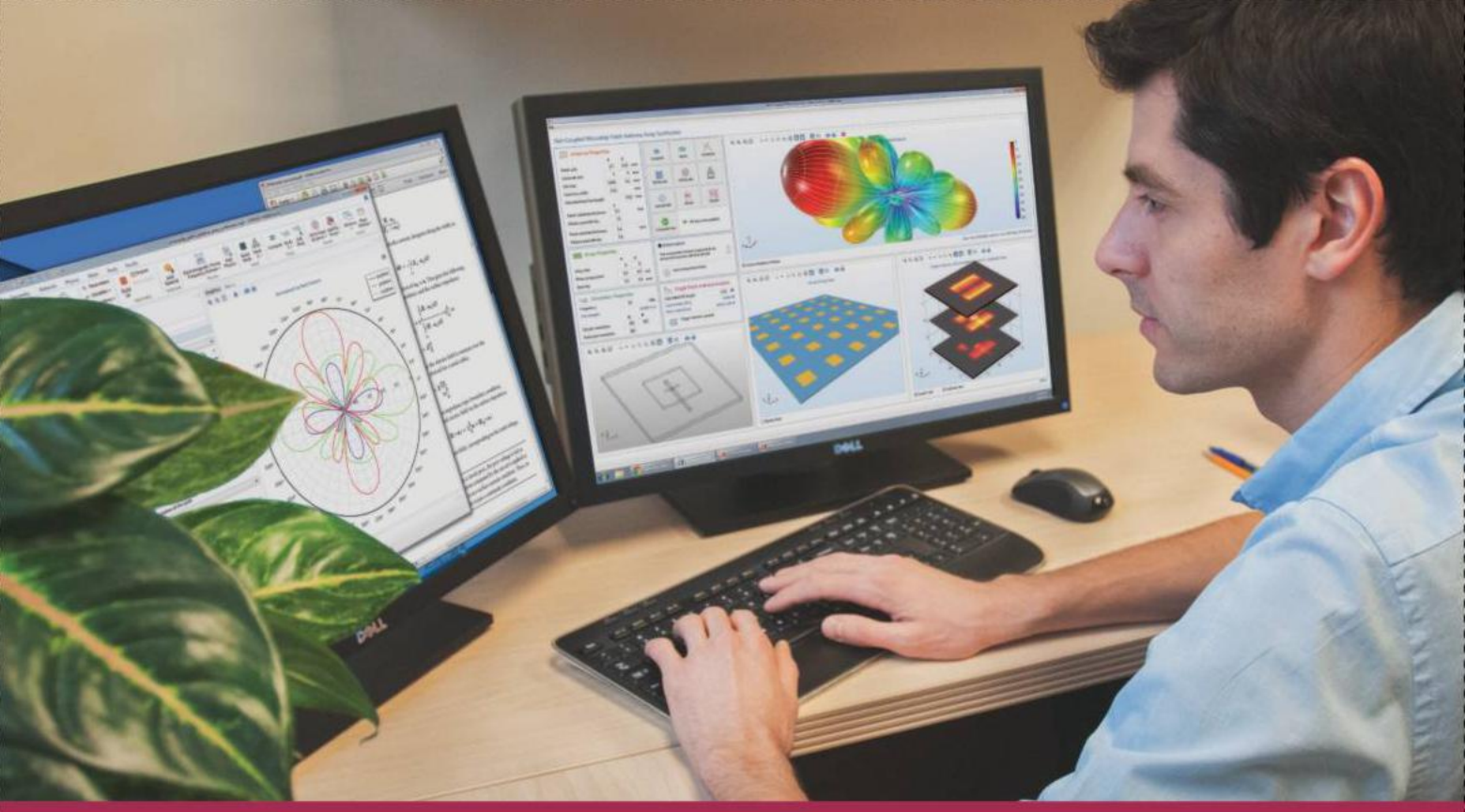

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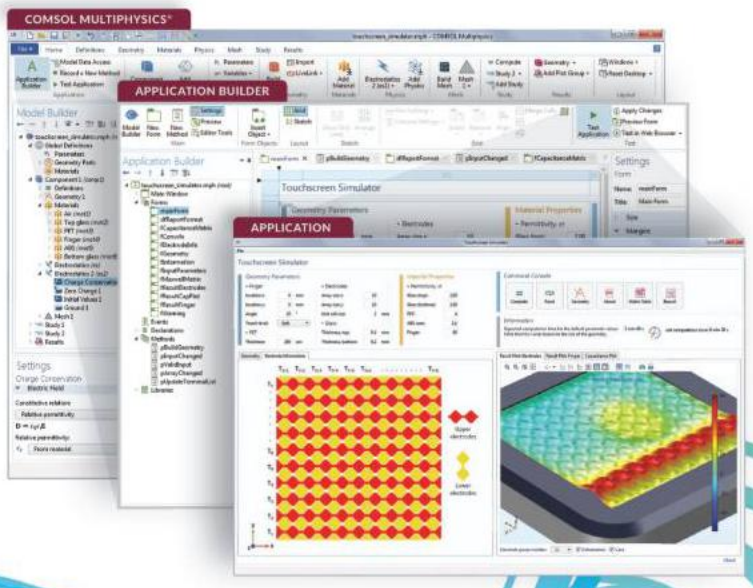

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