MATHEMATICS
Quest for the Enormous Theorem

BIOLOGY
Life at Hell's Gate

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Mystery of the Hidden Cosmos

Dark matter may be much weirder than physicists thought

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ON THE COVER

Spiral galaxies, such as the one depicted here, are thought to be cocooned in clouds of invisible dark matter that contribute an extra gravitational pull to keep the galaxies spinning as fast as they do. This dark matter was traditionally assumed to be made of a single type of particle, but theorists increasingly suspect that it comprises an entire unseen universe of dark species. Illustration by Ron Miller.

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Photograph by Peter Rigaud

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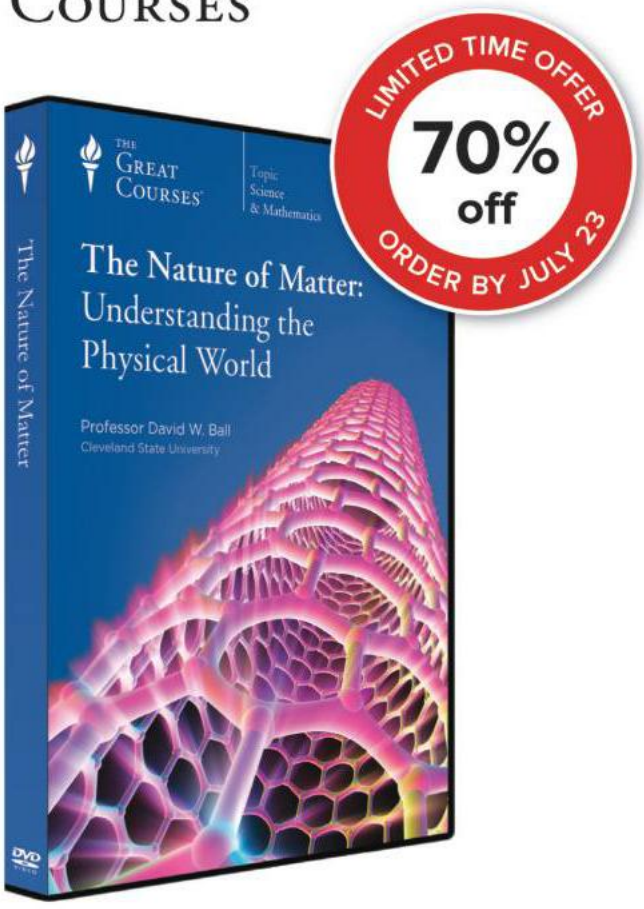

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Mariette DiChristina is editor in chief of *Scientific American*. Follow her on Twitter @mdichristina

The Shadow Universe

GIVEN THE INKY BLACKNESS OF space, I suppose it shouldn't have been surprising that we can't detect the parts of the cosmos that do not glow like the stars or radiate other types of energy. Cosmologists, observing galaxies rotating at speeds too fast to be possible given those observable components, have hypothesized unseen particles called dark matter.

What is it doing, and what is its composition? In "Mystery of the Hidden Cosmos," Bogdan A. Dobrescu and Don Lincoln delve into the complexity of this unseen universe. Dark matter could contain a world of particles. Dark atoms and molecules could perhaps clump together into galactic disks that overlap with the ordinary matter disks and spiral arms of galaxies such as Andromeda. Experiments are under way with the aim of detecting such complex dark matter. "The real message," Dobrescu and Lincoln write, "is that we have a mystery before us and that we do not know what the answer will be." To find out how cosmic detectives aim to piece together the clues, turn to page 32. SA

GLOBAL GATHERING

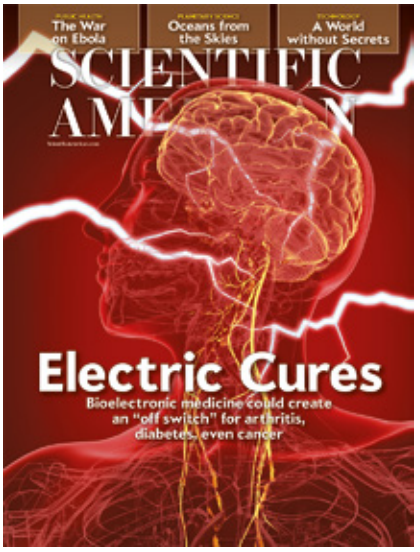
The smiling people in the photograph are members of *Scientific American*'s international family: the magazine is translated into 14 languages; its sister publication, the bimonthly *Scientific American Mind*, is translated into seven. Every year we try to gather to discuss how better to serve our readers and the global enterprise that is science. Interestingly, the first *Scientific American* translated edition was started when the magazine was already 45 years old—in 1890!—*La América Científica é Industrial*. That edition was eventually folded, and it was some decades before we firmly established a series of translations that we see today. Now it's hard to imagine it otherwise. —*M.D.*

MEMBERS of *Scientific American*'s international editions met in Paris this year.

RICHARD ZINKEN

Illustration by Nick Higgins

editors@sciam.com



March 2015

"No one would be okay with a placebo-controlled Ebola vaccine trial if it involved their own family and friends."
SUSAN RUSSELL *BOARDMAN, ORE.*

FIGHTING EBOLA

Helen Branswell's "Ebola War" provides excellent coverage of the many unknowns regarding the Ebola virus, as well as the unprecedented speed with which the two most promising vaccines are being tested. Yet although vaccines, and greatly improved health care infrastructure, are essential to Ebola prevention and containment, little mention was made of another critical dimension: the early, active and sustained engagement of affected communities and their leaders and networks. Attacks on health care facilities and personnel, borne of rumors that the outsiders were intentionally spreading Ebola, are reminders that the best-intentioned efforts can fail when affected communities are not involved as part of the solution.

Enhanced community engagement will be critical to vaccine testing and rollout in affected regions. But it will also help build local capacity and readiness before the next Ebola crisis has a chance to take hold.

MEREDITH MINKLER
University of California, Berkeley, School of Public Health
FREDERICK MARAIS
Western Cape Department of Health, South Africa

I was shocked to read there was a placebo-based trial of Ebola vaccines in infected areas. This seems beyond unethical. No one would be okay with this Russian roulette game if it were their own family and friends involved in the study.

SUSAN RUSSELL
Boardman, Ore.

I was disappointed that the author mainly cites the competing vaccines by their manufacturers' names ("GlaxoSmithKline vaccine" and "New Link vaccine"). Doing so is a bit off, don't you think?

HATEM A. TAWFIK
Cairo, Egypt

OUR OCEANS' ORIGINS

Readers of "Oceans from the Skies," by David Jewitt and Edward D. Young, on whether Earth's water originated from asteroids, comets or another source might be interested to know that the observations of two comets with Earth-like deuterium/hydrogen (D/H) ratios, as well as the detection of evidence of water on Ceres referred to by the authors, were carried out using the HIFI instrument on the Herschel Space Observatory. (We have both worked extensively with Herschel.)

High-resolution spectroscopy with a submillimeter telescope is a valuable tool for observing numerous comets and asteroids and thus addressing the issue of the origin of the Earth's oceans on a statistical rather than an object-by-object basis.

PAUL GOLDSMITH
NASA Jet Propulsion Laboratory
DAREK LIS
Laboratory for Studies of Radiation and Matter in Astrophysics and Atmospheres (LERMA), Paris

ELECTRICAL MEDICINE

"Shock Medicine," Kevin J. Tracey's article on the inflammatory reflex—the body's circuit for keeping the immune system from becoming overactive or underactive—contains an apparent paradox. Cutting the vagus nerve blocked fever caused by the signaling molecule interleukin-1, presumably the result of systemic release of the inflammatory molecule tumor necrosis factor (TNF). Cutting the nerve also blocked the systemic release of TNF after its injection in the brain. But stimulating the vagus nerve also reduced systemic TNF release.

To achieve the same effect as cutting the nerve would seem to require a blocking current, not a stimulating current. Could it be that the stimulating current somehow selectively stimulated only the sensory input, which then reflexively reduced the motor output by the vagus?

HAROLD WILKINSON
Department of Neurosurgery, Massachusetts General Hospital

I wonder whether Tracey has considered that acupuncture may somehow mimic the responses he found. I haven't tried it, but friends have reported positive experiences, including for migraines.

EVELYN MCDONALD
Fernandina Beach, Fla.

TRACEY REPLIES: Wilkinson correctly proposes that signals in the vagus nerve can either enhance or inhibit inflammation. The vagus nerve has almost 100,000 fibers, which mediate millions of discrete biochemical effects. The challenge and opportunity to developing bioelectronic medicine is to be able to deliver specific signals that target individually defined circuits. Our results indicate that inflammation can be inhibited by targeting only about 5 percent of these vagus nerve fibers in rodents.

In answer to McDonald: there has been extensive interest in the scientific and medical community about the relation between acupuncture and controlling inflammation, and many labs are studying it. For example, Luis Ulloa of Rutgers New Jersey Medical School has published a study suggesting that electrically stimulating an acupuncture point in the leg inhibits inflammation by activating vagus nerve signals to the adrenal gland.

PARK POWER

"Dust Up," by Mark Fischetti [Graphic Science], discusses a "gigantic reservoir of

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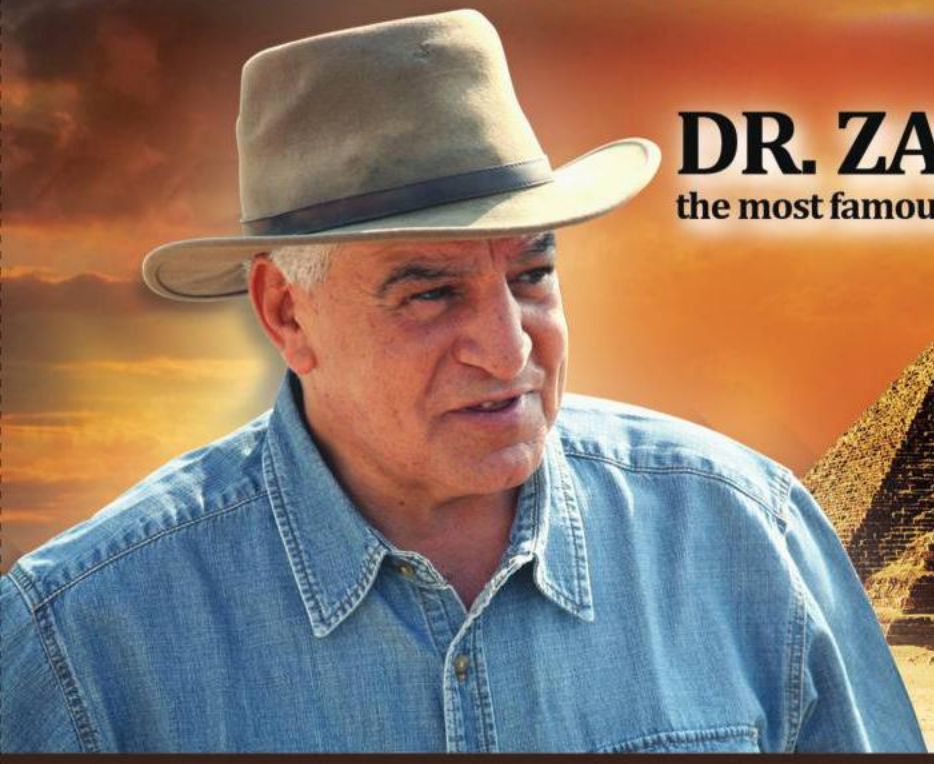

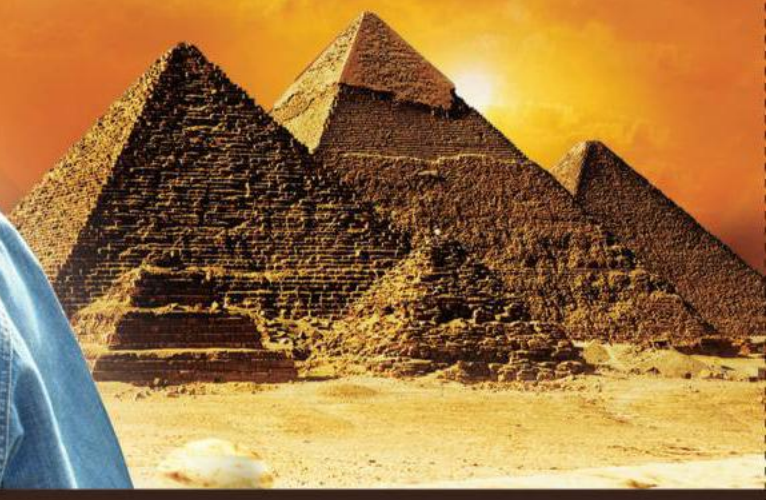

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Group photo - February 2015 Egypt tour with Dr. Zahi Hawass.

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magma" below Yellowstone National Park.

So why are we not tapping that reservoir for geothermal energy? Power plants could be located outside of the park and use horizontal drilling to access it.

BRUCE EMERICK
Carriere, Miss.

ALCOHOL'S DANGERS

In "Forging Doubt" [Skeptic], Michael Shermer discusses how industries for products that have ill effects plant doubt of those effects in the mind of the public.

Why did Shermer omit alcohol from such industries? It is more dangerous than food additives and flame retardants.

RICHARD POOLE
Longwood, Fla.

SHERMER REPLIES: Poole makes a good point that also applies to the legalization of marijuana. Although it may be debatable whether booze or pot is worse, there is no question that a double standard exists that has far more to do with politics and the law than with science and evidence. If we were consistent, we would apply the same standards of health and safety to alcohol as we do to other products, but humans and societies are nothing if not inconsistent.

TRAVEL COMPLICATIONS

"Quick Hits" [Advances] includes a short reference to the California High-Speed Rail project that repeats its proponents' claim of a travel time of 2.5 hours between San Francisco and Los Angeles. This claim is both the truth and a fabrication: it is only the time "city to city."

Including travel to the station, security, wait time, renting a car in Los Angeles and driving to one's final destination would make the "door to door" time much longer. In addition, drivers can carry more and have their own car when they arrive.

RUDY IWASKO
Sacramento, Calif.

ERRATUM

"Shock Medicine," by Kevin J. Tracey, incorrectly cites the *Scientific American* article "Treating Depression at the Source," by Andres M. Lozano and Helen S. Mayberg, as published on February 2014. The correct date is February 2015.

LETTERS TO THE EDITOR

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Letters may be edited for length and clarity. We regret that we cannot answer each one. Post a comment on any article at ScientificAmerican.com/jul2015

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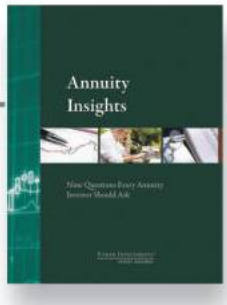

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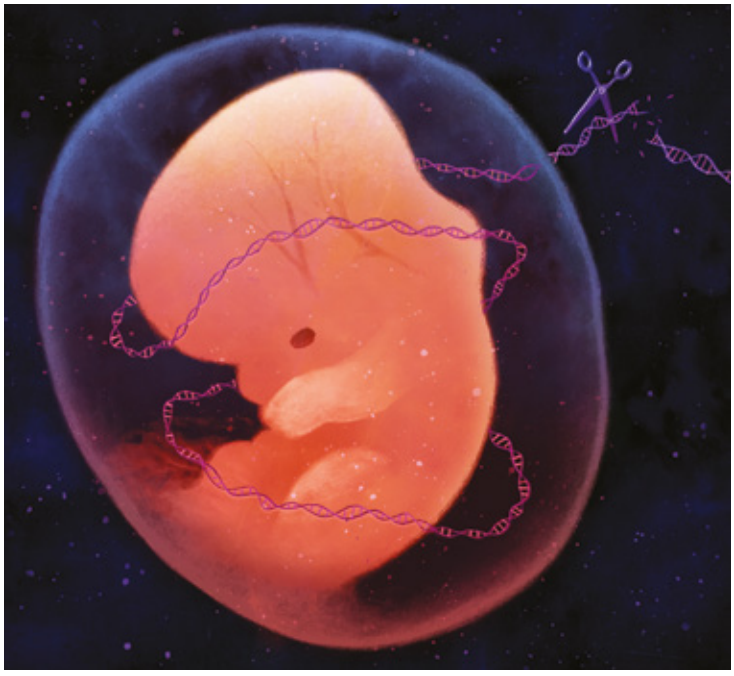

Why Embryos Should Not Be Off-Limits

Learning to alter their genes safely could prevent inherited diseases

To rid families of the curse of inherited diseases, medical geneticists have dreamed about changing human DNA before birth. The dream is also a nightmare, however, because it raises the specter of designer babies or creating harmful mutations. Now a precision genome-editing technique known as CRISPR-Cas9 has brought both dream and nightmare to the edge of reality.

The technique makes snipping out troublesome DNA from a cell's nucleus incredibly easy and cheap, compared with other methods. Scientists have been testing whether it can be used to treat genetic diseases, such as cystic fibrosis, and other scourges, such as HIV, in mature human cells. But no one had attempted to edit cells that can pass DNA down through generations: those of sperm, eggs or very early stage embryos. Such cells belong to what is known as the germ line. In April a team at Sun Yat-sen University in China revealed that it had crossed that line.

Rumors of such work had already elicited alarm. In March authors of a widely publicized editorial in *Nature* called for a moratorium on all human germ line modification, whether for research or clinical use, as did the Center for Genetics and Society in Berkeley, Calif. But total prohibition would be a mistake.

The Chinese team used CRISPR on early-stage embryos that carried genetic material from two sperm instead of the usual one. Such embryos do not develop normally and are therefore discarded by fertility clinics. The investigators tried to repair a mutation in a gene that causes a potentially fatal blood disorder known as beta thalassemia. The results of their study, published in the journal *Protein & Cell,* showed that CRISPR failed to repair the targeted mutation in most of the embryos and caused unintended changes elsewhere in the genome. (*Scientific American, Nature* and *Protein & Cell* are part of Springer Nature.) The research demonstrated that the technology involves far too many unknowns at present to justify any risks to human life.

Clearly, we need a moratorium on genome modification of germ line cells intended for establishing pregnancy. Scientists have much to learn about how CRISPR works. More fundamentally, they still know very little about how genes interact with one another and with the environment to cause disease. Funding agencies should not support studies with embryos suitable for implantation in the uterus, nor should journals publish such work.

But scientists should be permitted to conduct basic research on human germ line modification, as the International Society for Stem Cell Research and other groups have argued. This work could involve early-stage, nonviable embryos. Such engineering could conceivably stop devastating genetic disorders such as Huntington's disease and muscular dystrophy before they start in offspring—and keep the DNA from being transmitted to further descendants. The risk, though, is that inadvertent, harmful changes would also get passed on. Researchers need to conduct extensive studies before clinical use can be contemplated. Currently prospective parents using in vitro fertilization can have early embryos screened for certain genetic disorders. Some couples, however, may be unable to produce disease-free embryos or may have ethical concerns about making more embryos than they will use. Germ line editing could eventually help them.

In the U.S., we wish basic work on the germ line could be carried out with federal funding because it would provide more resources and greater transparency, but such research will have to get money from private and state-funded initiatives. In the wake of the *Protein & Cell* study, the National Institutes of Health reiterated that it will not fund research involving modification of human embryos, citing legal prohibitions as well as safety concerns.

Those issues show that scientific and government groups must engage the public in discussions about germ line changes and use that dialogue to form new policies. CRISPR is the most powerful genome-editing tool that scientists have. We need to explore its potential to avert the horrors of genetic diseases but do so without jeopardizing our values or harming generations of human lives. SA

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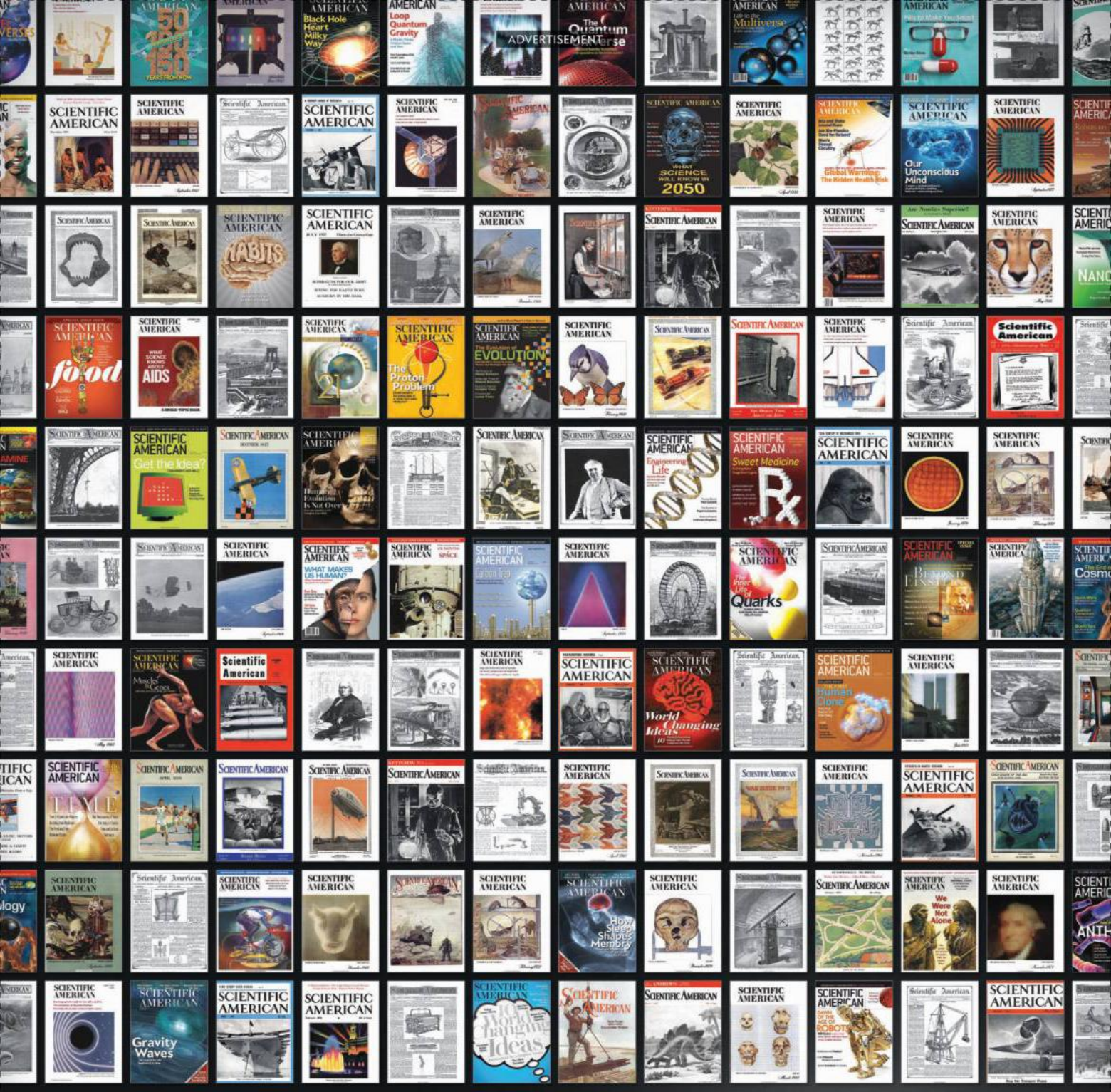
Illustration by Steven Hughes



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Commentary on science in the news from the experts

Michael West is director of Nantucket's Maria Mitchell Observatory and author of *A Sky Wonderful with Stars: 50 Years of Modern Astronomy on Maunakea*, to be published this month by the University of Hawaii Press.

Star Wars

Settling the fight over a telescope on a Hawaiian holy site

"The ancient Hawaiians were astronomers," wrote Queen Liliuokalani, Hawaii's last reigning monarch, in 1897. *Kilo hōkū,* or "star watchers," were among the most esteemed members of Hawaiian society. Sadly, all is not well with astronomy in Hawaii today. Protests have erupted over construction of the Thirty Meter Telescope (TMT), a giant observatory that promises to revolutionize humanity's view of the cosmos.

At issue is the TMT's planned location on Mauna Kea, a dormant volcano revered by some Hawaiians as the *piko,* or "umbilical cord," that connects the Hawaiian Islands to the heavens. But Mauna Kea is also home to some of the world's most powerful telescopes. Perched in the Pacific Ocean, Mauna Kea's peak rises above the bulk of our planet's dense atmosphere, where conditions allow telescopes to obtain images of unsurpassed clarity. This makes Mauna Kea the premier astronomical site in the Northern Hemisphere, if not the world. Building the TMT elsewhere, as some opponents have suggested, would be like clipping the wings of Mauna Kea's indigenous palila bird, limiting its ability to soar.

Opposition to telescopes on Mauna Kea is nothing new. A small but vocal group of Hawaiians and environmentalists have long viewed their presence as desecration of sacred land and a painful reminder of the occupation of what was once a sovereign nation. For some, nothing less than a return of the mountain to its pristine state is acceptable. For others, the observatories are simply a convenient lightning rod to spark discussion of larger social issues affecting the islands' indigenous people.

But astronomers were caught off guard by the vehemence of the opposition to the TMT. Many sincerely believe that due diligence was done by engaging native Hawaiians in dialogue over the past seven years of planning, holding more than 20 public meetings for community input, and contributing $1 million annually in support of science and technology education on the island of Hawaii. The telescope will also pump jobs and money into the local economy.

Some blame for the current controversy belongs to astronomers. In their eagerness to build bigger telescopes, they forgot that science is not the only way of understanding the world. They did not always prioritize the protection of Mauna Kea's fragile ecosystems or its sanctity to the islands' inhabitants. Hawaiian culture is not a relic of the past; it is a living culture undergoing a renaissance today.

Yet science has a cultural history, too, with roots going back to the dawn of civilization. The same curiosity to find what lies beyond the horizon that first brought early Polynesians to Hawaii's shores inspires astronomers today to explore the heavens. Calls to dismantle all telescopes on Mauna Kea or to ban future development there ignore the reality that astronomy and Hawaiian culture both seek to answer big questions about who we are, where we come from and where we are going.

The TMT represents the continuation of a journey begun long ago. Astronomy is not just the study of distant planets, stars and galaxies. It is also the study of something much closer to home—us. One of astronomy's most profound discoveries is that we are made from the ashes of stars that burned out long ago. Perhaps that is why we explore the starry skies, as if answering a primal calling to know ourselves and our true ancestral homes. As philosopher Alan Watts wrote, "You are that vast thing that you see far, far off with great telescopes."

In the spirit of compromise, the astronomy community is changing its use of Mauna Kea. The TMT site was chosen to minimize the telescope's visibility around the island and to avoid archaeological and environmental impact, and the TMT will pay $1 million annually (in addition to the STEM funding mentioned earlier) to lease the land on which it resides, with 80 percent of those funds going to stewardship of the mountain. To limit the number of telescopes on Mauna Kea, old ones will be removed at the end of their lifetimes and their sites returned to a natural state.

There is no reason why everyone—Hawaiian and non-Hawaiian alike—cannot be welcomed on Mauna Kea to embrace their cultural heritage and to study the stars. Holding the TMT or other telescopes hostage will not remedy past injustices suffered by the Hawaiian people, as much as we agree there is work on this front that remains to be done. "The world cannot stand still," Queen Liliuokalani said. "We must either advance or recede." SA

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Illustration by Julian Callos

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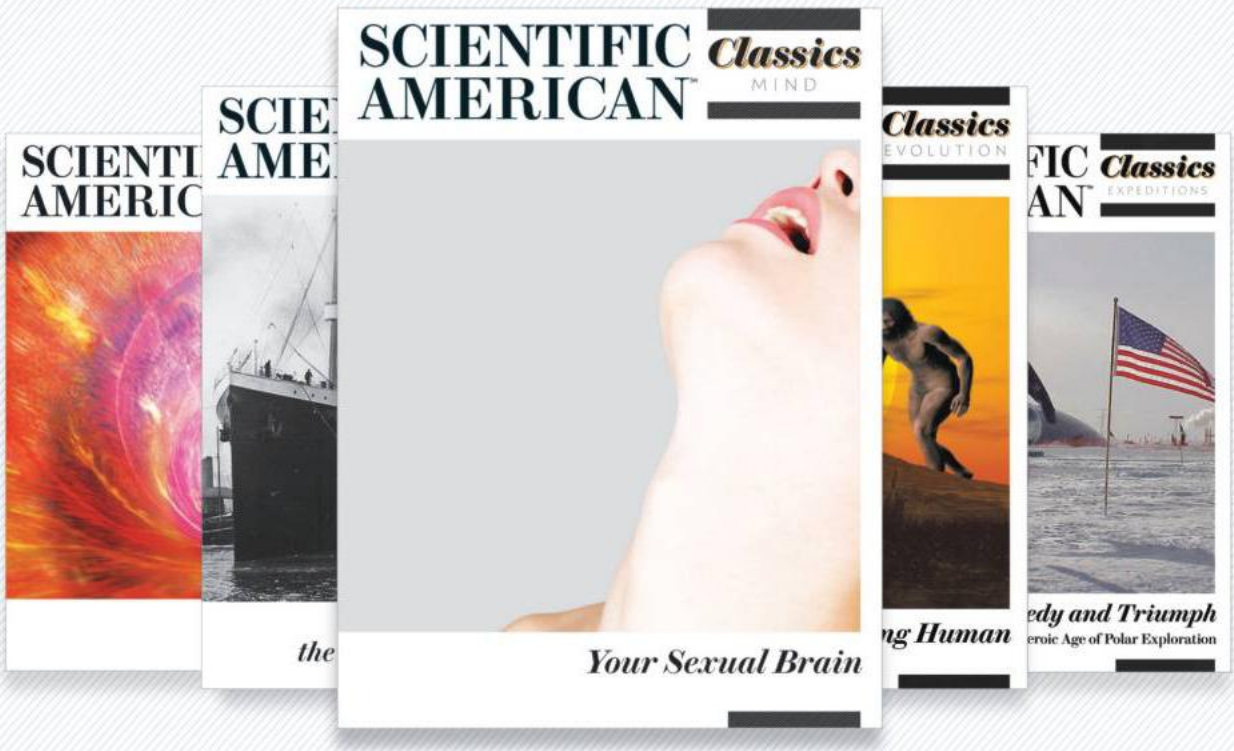

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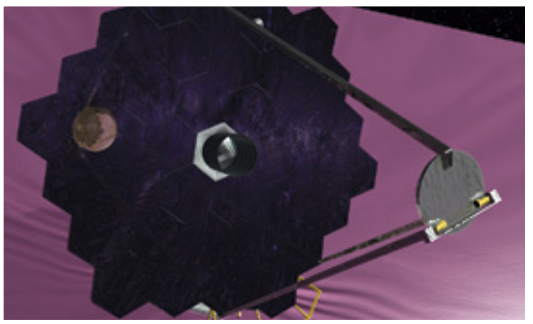
ADVANCES

Dispatches from the frontiers of science, technology and medicine



The rising price of the Webb telescope (*above*) has made proposals for even bigger observatories, such as the High-Definition Space Telescope and others (*right*), controversial.

ASTRONOMY

Go Big or Go Home

As the Hubble enters its twilight years, astronomers are searching for a supersize successor to expand our cosmic view

Any award for the most productive observatory in history would certainly go to the Hubble Space Telescope. But the Hubble's days are numbered—its instruments and orbit continue to degrade—and its inevitable demise will result in a significant data-collection gap for astrophysics and cosmology. Because Earth's atmosphere filters out most ultraviolet wavelengths, they are accessible only from space, where Hubble lives. Neither of NASA's next-generation observatories—the 6.5-meter James Webb Space Telescope and a 2.4-meter repurposed infrared spy satellite called WFIRST—will fill these wavelength gaps. "When Hubble goes, it goes," says John Mather, a Nobel laureate astrophysicist at the NASA Goddard Space Flight Center. "And we don't have anything else on the books that does what it does."

Mather and other astronomers are proposing a supersize successor with a mirror 10 to 12 meters in diameter—four to five times larger than Hubble's. That would be big enough to fulfill several high-priority items on astronomers' wish lists, revolutionizing studies of faraway galaxies, observations of planets in the outer solar system and searches for life on Earth-like exoplanets. Provisionally called the High-Definition Space Telescope, or HDST, the proposed telescope would observe, as Hubble does, at optical, ultraviolet and near-infrared wavelengths. Befitting its high-definition moniker, HDST's mirror could resolve structures about 300 light-years across in galaxies on the opposite side of the visible universe—something useful for understanding star formation, as well as the nature of dark matter and dark energy. And it would allow astronomers to

Continued on page 16

COURTESY OF DAVID HIGGINBOTHAM, MARSHALL SPACE FLIGHT CENTER AND NASA (*top*); COURTESY OF GODDARD SPACE FLIGHT CENTER AND NASA (*bottom*)

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The First Humans
The Neanderthals: Another Kind of Human
The Rise of Homo Sapiens

PSYCHOLOGY

Your Memories Are Not Your Own
Rationality Needs Feelings
Personality Matters
Moral Reasoning and Moral Identity
Achieving the Good Life

ASTROPHYSICS

The State of the Universe Report
In the Beginning
Oh Dear, What Could Dark Matter Be?
Dissonance in the Cosmic Symphony

SPEAKERS

Michael Starbird, Ph.D.
Monisha Pasupathi, Ph.D.
Chris Stringer, Ph.D.
Glenn Starkman, Ph.D.

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Continued from page 14

closely examine dozens of potentially Earth-like exoplanets for signs of alien life. The plan appears in a summer report from the Association of Universities for Research in Astronomy.

Some researchers involved with HDST worry, however, that no matter how broadly appealing such a powerful instrument might be, any proposal for a supersize space telescope is destined to be a nonstarter: although giant observatories are astronomically useful for researchers, they also tend to be deemed astronomically expensive, especially lately. "NASA's gotten more conservative since we started the Webb," says Mather, the Webb's senior project scientist. The Webb was originally targeted for a 2011 launch and an estimated cost of $1.6 billion, but current estimates aim for a launch no earlier than October 2018, with a cost that has swelled to nearly $9 billion. "After the telescope was nearly killed because of cost overruns," Mather says, "no one wants to think big anymore."

No astronomer involved with the HDST report will publicly hazard a guess at the required budget for a telescope of this magnitude—only that it would be quite large. Skeptical of the financial feasibility of HDST, critics suggest that a somewhat smaller, Webb-size broadband telescope would better serve the community. Others say a new generation of ground-based 30-meter-class observatories now under construction could do much of the same science for a fraction of the cost.

But those approaches are unlikely to deliver the answers space scientists are looking for, points out Marc Postman, an astronomer and HDST report co-author at the Space Telescope Science Institute. Trapped below Earth's ocean of air, even the largest ground-based observatories will be stymied by starlight-warping turbulence and by airglow, faint light emitted by atmospheric chemical reactions that can corrupt delicate observations. Further, neither they nor the Webb can directly image and investigate large numbers of exoplanets, which decreases the odds of finding any that support life. For some questions, only a large, broadband space telescope offers hope of answers.

The dream telescope could head for the skies as soon as the early 2030s, the report authors say, but only if NASA and other space agencies begin planning for it now. Such a long incubation for HDST may seem excessive but is actually an improvement over Hubble's, which began in 1946 with a visionary report from astronomer Lyman Spitzer. Transformative astrophysics leaps such as those that Hubble provided, and that its eventual successor also could offer, will require big investments not only of money but of time, Postman explains. "You don't make revolutionary changes in our understanding of the cosmos by taking small, incremental steps." —*Lee Billings*

BY THE NUMBERS

Dams over the Decades

Construction of large dams in the U.S. mostly came to a halt in the 1970s. Many are now unsafe, inefficient or no longer needed, requiring removal—events that geologists and biologists alike will follow closely to observe how these unimpeded rivers and their wildlife respond. —*Sarah Lewin*

538
Dams removed in the 90 years before 2005.

548
Dams removed from 2006–2014.

10 million
Cubic meters of stored sediment released on removal of two dams (64- and 32-meter-high structures) in Washington State last year, the largest release to date.

SOURCES: "1000 DAMS DOWN AND COUNTING," BY J. E. O'CONNER ET AL., IN *SCIENCE*, VOL. 348; MAY 1, 2015 (*dam removals*); "THE REMAINS OF THE DAM: WHAT HAVE WE LEARNED FROM 15 YEARS OF US DAM REMOVALS?" BY GORDON E. GRANT AND SARAH L. LEWIS, IN *ENGINEERING GEOLOGY FOR SOCIETY AND TERRITORY*, VOL. 3. EDITED BY GIORGIO LOLLINO ET AL. SPRINGER, 2015 (*sediment release*)

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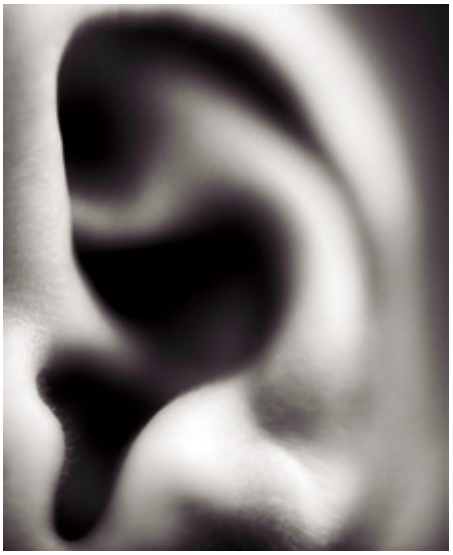


RICARDO DIAS/Getty Images

EVOLUTION

Sound Check

A 100-year ear debate comes to an end

Evolutionary biologists have long wondered why the eardrum—the membrane that relays sound waves to the inner ear—looks in humans and other mammals remarkably like the one in reptiles and birds. Did the membrane and therefore the ability to hear in these groups evolve from a common ancestor? Or did the auditory systems evolve independently to perform the same function, a phenomenon called convergent evolution? A recent set of experiments performed at the University of Tokyo and the RIKEN Evolutionary Morphology Laboratory in Japan resolves the issue.

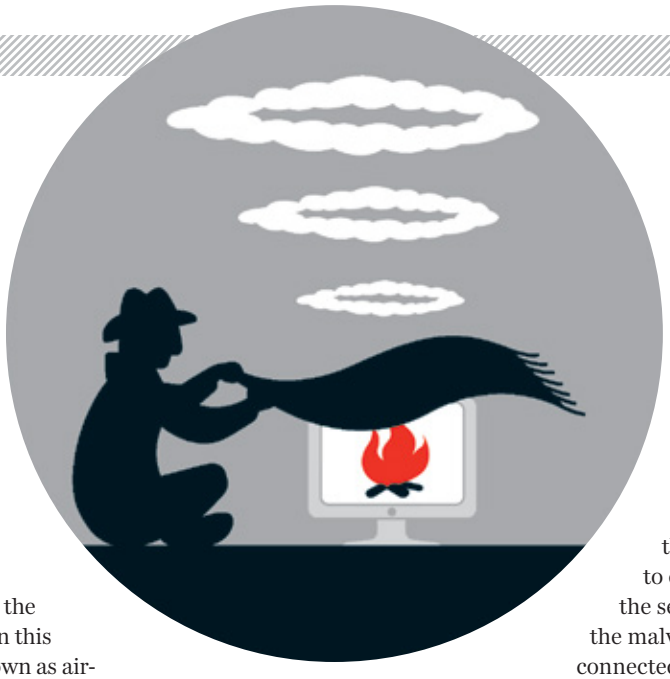
When the scientists genetically inhibited lower jaw development in both fetal mice and chickens, the mice formed neither eardrums nor ear canals. In contrast, the birds grew two upper jaws, from which two sets of eardrums and ear canals sprouted. The results, published in *Nature Communications,* confirm that the middle ear grows out of the lower jaw in mammals but emerges from the upper jaw in birds—all supporting the hypothesis that the similar anatomy evolved independently in mammals and in reptiles and birds. (*Scientific American* is part of Springer Nature.) Fossils of auditory bones had supported this conclusion as well, but eardrums do not fossilize and so could not be examined directly.

Hear, hear for genetics! —*Sarah Lewin*

TECHNOLOGY

Hacking Heats Up

The warm air a computer gives off can reveal once private information



The most secure computers in the world can't "Google" a thing—they are disconnected from the Internet and all other networks. The U.S. military and the National Security Agency rely on this attack-prevention measure, known as air-gapping, as does *The Intercept,* the media outlet co-founded by Glenn Greenwald, who was instrumental in disclosing the NSA's extensive domestic surveillance program. But where there's a will, there's a way: a team of doctoral students at Ben-Gurion University of the Negev in Israel announced it can obtain information from an air-gapped computer by reading messages encoded in the heat given off, like smoke signals, by its processors.

All computers have built-in thermal sensors, which detect the heat produced by processors and trigger the rotation of fans to avoid damage to components. To achieve the hack in an office setting, snoopers would infect two adjacent desktop PCs—one air-gapped, the other connected to the Internet—with malware that can take control of the machines and enable them to decode messages hidden in the sensor data. A virus carrying the malware could infect the Internet-connected machine fairly easily, whereas a USB drive or other hardware approach would be required with the air-gapped machine—a feat that could prove difficult at high-security locations.

In a scenario in which a hacker sought a password stored on the air-

Illustrations by Thomas Fuchs

Researchers can obtain information from an air-gapped computer by reading messages encoded in the heat given off, like smoke signals, by its processors.

gapped computer, the malware could instruct the computer's central processor to perform work in a pattern of activity that reveals those characters. Each spate of activity would produce a puff of warm air that would travel to the connected computer, where its thermal sensors would log that single bit of information. Over time, voilà, a set of bits representing the password. The connected computer could then send that information to the interested party. The computer scientists call their hack BitWhisper.

If it sounds awfully slow, it is. The compromised computers can transmit only a maximum of eight bits per hour and can be located no more than 16 inches apart. But that rate is enough to get what you need, says Yisroel Mirsky, one of the co-authors of the research, which will be presented at the IEEE Computer Security Foundations Symposium in Verona, Italy, this month. "You need only about five bits," he says, for a simple message, such as a command from the connected computer to the disconnected one, to initiate a data-destroying algorithm.

BitWhisper might seem too elaborate—after all, if one can get malware onto a computer via USB, why bother with the heat channel? Mirsky notes that this setup allows a hacker to control an air-gapped computer without physically sitting at it. Also, a computer heating up is unremarkable, so the hack could escape notice, says Anil Madhavapeddy, who studies unconventional ways to transmit information at the University of Cambridge and was not involved in the study. "In general, as computers get faster and the data contained in them more valuable," he explains, "even the very slow covert channels are useful for attackers because they can just sit back and let them run for hours or even days to leak important information while staying under the radar."

Of course, stopping such an attack is simple: keep air-gapped computers far away from any computers on a network or insert a sheet of insulation between machines. Given all the conditions BitWhisper would need to work in the real world, it might just be easier to find a whistle-blower. —*Jesse Emspak*

MEDICINE

Transfusion Solution

Blood banks begin using a pathogen-scrubbing method in donations this summer

Blood banks do all they can to ensure that donations carry no pathogens that could infect and possibly kill recipients. But screening tests for the microorganisms that cause some tropical diseases, such as dengue and chikungunya, do not exist, and these pathogens have been spreading into the U.S. in recent years because of global warming. Meanwhile tests for viruses such as HIV and hepatitis C can take up valuable time, and pathogens that have not yet been identified may be lurking in blood, as happened in the early days of HIV.

Now U.S. blood banks have a way to clear donations of pathogens: last December the Food and Drug Administration approved the INTERCEPT Blood System, making it the first technology available to rid platelets (the clotting components of blood) and plasma (the fluid) of nearly all possible infectious agents. Developed by Cerus, the technology mangles the nucleic acids (RNA or DNA) in viruses and bacteria, thereby preventing the pathogens from reproducing in a recipient's body. Technicians first add a molecule capable of inserting itself into the DNA or RNA to the donated material, then expose the mixture to ultraviolet light (*right*). The light causes the molecules to bind irreversibly to the nucleic acids and thus prevent their replication. The procedure does no harm to the plasma or platelets because they contain no nucleic acids of their own. The procedure varies slightly for red blood cells (which also lack nucleic acids)—a use that the FDA has yet to approve. Before this technique became available in the U.S., blood donations from chikungunya- and dengue-afflicted areas had to sit on the shelf for two days while donors were monitored for disease symptoms—a difficult constraint because platelets have only a five-day shelf life.

Europe has relied on the INTERCEPT system since 2002, but the FDA withheld its approval until postmarket data on safety and efficacy became available—and the threat of dengue and chikungunya in the U.S. grew. This summer SunCoast Blood Bank in Florida and Blood Bank of Delmarva, which serves parts of Delaware, Maryland and Virginia, are the first U.S. blood banks to use the technology. The National Institutes of Health also signed a supply agreement with Cerus in May, and a recent *New England Journal of Medicine* editorial advocated for a national mandate to use a system such as INTERCEPT to reduce risks from pathogens.

"We in the U.S. probably have the safest blood supply in the world," says SunCoast CEO Scott Bush, "but this technology offers an extra layer of protection." —*Tara Haelle*

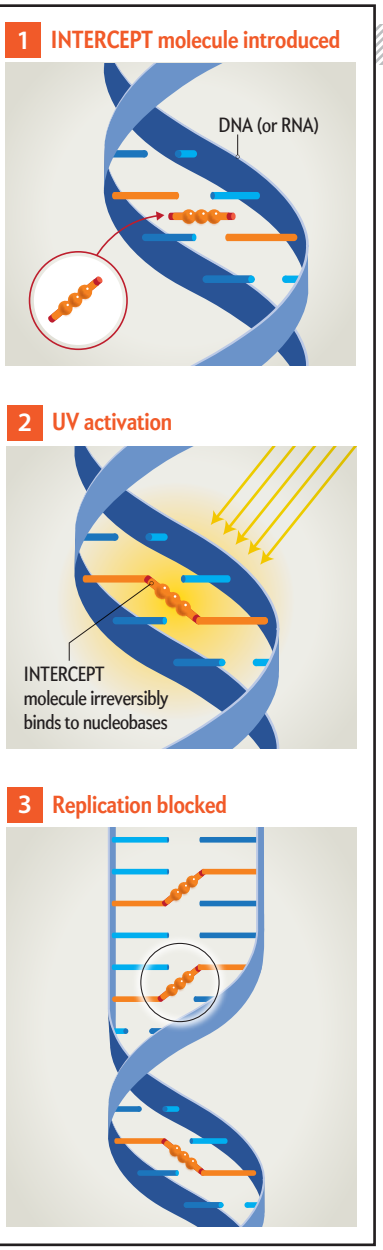
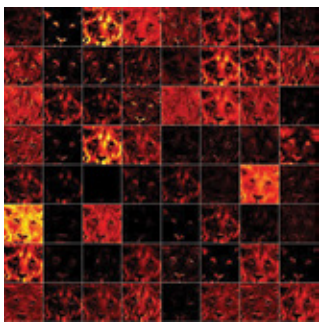


Illustration by 5W Infographics

CONSERVATION

Facebook for the Ferocious

Lion researchers track the cats' whereabouts with new facial-recognition technology



LINC software scans facial features for patterns that can match an image to an individual.

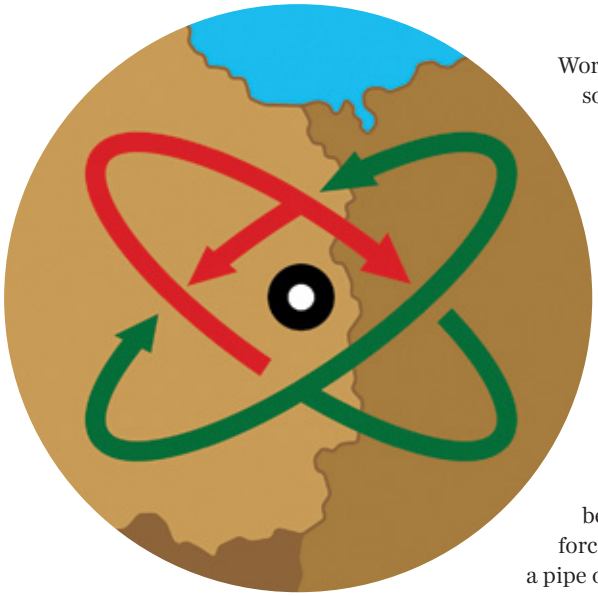
Even the king of the jungle can't escape getting his picture taken these days. In June the Kenya-based Lion Guardians launched the Lion Identification Network of Collaborators (LINC). The database of lion profiles was built with the first facial-recognition software specifically designed to analyze the mugs of these big cats and distinguish them from one another. With LINC, the conservation organization and other wildlife researchers will have an easier way to monitor the beasts' whereabouts. Their movements throughout Africa are poorly understood, and tracking efforts come with a host of difficulties: GPS transmitters are expensive, run out of batteries every one to three years, and can be fitted only when an animal is sedated. In addition, unlike leopards, cheetahs and tigers—whose spots and stripes make identification fairly easy—adult lions lack recognizable coat patterns.

Within the next few months about 1,000 lions will be added to LINC; the more photographs that are entered, the more accurate the software will become at identifying an individual. By keeping tabs on the cats' peregrinations, conservationists can better understand where lions find mates, water and prey, for example, as well as the nuanced changes to population dynamics caused by human expansion.

One need not get up close and personal to capture useful pictures. Shots snapped from up to 100 feet away will do the trick, says Stephanie Dolrenry, co-founder of Lion Guardians. Photo bombers and the most skittish lions alike typically turn to look at their pursuers before running away.

—Millie Kerr

COURTESY OF JUSTIN DOWNS, IEF R&D (*grid of lions*); GK AND VICKY HART *Getty Images* (*lion's head*)



PHYSICS

Blitzkrieg Basics

Gas law can model war maneuvers

In 1939 Nazi Germany debuted the "lightning war," or *blitzkrieg,* in Poland. This deadly military offensive involved mounting a burst of firepower-heavy attacks to cause confusion and break through an enemy's lines unexpectedly. Nearly 80 years later Russian physicists have found they can model this surprise tactic with a scientific law: the kinetic theory of gases.

The parallels are obvious enough, with some creative thought. Both armies and gases have densities—troops per square kilometer or atoms per cubic meter. Basic units also have measurable cross sections that define territorial coverage—for troops, average weapon range, and for atoms of gas, electron orbital reach. And for both entities, when cross sections overlap, confrontations occur. Further, in the case of a blitzkrieg, defenders' dispersion can be seen as resembling the widely separated atoms of a gas.

Thus, physicists Vladimir Aristov and Oleg Ilyin of the Russian Academy of Sciences took historical military data about the German and Polish forces in World War II—the number of soldiers, tanks, aircraft and artillery, as well as the initial invasion speed of motorized vehicles—and replaced each unit with gas molecules in a mathematical model based on kinetic theory. Atoms or molecules of gas conforming to this theory dart around randomly and collide with one another frequently, but order can be imposed by, for example, forcing the gas to flow through a pipe or nozzle. In Aristov and Ilyin's model, the German army was a fast-moving, concentrated stream of gas atoms that rapidly penetrated the widely spaced gas atoms that represented the Polish army.

According to the model's calculations, which account for slowing speeds from collisions, the Germans should have moved 50 kilometers a day—precisely their actual pace during the seven-day, 350-kilometer trek to Warsaw. The researchers also ran calculations for the blitzkriegs of France in 1940 and of Stalingrad in 1941 and found that the model's predictions matched the historical front movements in those cases, too. The analogy broke down, however, when the initial surprise attack ended, and defending troops of atoms started to "fight" more effectively. The research was published in April in the journal *Physical Review E.*

Attempts to explain sociohistorical phenomena with physics abound. For decades scientists have modeled events such as the spread of the Black Death in the 14th century with slow diffusion models, which describe processes such as the random drift of a drop of ink in a glass of water. Kinetic theory is best applied to more rapid, direct processes—such as a swift invasion. Ilyin says that their model could be used to predict the rates of future war-front advances but only if the opposing sides abide by conventional tactics—unlikely these days given the availability of nuclear weapons and unmanned drones. —*Tim Palucka*

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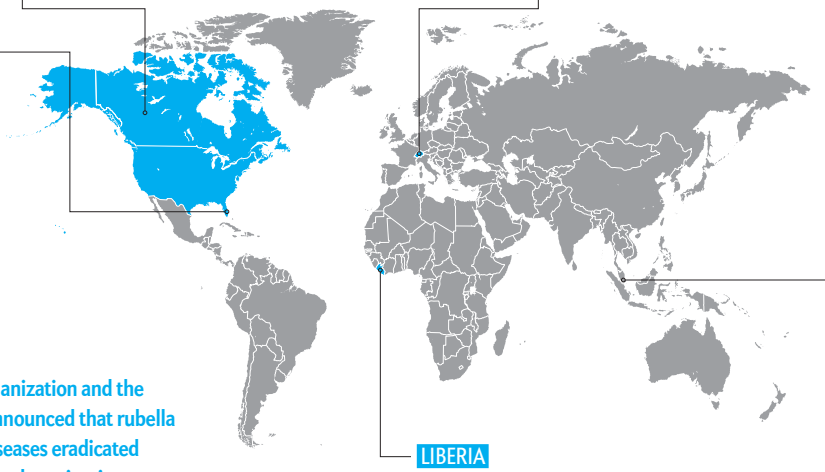
IN THE NEWS

Quick Hits

CANADA
The first baby was born with the help of a new in vitro fertilization procedure that adds the mitochondria from stem cells to an egg. The addition may increase the success rate of IVF. It is not currently available in the U.S.

SWITZERLAND
The Swiss Post puts drones to work this summer during a trial period delivering packages. The same model of aircraft has already been used to distribute emergency medical supplies in other countries, such as Haiti.



U.S.
The world's largest hurricane simulator begins tests at the University of Miami. It mobilizes 38,000 gallons of water with wind speeds of up to 156 miles per hour and is six times larger than any previous experimental setup.

SINGAPORE
The prime minister publicly shared code he wrote for an automatic Sudoku solver, simultaneously revealing the extent of his computer programming skills.

THE AMERICAS
The Pan American Health Organization and the World Health Organization announced that rubella joins smallpox and polio as diseases eradicated from the region with widespread vaccination.

LIBERIA
Geologists discovered that a spiny African plant seems to grow in dense, forested areas only over kimberlite, a mineral from which most of the world's diamonds are mined.

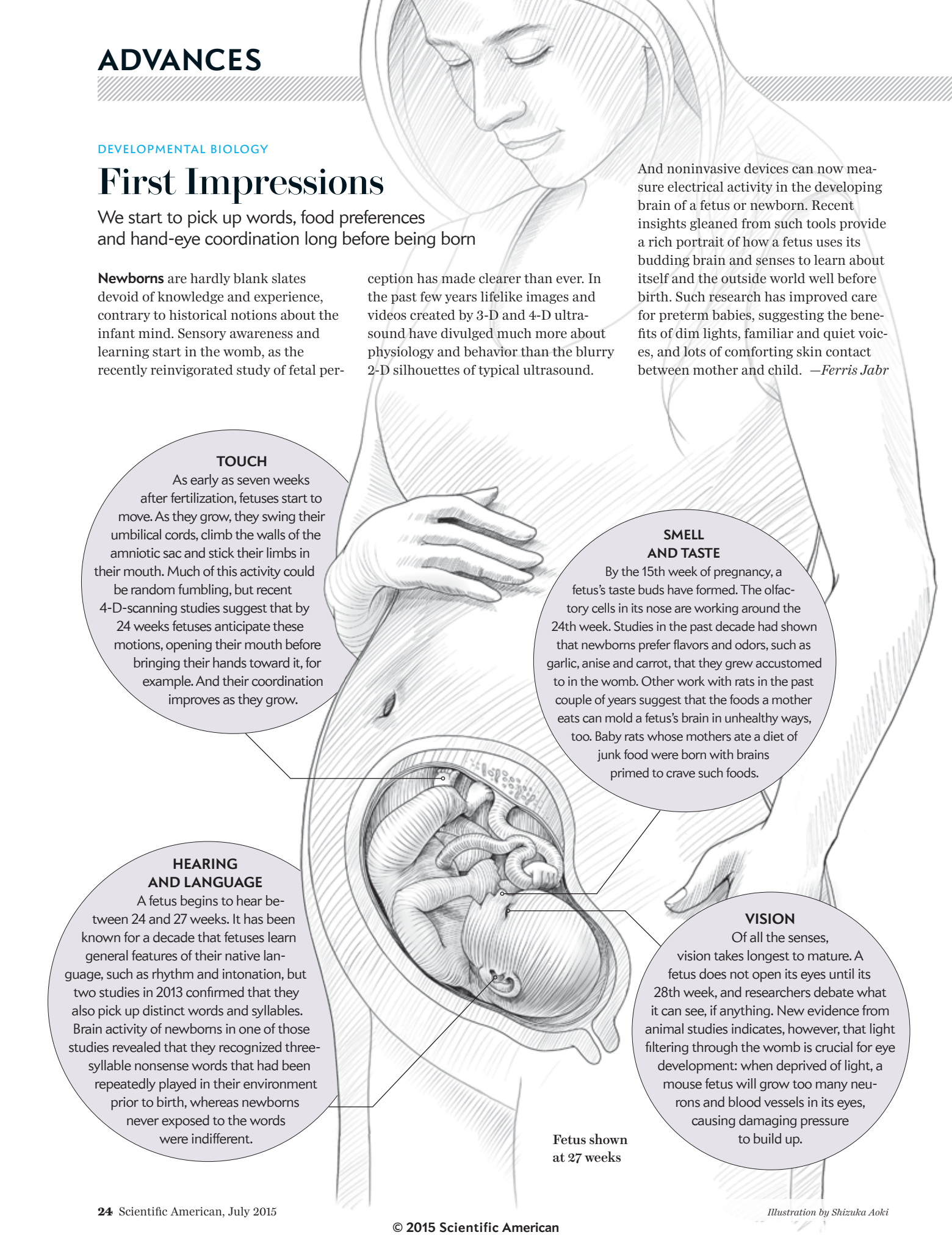
For more details, visit www.ScientificAmerican.com/jul2015/advances

DEVELOPMENTAL BIOLOGY

First Impressions

We start to pick up words, food preferences and hand-eye coordination long before being born

Newborns are hardly blank slates devoid of knowledge and experience, contrary to historical notions about the infant mind. Sensory awareness and learning start in the womb, as the recently reinvigorated study of fetal perception has made clearer than ever. In the past few years lifelike images and videos created by 3-D and 4-D ultrasound have divulged much more about physiology and behavior than the blurry 2-D silhouettes of typical ultrasound. And noninvasive devices can now measure electrical activity in the developing brain of a fetus or newborn. Recent insights gleaned from such tools provide a rich portrait of how a fetus uses its budding brain and senses to learn about itself and the outside world well before birth. Such research has improved care for preterm babies, suggesting the benefits of dim lights, familiar and quiet voices, and lots of comforting skin contact between mother and child. *—Ferris Jabr*



TOUCH

As early as seven weeks after fertilization, fetuses start to move. As they grow, they swing their umbilical cords, climb the walls of the amniotic sac and stick their limbs in their mouth. Much of this activity could be random fumbling, but recent 4-D-scanning studies suggest that by 24 weeks fetuses anticipate these motions, opening their mouth before bringing their hands toward it, for example. And their coordination improves as they grow.

SMELL AND TASTE

By the 15th week of pregnancy, a fetus's taste buds have formed. The olfactory cells in its nose are working around the 24th week. Studies in the past decade had shown that newborns prefer flavors and odors, such as garlic, anise and carrot, that they grew accustomed to in the womb. Other work with rats in the past couple of years suggest that the foods a mother eats can mold a fetus's brain in unhealthy ways, too. Baby rats whose mothers ate a diet of junk food were born with brains primed to crave such foods.

HEARING AND LANGUAGE

A fetus begins to hear between 24 and 27 weeks. It has been known for a decade that fetuses learn general features of their native language, such as rhythm and intonation, but two studies in 2013 confirmed that they also pick up distinct words and syllables. Brain activity of newborns in one of those studies revealed that they recognized three-syllable nonsense words that had been repeatedly played in their environment prior to birth, whereas newborns never exposed to the words were indifferent.

VISION

Of all the senses, vision takes longest to mature. A fetus does not open its eyes until its 28th week, and researchers debate what it can see, if anything. New evidence from animal studies indicates, however, that light filtering through the womb is crucial for eye development: when deprived of light, a mouse fetus will grow too many neurons and blood vessels in its eyes, causing damaging pressure to build up.

Fetus shown at 27 weeks

Illustration by Shizuka Aoki

LAUREN NICOLE *Getty Images*

MATERIALS SCIENCE

Build-a-Battery

An extruded alternative to conventional cells

Printing batteries is the future of sustainable energy, according to engineers at PARC, the renowned California-based research and development company owned by Xerox. They recently debuted a cost-saving manufacturing process that could someday squeeze out all the parts of a battery at once—like striped toothpaste from the tube.

Today building a battery requires multiple steps. First, two separate machines fabricate electrodes by spreading pastelike layers of energy-storing materials on sheets of metal. After those sheets are dried and compressed, they are cut to size and sandwiched around a plastic separator to prevent electrical shortages. Last, the battery is packaged in a nonconductive material and filled with a liquid electrolyte that can carry charge between the electrodes.

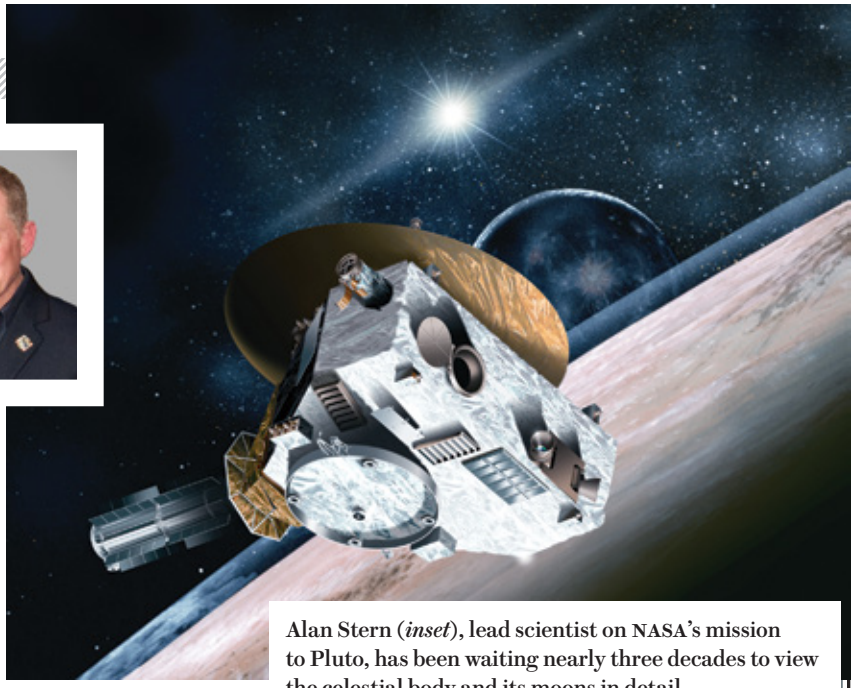
The new battery-printing method simplifies that process. In April at a Materials Research Society meeting in San Francisco, PARC's Corie Cobb presented nozzles and materials that would enable manufacturers to print two thirds of a battery in one go. The two-headed printing nozzle can simultaneously extrude a lithium-ion cathode and a polymer separator. For now, until Cobb figures out a combination of materials that will not commingle during printing, a technician must add a graphite anode manually. But when all three components can be printed at once, Cobb and her colleagues estimate the triple-stripe process could reduce manufacturing costs by 15 percent. Still, battery makers have already shown interest in the double-stripe version. The prototype batteries perform as well as batteries made with the conventional process and the same materials.

Less expensive batteries are key to making more affordable electric vehicles and enabling electric utilities to purchase and store additional grid-stabilizing energy from variable wind and solar sources. In the long run, batteries could also be printed into custom shapes for new types of gadgets—instead of the rectangles and circles designers must work around today. —*Katherine Bourzac*

Q&A

Poised for Pluto

A long-awaited flyby approaches



Alan Stern (*inset*), lead scientist on NASA's mission to Pluto, has been waiting nearly three decades to view the celestial body and its moons in detail.

Pluto was still a planet when a spacecraft began its journey nine years ago to that small, cold hunk of rock and ice. This month the NASA probe—the fastest spacecraft ever launched—finally reaches its primary target after a five-billion-kilometer cruise. On July 14 it will fly past what is now classified as a dwarf planet, becoming the first spacecraft to visit that faraway world and in doing so completing the initial exploration of our solar system that was conceived with the first interplanetary missions half a century ago. Already the approaching spacecraft, called New Horizons (*above*), has snapped unprecedented pictures, spying what looks to be an ice cap at one of Pluto's poles. At its closest, New Horizons's suite of cameras, spectrometers and sensors will scrutinize the body's surface and atmosphere from an altitude of just 12,500 kilometers. *Scientific American*'s Lee Billings and New Horizons's principal investigator Alan Stern, a planetary scientist, discussed this historic, long-awaited mission. Edited excerpts follow.

A common conception of Pluto is that it is an inert snowball. Why send a spacecraft to visit it?

We now know Pluto is a dynamic world. We've seen its brightness changing, maybe because of snow moving around; its surface pressure has tripled since the late 1980s; and its temperature is changing in ways that we don't fully understand. We also now know Pluto has a rich system of satellites, a big moon, Charon, and at least four smaller ones, Nix, Hydra, Kerberos and Styx. We don't know a lot about the smaller ones, but Charon has crystalline ice and ammonium hydrates on its surface that may be related to recent outflows from its interior. So maybe Charon has geysers. We also have predictions that Pluto and Charon might actually share a common atmosphere. Some researchers predict that one or both may have or have had subsurface oceans. We'll know a lot more once we study them up close.

I tend to think of Pluto and its moons as presents sitting under a Christmas tree. They're wrapped, and from Earth all we can do is look at the boxes to see whether they're light or heavy, to see if something maybe jiggles a bit inside. We're seeing intriguing things, but we really don't know what's in there. I've been waiting 26 years to unwrap these presents. This year Christmas comes in July!

What do you expect to find in those boxes?

That's hard to answer. It's not just that no one has ever visited Pluto before. No one has ever visited this *type* of planet. We began planning this mission back in 1989, after Voyager 2's encounter with Neptune, and back then hardly anyone even knew the Kuiper belt existed. It's a vast region populated by lots of small bodies and a few very exotic, very diverse small planets. New Horizons isn't just visiting Pluto; it's visiting this entire region. Whatever it finds, this will be a signal moment for planetary exploration—the capstone to our first reconnaissance of the planets of our solar system.

What will New Horizons do after the flyby?

We've found two small objects, each roughly 50 kilometers across, for a potential post-Pluto flyby in 2019. They're both about a billion miles beyond Pluto, but they're in different directions, so we have to choose whether to go to one or the other. These are ancient, primordial building blocks of the Kuiper belt planets, and we could see them up close! We're looking forward to writing an extended mission proposal next year to convince NASA to let New Horizons visit one of them. Beyond that mission, the spacecraft is healthy and could run into the mid- to late 2030s.

Do you think we'll send another mission to Pluto or the Kuiper belt?

There is no current plan for that by any space agency. We may never do anything like this again. In fact, whether we go back depends on what New Horizons finds and how it might change our priorities in planetary science. If the Pluto system is sufficiently enticing, then I expect we'll see mission proposals to return. Can you come back and ask me in six months?

COURTESY OF JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY AND SOUTHWEST RESEARCH INSTITUTE (*Pluto*); COURTESY OF RAYNA TEDFORD (*Stern*)

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Karen Weintraub is a freelance health/science journalist based in Cambridge, Mass., who writes regularly for the *Boston Globe*, *USA Today* and the *New York Times*.

Can We Stop Aging?

Some researchers believe they will soon be able to slow or even stop the body's clock—at least for a little while

The majority of older Americans live out their final years with at least one or two chronic ailments, such as arthritis, diabetes, heart disease or stroke. The longer their body clock ticks, the more disabling conditions they face. Doctors and drug companies traditionally treat each of these aging-related diseases as it arises. But a small group of scientists have begun championing a bold new approach. They think it is possible to stop or even rewind the body's internal chronometer so that all these diseases will arrive later or not at all.

Studies of centenarians suggest the feat is achievable. Most of these individuals live that long because they have somehow avoided most of the diseases that burden other folks in their 70s and 80s, says Nir Barzilai, director of the Institute for Aging Research at the Albert Einstein College of Medicine. Nor does a centenarian's unusual longevity result in an end-of-life decline that lasts longer than anyone else's. In fact, Barzilai notes, research on hundreds of "super agers" suggests exactly the opposite. For them, illness typically starts later and arrives closer to the end. "They live, live, live and then die one day," he says.

Researchers have already developed various techniques to increase the life span of yeast, worms, flies, rats and perhaps monkeys. Adapting these measures to people seems like the next logical step. "There's an emerging consensus that it's time to take what we've learned from aging [research] and begin to translate that into helping humans," says Brian Kennedy, CEO and president of the Buck Institute for Research on Aging, an independent research group in Novato, Calif.

Delaying the aging process by even a few years could offer enormous social benefits as populations around the globe grow increasingly older. The U.S. Census Bureau estimates that one in five Americans will be older than 65 by 2030—up from one in seven in 2014. In 2013 an estimated 44 million people around the world suffered from dementia. That number is expected to jump to nearly 76 million in 2030 and 135 million in 2050—with not nearly enough younger people in a position to be able to take care of them.

Among the handful of approaches that researchers are studying, three stand out. Still unclear: whether the potential benefits outweigh the risks of the treatments.

EVIDENCE

OF COURSE, TO CONCLUSIVELY determine whether a treatment works, investigators need a definition of aging and a way to measure the process. They have neither. If a kidney cell divided yesterday, is it one day old or as old as the person in whom it resides? Still, research over the past decade has offered several hints that the damaging aspects of aging—however you define it—can be slowed.

In a 2005 study, Thomas Rando, director of the Paul F. Glenn Center for the Biology of Aging at Stanford University, showed that an elderly mouse whose bloodstream was surgically linked to a young mouse recovered its youthful wound-healing powers. Somehow the older rodent's stem cells, which are responsible for replacing damaged cells, became more effective at giving rise to new tissue. Harvard University biologist Amy Wagers has since found a protein, dubbed GDF11, in the blood that may have contributed to the faster healing. Her experiments, published in *Science* in 2014, found more

Illustration by Victo Ngai

of the protein in younger mice than in older ones; when injected in older mice, GDF11 appeared to restore muscles to their youthful structure and strength. A new study, in *Cell Metabolism,* calls that finding into question, however, suggesting that GDF11 increases with age (and may even inhibit muscle restoration) and that some other factor must make the cells act younger.

A second approach consists of examining about 20 currently existing medications and nutritional supplements at a level of detail that has never before been possible to see whether they might actually affect the aging process. For example, researchers at Cardiff University in Wales and their colleagues reported in 2014 that patients with type 2 diabetes who took the drug metformin lived, on average, 15 percent longer than a group of healthy people who did not suffer from the metabolic disorder but were similar in nearly all other respects. Scientists speculate that metformin interferes with a normal aging process, called glycation, in which glucose combines with proteins and other important molecules, gumming up their normal workings. The metformin finding is particularly striking because people who have diabetes, even if it is well controlled, typically have somewhat shorter life spans than their healthy counterparts.

Meanwhile, in a study of 218 adults published late last year in *Science Translational Medicine,* researchers at pharmaceutical company Novartis showed that a compound called everolimus, which is chemically similar to rapamycin (a drug used to prevent kidney rejection in transplants), improved the effectiveness of the flu shot in people older than 65.

As individuals age, their immune systems do not mount as strong an antibody response to the inactivated virus in the vaccine as they once did; thus, older people are more likely to get sick if they later encounter a real flu virus. Tests showed that study patients given everolimus had a higher concentration of germ-fighting antibodies in their blood than their untreated counterparts. Investigators interpreted this finding as a sign that the drug had rejuvenated the subjects' immune systems.

As with any drug, side effects were an issue. Members of the treated group were more likely to develop ulcers in their mouth, which may limit the widespread usefulness of the medication for treating aging. Cost may be another factor; everolimus, which was approved by the U.S. Food and Drug Administration for its cancer-fighting properties, costs more than $7,000 a month at doses appropriate for cancer. Not yet known: how much everolimus would cost and how long it would be needed, if used as an antiaging drug.

Nevertheless, the results support the idea that aging can be slowed. Indeed, everolimus and other rapamycinlike drugs have been shown to dramatically extend the life span of mice, preventing diseases such as cancer and reversing age-related changes to the blood, liver, metabolism and immune system.

A third, completely different approach involves diet. Restricting the consumption of calories was long ago shown to help mice to live longer. Whether limiting food intake (without causing malnutrition) might benefit humans as well is not so clear. For one thing, very few people can or want to maintain such low-calorie diets for the decades needed to prove definitively that this approach works. But it may turn out that such drastic steps are unnecessary. Valter Longo, director of the Longevity Institute at the University of Southern California, has shown that he can extend the life span of mice merely by limiting their food on alternate days or by cutting down on the amount of protein they consume. Such intermittent fasting may turn out to be more palatable for people, although its benefits remain unproved.

CAVEATS

LIVING LONGER may come with trade-offs. Making old cells young again will mean they will start dividing again. Controlled cell division equals youthfulness; uncontrolled cell division equals cancer. But at the moment, scientists are not sure if they can do one without the other.

Figuring out the right timing for treatment is also complicated. If the goal is to prevent multiple diseases of aging, do you start your antiaging therapies when the first disease hits? The second? "Once you're broken, it's really hard to put you back together. It's going to be easier to keep people healthy," Kennedy says. So it probably makes more sense to start treatment years earlier, during a healthy middle age. But the research needed to prove that supposition would take decades.

If various diseases can be pushed off, the next obvious question is by how long. James Kirkland, who directs the Mayo Clinic's Robert and Arlene Kogod Center on Aging in Rochester, Minn., says it will take at least another 20 years of study to answer that question. Scientists have successfully extended the life span of worms eightfold and added a year of life to three-year-old lab mice. Would these advances translate into an 80-year-old person living five or six centuries or even an extra 30 years? Or would they get just one more year? Life extension in people is likely to be more modest than in yeast, worms, flies or mice, Rando says. Previous research has suggested that lower-order creatures benefit the most from longevity efforts—with yeast, for instance, deriving a greater benefit in caloric-restriction experiments than mammals. "The closer you get to humans, the smaller the effect" on life span, he says. And what magnitude of benefit would someone need to justify taking—and paying for—such a treatment? "Do you take a drug your whole life hoping to live 4 percent longer or 7 percent longer?" Rando asks.

What, if anything, do antiaging investigators themselves do to try to slow their own aging? The half a dozen scientists interviewed for this article all said that they make concerted efforts to extend their own life span. One was grateful for a diagnosis of prediabetes, which meant a legitimate prescription for metformin. The research is getting so solid, Kennedy says, that he is having a tougher time convincing himself not to take some drugs than to take them.

All the experts say they try to live healthy lives, aside from enduring high-pressured jobs. They try to get close to eight hours of sleep, eat moderate amounts of nutritious foods and get lots of exercise. None of them smokes. Most Americans, unfortunately, do not follow such healthy habits. The greatest irony would be to discover that a pill is not, in the end, any more effective than the healthy habits we already ignore. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/jul2015

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

iResearch Subject

Our smartphones may change the face of health studies—now that we can all choose to be participants

For a recent breast cancer study, epidemiologist Kathryn H. Schmitz of the University of Pennsylvania sent out 60,000 letters—and netted 351 women. Walking each participant through the paperwork took 30 minutes or more. Such inefficient methods of finding test subjects have been the norm for medical research.

Yet there's a wealth of data out there from the billion smartphones and 70 million wearable health trackers we buy every year. Their sensors generate terabytes of data every day about our activity, sleep and behavior. Those data would be fantastically useful to medical investigators—if only they could get at them.

For the first time, there's a way. It's free software from Apple called ResearchKit.

ResearchKit lets researchers build apps to do the recruitment and data collection for them. You, the participant, know exactly who's getting this information, and you can opt out of any part at any time. The data go directly to the research institution; Apple has no access.

These apps can incorporate both self-reported data ("How are your symptoms today?") and information from the phone's microphone, camera, motion sensor, GPS, and so on. So instead of providing updates once every six months, you're generating data hundreds, if not thousands, of times a day.

Before ResearchKit's release in April, Apple worked with leading institutions to develop the first wave of five apps. Cardiologist Michael McConnell and a team at the Stanford University School of Medicine, for example, developed MyHeart Counts, an app for monitoring cardiac health. It tracks your activity (using the phone's motion sensors) and asks you to take a walking test every three months. The app attempts to correlate activity, fitness and risk factors over time; eventually it gives you personalized suggestions—something else traditional studies don't usually do.

Within the first 24 hours, 10,000 participants signed up for the study.

"ResearchKit solves a number of the current challenges to clinical research," McConnell told me. With it, you can recruit more people, bring costs down and allow for better sharing of research data, he said.

Eric Schadt, a geneticist at the Icahn School of Medicine at Mount Sinai, developed an app called Asthma Health. It surveys you about your condition each day and correlates your responses with your local weather, pollution and pollen counts (via your phone's GPS). Within 72 hours, 5,000 asthma sufferers had enrolled—a number, Schadt says, that would have taken him years to amass in the old days. Other apps developed before the release include GlucoSuccess (for monitoring diabetes), mPower (for Parkinson's disease) and Share the Journey (for breast cancer). They are all free. You can participate in the latter three studies even if you don't have the disease; your data are helpful as controls.

This may all sound wonderful, but what's in it for Apple?

Your first guess might be: "To sell more iPhones, of course." Except that here's the best part: Apple has made ResearchKit open source. It's free to anyone—even Apple's rivals, such as Google or Samsung—to use, modify or co-opt.

The ResearchKit idea seems promising. But it's worth pointing out that the reliance on a smartphone limits the participant pool to people who have one. Studies that require body scans, fluid samples or hospital-grade precision are off the table, too.

But compared with in-person and even Web-based studies, these apps can be far more present and easier to stick with, and they can generate more kinds of useful data. Studies that used to be slow, small and local can now be fast, huge and global. And that could mean better health and longer lives for us all. SA

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The first five ResearchKit apps reviewed: ScientificAmerican.com/jul2015/pogue

Illustration by Julian Callos

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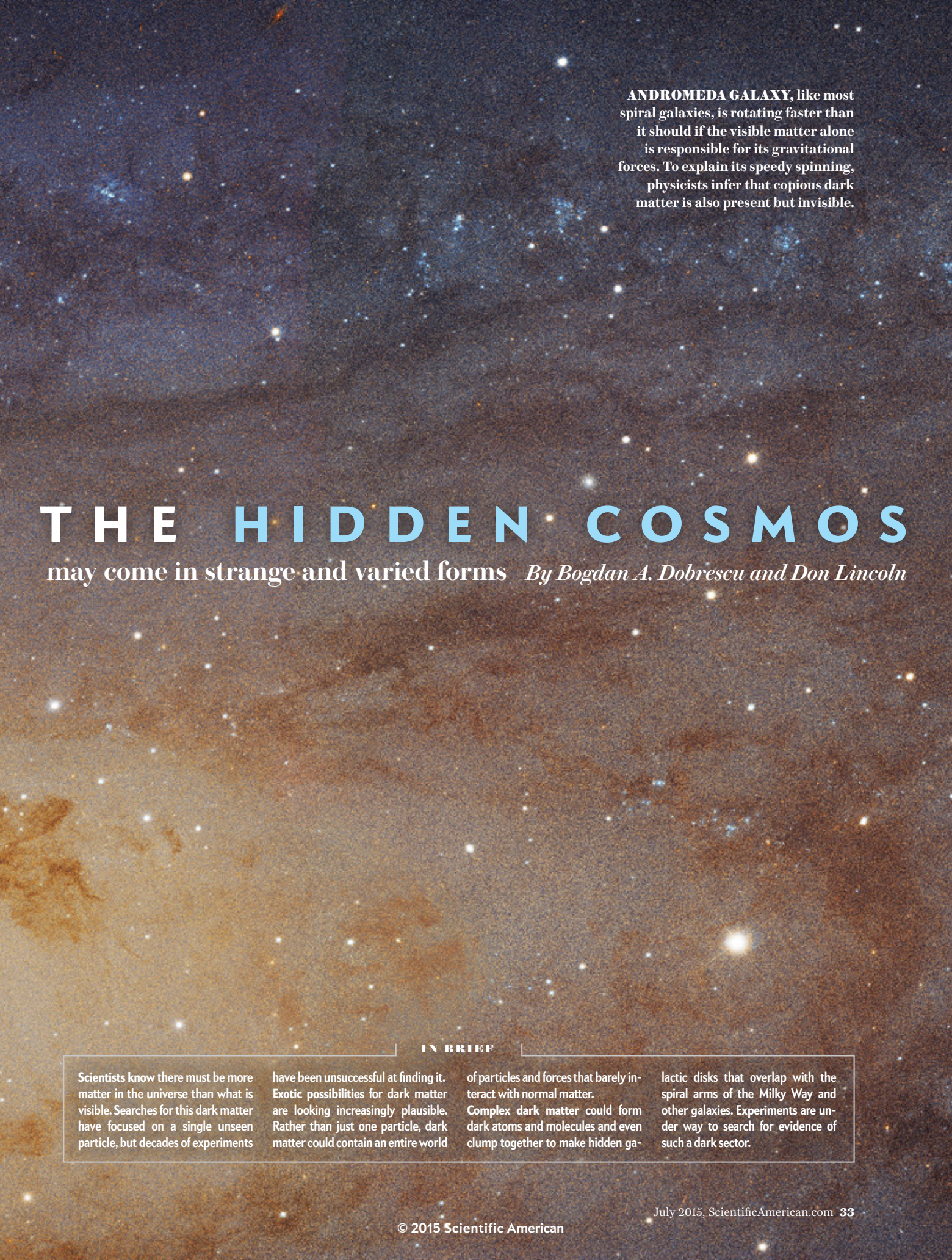
ASTROPHYSICS

MYSTERY OF

The invisible dark matter particles that dominate the universe



ANDROMEDA GALAXY, like most spiral galaxies, is rotating faster than it should if the visible matter alone is responsible for its gravitational forces. To explain its speedy spinning, physicists infer that copious dark matter is also present but invisible.

THE HIDDEN COSMOS

may come in strange and varied forms

By Bogdan A. Dobrescu and Don Lincoln

IN BRIEF

Scientists know there must be more matter in the universe than what is visible. Searches for this dark matter have focused on a single unseen particle, but decades of experiments have been unsuccessful at finding it. Exotic possibilities for dark matter are looking increasingly plausible. Rather than just one particle, dark matter could contain an entire world of particles and forces that barely interact with normal matter. Complex dark matter could form dark atoms and molecules and even clump together to make hidden galactic disks that overlap with the spiral arms of the Milky Way and other galaxies. Experiments are under way to search for evidence of such a dark sector.

Bogdan A. Dobrescu is a researcher in theoretical particle physics at Fermi National Accelerator Laboratory in Batavia, Ill., focusing on new particles and their interactions. Recently he has explored the possibility that dark matter may be produced by the main accelerator at Fermilab and then observed in neutrino detectors.

Don Lincoln is a senior physicist at Fermilab who conducts research using data from CERN's Large Hadron Collider. He is author of several science books for the public, including his most recent one, *The Large Hadron Collider: The Extraordinary Story of the Higgs Boson and Other Stuff That Will Blow Your Mind* (Johns Hopkins University Press, 2014).

THE BEAUTIFUL SPINNING PINWHEEL OF THE ANDROMEDA GALAXY, OUR CELESTIAL neighbor, poses a mystery. The breakneck speed of its rotation cannot be explained by applying the known laws of physics to the disk's visible matter. By rights, the gravity generated by the galaxy's apparent mass should cause the stars in the periphery to move more slowly than they actually do. If the visible matter was all there was, Andromeda, and nearly all such quickly rotating galaxies, simply should not exist.

Cosmologists believe that some unseen kind of matter—dark matter—surrounds and permeates Andromeda and other galaxies, adding the necessary gravitational force to keep them spinning as observed. Dark matter, which appears to contribute about 25 percent of the universe's mass, would also explain other aspects of the cosmos, including the exceedingly fast motion of galaxies within clusters of galaxies, the distribution of matter arising when two clusters collide and the observation of gravitational lensing—the bending of light by gravity—of distant galaxies.

The simplest theories of dark matter postulate a single kind of as yet undiscovered particle contributing the unseen mass. But despite decades of searching for direct evidence of the dark matter particle, no one has been able to prove its existence. Further, a few discrepancies remain between astronomical observations and this simple theory. The combination of these residual disagreements with the failure to detect this elusive substance has led some scientists to question the traditional theories and imagine a more complicated form of dark matter. Instead of a single type of particle, dark matter might be made of a wider array of dark species. After all, ordinary matter comes in many forms—maybe dark matter is similarly complex.

Over the past few years scientists have increasingly come to suspect that several varieties of dark matter exist and, perhaps even more intriguing, that previously unsuspected forces act strongly on dark matter and very feebly (or not at all) on ordinary matter. Recent observations of colliding galaxies may provide preliminary support for this hypothesis, and such forces could help explain some of the discrepancies between the basic dark matter model and observations. If complex dark matter exists, it would make for a more interesting and intricate universe than cosmologists usually imagine.

HIDDEN MATTER

ALTHOUGH WE DO NOT YET KNOW what constitutes dark matter, we do know something about its properties from our observations of how it influences normal matter and from simulations of its gravitational effects. For instance, it must be moving much slower than the speed of light; otherwise the density fluctuations present in the early universe would not lead to the galactic structures observed today. Because it does not absorb or emit electromagnetic radiation, it must be electrically neutral. The particles that compose dark matter are probably massive, or else they would have to be moving near the speed of light, which data from the early universe rule out. They cannot interact via the strong force, which binds atomic nuclei together; otherwise we would have seen evidence in dark matter's interaction with high-energy charged particles called cosmic rays. Until recently, scientists believed that dark matter might interact via the weak force (responsible for radioactive decay), but new observations have undercut that notion. (Although it remains possible that dark matter could still experience weak force interactions, to be consistent with observations such interaction is plausible only if additional as yet undetected particles exist besides dark matter.)

We also know that dark matter must be stable on cosmic timescales. The reason is simple: there is no credible mechanism to continually produce dark matter; thus, dark matter must be primordial, meaning that it originated in the big bang. Saying a particle is stable hides a profound truth; its stability tells us that it possesses a property that is "conserved"—it cannot change—and thereby forbids the particle to decay, which would alter the conserved property. We can illustrate the meaning of this term by invoking the familiar electrical charge, which ensures that the electron is stable. It is a truism of physics that particles decay into lighter ones unless something prevents that decay. The electron is electrically charged, and the only known stable particles lighter than it are electrically neutral: the photon and the neutrinos. Energy considerations would allow the electron to decay into these objects, but because conservation of charge prohibits such decays, the electron stays an electron.

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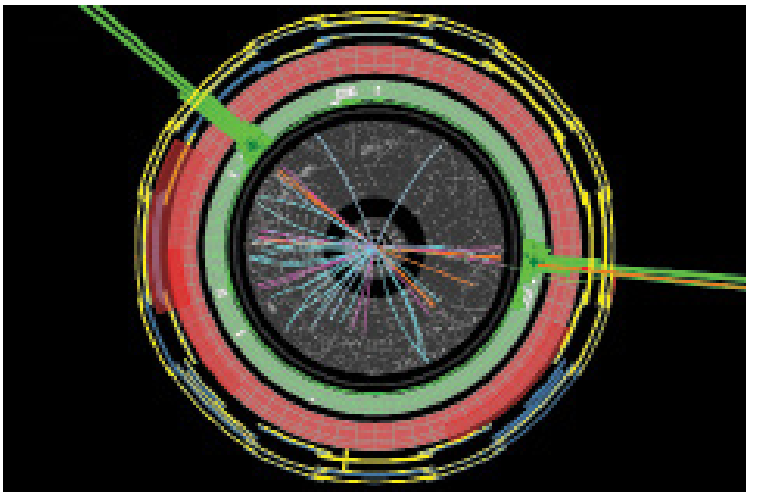
Most dark matter theories assume the dark particles have a conserved quantity called, for historical reasons, parity, with the dark matter particle having a parity of –1 and all other known particles having a parity of +1. A dark matter particle is then forbidden from decaying into ordinary matter by this parity because if the dark entity disappeared and ordinary particles appeared, the parity would not be conserved.

The simplest theory that meets all the conditions physicists have outlined posits a single particle responsible for dark matter called a WIMP, for weakly interacting massive particle. (The term "weakly" here is used in the generic sense and does not necessarily mean the weak nuclear force.) WIMPs make sense for many theoretical reasons, but they are proving harder to find than many physicists expected. Since the 1990s scientists have been running various experiments aimed at directly detecting WIMPs through their very rare interactions with ordinary matter.



PROTON-PROTON COLLISIONS such as this one at the ATLAS detector at CERN's Large Hadron Collider show features (*green lines*) consistent with some theories of dark photons.

To achieve the necessary sensitivity, the detectors are cooled to extremely low temperatures and buried deep underground to shield them from ubiquitous cosmic rays, which can mimic a dark matter signature. Yet despite increasingly powerful experiments, no conclusive sign of WIMPs has emerged. And whereas the WIMP model does explain many aspects of our observed universe, it does not account for everything. For example, WIMP theories predict that a much greater number of small satellite galaxies should be orbiting the Milky Way than apparently do swirl around it and that dark matter should be even denser in the center of galaxies than it seems to be based on the galaxies' observed rotation rates. The situation is evolving rapidly, however—the recent discovery of additional satellite galaxies by the Dark Energy Survey collaboration suggests the problem with the Milky Way's dwarf galaxies may simply be that many have yet to be found.

Ultimately, though, these WIMP shortcomings have left the door open for more unconventional dark matter models.

COMPLEX DARK MATTER

RATHER THAN A SINGLE PARTICLE constituting all of dark matter, one could imagine that several classes of dark matter particles exist, as well as a variety of forces that act only on dark matter. One idea that appears to reconcile all the observations and simulations is the possibility that dark matter particles interact with one another—essentially, dark matter particles may feel a force between them that is not felt by ordinary matter. These particles could, for instance, carry a new kind of "dark charge" that attracts or repels them while leaving them electrically neutral. Just as ordinary particles with electrical charge can emit photons (particles of light that are the carriers of the electromagnetic force), perhaps particles with dark charge could emit "dark photons"—not particles of light but rather particles that interact with dark charge in the same way that photons interact with electrical charge.

The parallels to the world of normal matter must end at a certain point, however. The reason we know that is the following: Suppose that the rules of the dark world exactly mirrored ours. In that world, dark atoms would form and emit dark photons at the same rate that ordinary matter emits ordinary photons. In our world, the emission of photons allows energy to be exchanged and is the reason galaxies eventually relax into disklike objects. Clouds of gas inside galaxies radiate electromagnetic energy, which results in the matter inside the clouds clumping together. Conservation of angular momentum precludes matter from contracting to a point, but a disklike structure forms easily. If the rules and forces governing the behavior of dark matter were the same as ours, the emission of dark photons would result in all dark matter galaxies forming flattened disks. Yet we know that the distribution of most of the dark matter required to explain our familiar galaxies is more like a spherical cloud. Thus, we can rule out an exact mirror world of dark matter.

Still, many alternatives remain. For instance, it is possible that a small fraction of dark matter mirrors the rules of our universe, whereas the larger fraction acts more like the simple WIMPs. Or perhaps the dark charge is effectively much smaller than the electrical charge of our electrons and protons, resulting in reduced dark photon emission. Theorists, including one of us (Dobrescu), are generating many ideas about possible particles and forces of the dark sector, using existing data to guide our thinking and constrain speculations. One of the simplest scenarios—involving just two kinds of dark matter particles—offers a glimpse of some of the physics that could operate in complex dark matter.

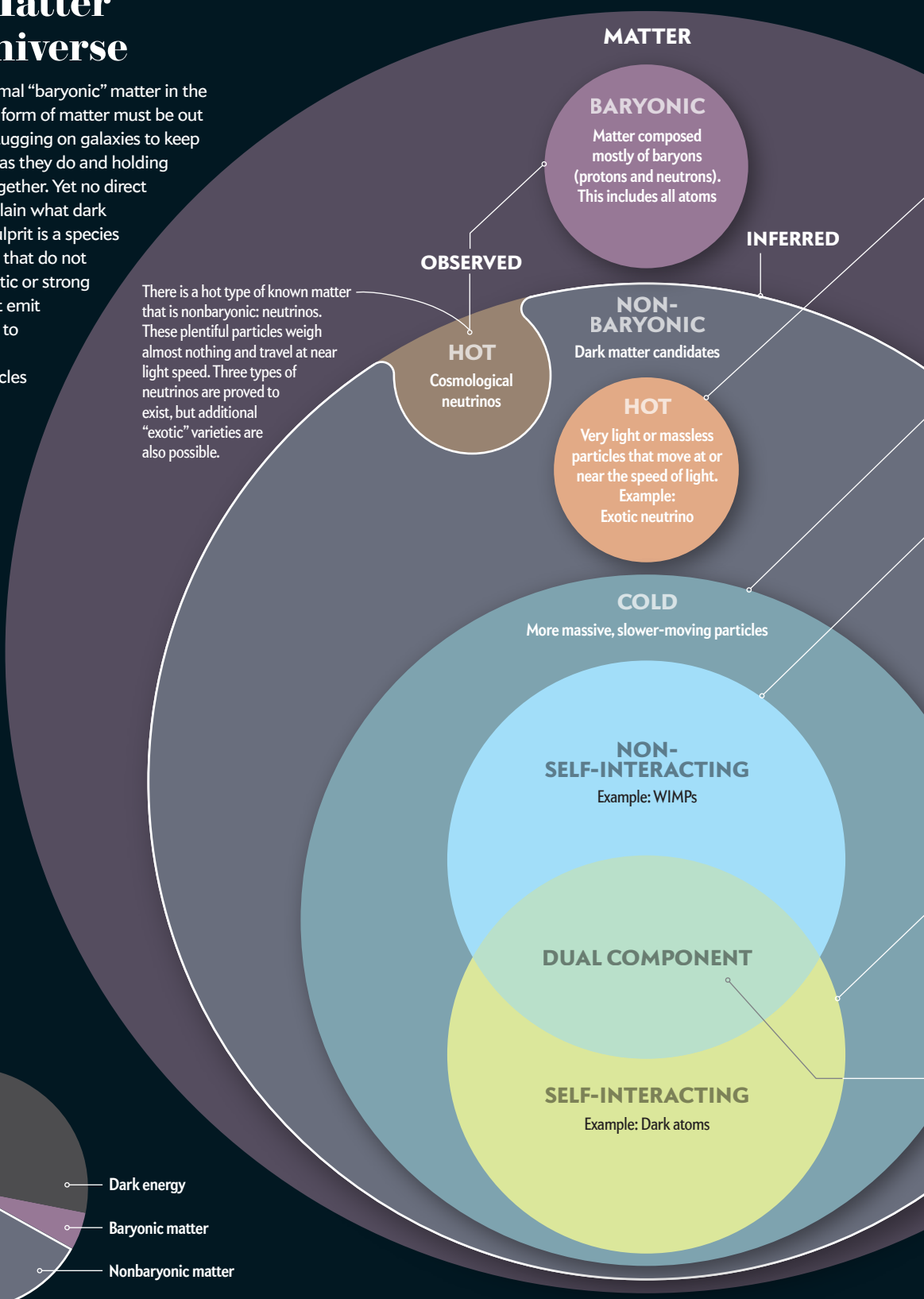
DARK PHOTONS

IMAGINE A DARK WORLD in which two kinds of dark charge exist—one positive and one negative. In this model, there is a form of dark electromagnetism, leading the dark matter particles to emit and absorb dark photons. Because, as postulated, these particles are charged in a way analogous to ordinary electromagnetism, positively and negatively charged dark matter particles should be able to meet and annihilate into dark photons, just as normal matter particles and their oppositely charged antimatter counterparts annihilate on contact, releasing photons.

We can make some conclusions about the strength of the dark electromagnetism force and thus how often dark matter

All the Matter in the Universe

In addition to the normal "baryonic" matter in the cosmos, some hidden form of matter must be out there, gravitationally tugging on galaxies to keep them spinning as fast as they do and holding clusters of galaxies together. Yet no direct evidence exists to explain what dark matter is. The likely culprit is a species of particle or particles that do not feel the electromagnetic or strong forces and thus do not emit or reflect light or bind to atomic nuclei. Exactly what form these particles take, however, is an open question.



The universe's total mass includes the matter—both baryonic and dark—and the dark energy that are causing the expansion of the cosmos to accelerate.

Illustration by Jen Christiansen

The Leading Dark Matter Candidates

HOT

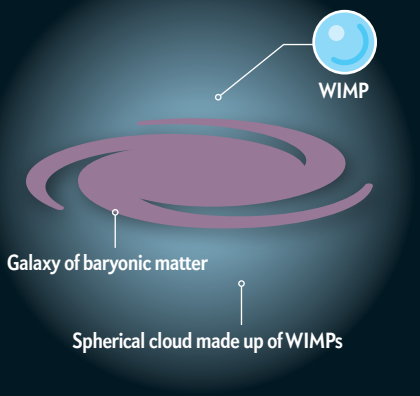
If dark matter was primarily made up of fast-moving particles, they never would have clumped together enough to form the spherical clouds that gave rise to individual galaxies. But some small component of the total dark matter could still be hot.

COLD

Slow-moving dark matter particles better account for galaxies and the observed distribution of matter throughout the universe. At least 95 percent of dark matter most likely is cold.

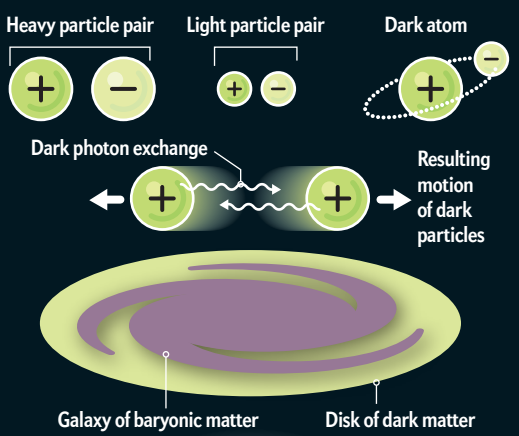
NONSELF-INTERACTING

The simplest kind of cold dark matter particle is a "weakly interacting massive particle," or WIMP, that rarely or never interacts with other particles of its own kind or ordinary matter. WIMPs would congregate into spherical clouds that would gravitationally attract normal baryonic matter to form galaxies.



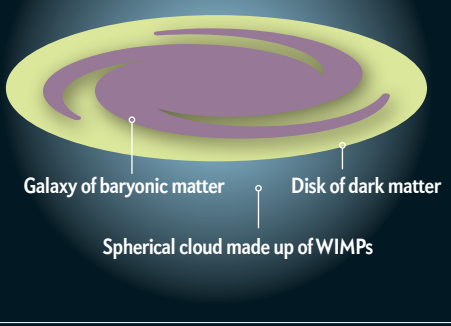
SELF-INTERACTING

If dark matter interacts with itself, it must do so through some dark force that does not act on baryonic matter. This force could be a kind of dark electromagnetism, leading to the possibility that dark particles carry either positive or negative dark charges and interact by exchanging force-carrying particles called dark photons. Dark electromagnetism could allow for multiple types of dark particles—some heavy and some light—that attract one another into arrangements akin to atoms. These could form disk structures in galaxies that overlap with the spiral arm disks of baryonic matter.



DUAL COMPONENT

Dark matter might be a mix of two types of cold particles—some non-self-interacting (such as WIMPs) and some self-interacting. This would result in both a spherical cloud of WIMPs around galaxies and a flattened disk of self-interacting particles.



annihilation occurs by considering how this force would affect galaxies. Recall that the reason galaxies have a flattened structure is that electromagnetism allows ordinary matter to lose energy and settle into disks. This energy loss occurs even without annihilation. Because we know that dark matter is primarily distributed spherically around most galaxies and does not collapse to a disk, we can conclude that it cannot lose energy via dark photon emission at the same rate that ordinary matter does. In a study published in 2009 Lotty Ackerman, Matthew R. Buckley, Sean M. Carroll and Marc Kamionkowski, all then at the California Institute of Technology, showed that this requirement implies that the dark charge must be very small, about 1 percent the value of the electrical charge. Yet even at such a low value, the force could still exist and effect significant consequences on galaxies.

DARK GALAXY

SO FAR WE HAVE DESCRIBED a version of dark matter consisting of a charged dark particle and its oppositely charged match emitting dark photons. But this scenario still pales in comparison to the complexity of ordinary matter. What would a dark matter world with multiple different charged particles look like?

There are many theories of complex dark matter that include two or more hypothetical dark particles. One particularly intriguing example was proposed in 2013 by JiJi Fan, Andrey Katz, Lisa Randall and Matthew Reece, all then at Harvard University, who referred to their model as "partially interacting dark matter." They assumed the bulk of dark matter was made up of WIMPs but also postulated a small component consisting of two classes of particles known as fermions: one heavy and one light, both of which carry dark charge. (Fermions are particles with a quantum-mechanical spin of ½; in our familiar world, protons, neutrons and the quarks that compose them are examples of fermions.) Because the dark fermions carry dark charge, they emit dark photons and can be attracted to one another.

Although one must be very cautious to not overinterpret the correspondence, the proposed situation is broadly similar to postulating a dark proton, a dark electron and a dark photon to carry the dark electromagnetism that binds them together. Depending on the mass and charges of the dark fermions, they could combine to create dark atoms with their own dark chemistry, dark molecules and possibly even more complex structures. The concept of dark atoms was explored in detail in 2010 by David E. Kaplan, Gordan Z. Krnjaic, Keith R. Rehermann and Christopher M. Wells, all then at Johns Hopkins University.

The Harvard physicists who proposed the dark matter fermions idea went on to derive an upper limit on the fraction of dark matter that may be strongly interacting with dark photons, given the constraints imposed by astronomical observations. They determined that its cumulative mass may be as large as that of all visible matter. In this model, the Milky Way galaxy consists of a large spherical cloud of WIMP-like particles, which contributes 70 percent of the total matter, encircling two flattened disks, each containing 15 percent of the matter. One disk is normal matter, which includes the spiral arms that we can see, and the other consists of strongly interacting dark matter. The two disks need not be exactly aligned, but they would have a similar orientation. In this picture, a dark matter galaxy basically coexists in the same space as our familiar Milky Way. A cautionary note: the dark matter galaxy would not include dark stars or large planets, because these would have been observed through their gravitational-lensing effects on ordinary matter.

The idea may sound radical, but the extra disk in our galaxy would do little to change the normal matter cosmos with which it coexists. After all, to be correct, any theories about dark matter have to be consistent with existing observations of visible matter. We could be living in such a universe without even knowing it.

Depending on the mass and charges of the dark fermions, they could combine to create dark atoms with their own dark chemistry, dark molecules and possibly even more complex structures.

EXPERIMENTAL PROSPECTS

SCIENTISTS CAN SEARCH FOR complex dark matter in the same ways they search for WIMPs: with sensitive underground detectors. One consequence of the partially interacting dark matter model, with its concentrated disk of matter roughly in the same plane as the visible matter of the Milky Way, is that this form of dark matter passing through our detectors would be denser than that predicted in WIMP models. The increased density could result in a greater probability of these detectors finding dark matter than conventional theory predicts.

In addition to conducting such experiments, physicists hope to make dark matter in particle accelerators, along with all the other exotic particles generated there. Because we know very little about how dark matter interacts with ordinary matter—and thus which particular processes inside the accelerator might give rise to it—scientists have embarked on a broad program of investigation. This program is sensitive to a variety of models of dark matter, ranging from the simple WIMP to a more complex dark sector, although we must make some assumptions, such as that dark matter interacts with ordinary matter via a force or forces that are much stronger than gravity (the weakest of all known forces) yet weak enough to not yet have been observed. This assumption is necessary because if dark matter interacts only gravitationally, we will never create it in any conceivable accelerator, nor will we see it in any direct search. This force would be different from the chargelike force through which dark matter might interact with itself.

SCIENTIFIC AMERICAN ONLINE Watch a video about complex dark matter at ScientificAmerican.com/jul2015/dark-matter

The Large Hadron Collider (LHC) at CERN near Geneva is the world's highest-energy accelerator, which gives it an edge when searching for heavier versions of dark matter (the more massive a particle is, the more energy it takes to produce it inside an accelerator), as well as for dark matter particles whose interactions become increasingly frequent as their energy rises. Because we already know dark matter can interact only very weakly with ordinary matter, we cannot expect to observe it directly in the detector, which is made of ordinary matter. Instead scientists search for dark matter by looking for collisions in which energy is missing. For example, two protons might collide and produce some ordinary particle or particles exiting one side of the collision and a couple of dark matter particles on the other. The signature of such an event is observed energy on one side of the detector with nothing on the other side. Scientists calculate how many collisions would be expected to show this striking configuration if dark matter did not exist and then look to see if there are more than expected.

So far no signs of such an excess have shown up inside the LHC—an indication that dark matter's interactions with ordinary matter must be very infrequent, if they occur at all. But a new opportunity for seeing signs of dark matter recently began with the start of the LHC's upgraded, higher-energy second run this spring. That means that the discovery of the century could be right around the corner.

In addition to the searches for dark matter we have just described, which are suitable for finding both WIMPs and complex dark matter, some approaches aim more specifically at the complex dark sector. Many of these search for the dark photon. Some models suggest that dark photons can continually transform into ordinary photons and back again via the laws of quantum mechanics, potentially presenting an opportunity to see the photons that result. Other models suggest certain dark photons have a nonzero mass (the use of the word "photon" is stretched in that case, in that they differ from the familiar massless photon). If a dark photon has mass, it can potentially decay into lighter particles. And because this dark photon can transform briefly into a normal photon, there is a small chance that it can produce pairs of electrons and their antimatter counterparts or similarly a matter-antimatter pair of muons (cousins of electrons) during the transformation process.

Consequently, experimental collaborations, including a project for which one of us (Lincoln) is a member, search for collisions that produce an electron-positron or a muon-antimuon pair. Such studies are ongoing at the LHC and at other accelerator facilities, such as at the KLOE-2 project at the National Institute for Nuclear Physics' Frascati National Laboratories in Italy, the Heavy Photon Search (HPS) experiment at the Thomas Jefferson National Accelerator Facility in Newport News, Va., and the BaBar detector experiment at SLAC National Accelerator Laboratory—and scientists are even digging through data more than a decade old taken by a SLAC experiment known as mQ.

Another interesting approach utilizes Fermi National Accelerator Laboratory in Batavia, Ill., to try to make beams of dark matter particles. Fermilab is currently generating intense beams of neutrinos that shoot at distant detectors. Neutrinos are very light subatomic particles that interact essentially exclusively through the weak nuclear force. If dark matter interacts with ordinary matter via particles like dark photons, it is possible that dark matter is being made in the same beams and can possibly be detected in Fermilab's MiniBooNE, MINOS or NOvA detectors.

Finally, scientists can search for astronomical signs that dark matter is interacting in situations such as when galaxies collide. In such scenarios, when the dark matter from one galaxy slams into the dark matter in another, the particles could repel one another by exchanging dark photons. Several studies of galaxy crashes have failed to find evidence of this phenomenon, but observations, published just a few months ago, of the cluster Abell 3827, which is particularly close to Earth and well oriented, hint at just such a pattern. Further observations of that and other galaxy collisions will be necessary to confirm the signal, but the data from this cluster so far look promising for complex dark matter models.

A COSMIC STUMPER

THERE IS NO QUESTION that we are facing a profound conundrum. On large scales, ordinary gravitationally bound matter does not act in ways consistent with the known laws of physics and the observed distribution of mass. Because of this disagreement, most scientists are confident that some form of dark matter exists. What form this matter takes, however, has become increasingly contentious as our experiments repeatedly fail to find evidence for the simplest dark matter models. For this reason and because of some persistent discrepancies between the simple WIMP model predictions and astronomical observations, complex dark matter theories are becoming more appealing. These models offer theorists more parameters to tune and thus to improve the agreement between data and theory. They also more closely match the variation and richness of normal matter.

A criticism of this approach may be that it works overly hard to keep the dark matter hypothesis alive. Could this situation be similar to the discredited idea of epicycles, whereby 16th-century astronomers tried to retain geocentrism by adding a constant series of tweaks to a fatally flawed theory? We think not, given that dark matter explains many astronomical conundrums remarkably well and there is no a priori reason why dark matter should be as simple as the WIMP hypothesis.

The real message is that we have a mystery before us and that we do not know what the answer will be. Until we find it, we must be open to myriad explanations, including the fascinating possibility that we might be living alongside a dark parallel reality. Could it be that a dark matter scientist has turned its attention to its skies and is wondering about us?

MORE TO EXPLORE

Dark Matter and Dark Radiation. Lotty Ackerman et al. in *Physical Review D,* Vol. 79, No. 2, Article No. 023519; January 23, 2009.

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Dark Worlds. Jonathan Feng and Mark Trodden; November 2010.

scientificamerican.com/magazine/sa

WHAT DOESN'T KILL YOU...

BRAIN HEALTH

Chemicals that plants make to ward off pests stimulate nerve cells in ways that may protect the brain against diseases such as Alzheimer's and Parkinson's

By Mark P. Mattson

IN BRIEF

Plants do not have the option of fleeing predators. As a consequence, they have developed an elaborate set of chemical defenses to ward off insects and other creatures that want to make them into a meal.

Toxic chemicals that plants use against predators are consumed by us at low levels in fruits and vegetables. Exposure to these substances causes a mild stress reaction that lends resilience to cells in our bodies.

Adaptation to these stresses, a process called hormesis, accounts for a number of health benefits, including protection against brain disorders, we receive from eating broccoli and blueberries.

Illustration By Bill Mayer

Mark P. Mattson is chief of the Laboratory of Neurosciences at the National Institute on Aging and a professor of neuroscience at the Johns Hopkins University School of Medicine. His discoveries have advanced understanding of nerve cell circuits during aging.

WHEN ASKED WHY EATING LOTS OF FRUITS AND VEGETABLES CAN IMPROVE HEALTH, many people will point to the antioxidants in these foods. That reasoning is logical because major diseases such as cancer, cardiovascular disease and diabetes involve cell damage caused by chemicals called free radicals that antioxidants neutralize.

As a neuroscientist working to understand what goes wrong in the brain, I have long been aware that free radicals disrupt and sometimes kill neurons. And conversely, I know that people who regularly consume vegetables, fruits and other plant products thought to contain high levels of antioxidants tend to have healthier brains and to be less likely to suffer from neurodegenerative diseases. But the antioxidants story is not quite so simple.

Indeed, when rigorously evaluated in controlled trials in animals and humans, antioxidants, such as vitamins C, E and A, have failed to prevent or ameliorate disease. How then do fruits and vegetables promote health?

The emerging answer has much to do with the strategies that plants have evolved over millions of years to protect themselves from pests. Bitter-tasting chemicals made by plants act as natural pesticides. When we eat plant-based foods, we consume low levels of these toxic chemicals, which mildly stresses cells in the body in much the same way that exercise or going without food for long periods does. The cells do not die—in fact, they get stronger because their response to the stress shores up their ability to adapt to still more stress. This process of bolstering cellular resilience is called hormesis—and a growing body of research indicates that it accounts for the health benefits of consuming fruits and vegetables. Understanding hormesis's effects may even provide new ways to prevent or treat some of the most devastating brain diseases, including Alzheimer's, Parkinson's and stroke.

STRESS IS GOOD

MY COLLEAGUES AND I HAVE COLLECTED some of the data on hormesis in the brain after coming to the work somewhat circuitously. In the early 1990s my team, then at the Sanders-Brown Center on Aging at the University of Kentucky, set out to investigate whether antioxidants could provide a treatment for Alzheimer's. We thought they might be helpful because we had seen beta-amyloid—the pernicious protein that accumulates excessively in the brains of Alzheimer's patients—wreaking havoc on brain cells in culture and knew that free radicals were involved in the destructive process. Unfortunately, when tested at various medical centers in a clinical trial led by Douglas R. Galasko and Paul Aisen, both at the University of California, San Diego, high doses of antioxidants had no benefit in Alzheimer's patients. We then shifted our efforts to a seemingly different problem, which serendipitously led us to develop a new hypothesis of why eating plant foods is good for brain health.

We and others had noted that people who exercise regularly, eat relatively few calories and experience a variety of intellectual challenges tend to maintain a higher level of brain functioning than people with the opposite way of life. They are less likely to suffer from Alzheimer's, Parkinson's or stroke. We wondered whether diet, exercise and intellectual activity influence brain function and disease susceptibility by affecting the same molecular processes in brain cells.

Beginning with a study in 1999 by Annadora Bruce-Keller, then a postdoctoral fellow in my laboratory and now a professor at Louisiana State University's Pennington Biomedical Research Center, we found that the neurons in the brains of rats on an alternate-day fasting diet were resistant to neurotoxins known to cause symptoms that mimic epilepsy and Huntington's disease, whereas normally fed animals succumbed to the chemicals. Shortly thereafter, I was recruited to head the Laboratory of Neurosciences at the National Institute on Aging, where our research found that fasting every other day also protects the brain in animal models of Alzheimer's, Parkinson's and stroke.

As we worked to understand why fasting was good for the brain, it became clear that neurons were responding to food deprivation by mobilizing molecular defenses against free radicals and the accumulation of beta-amyloid. The defense systems entailed producing proteins known as neurotrophic factors, such as brain-derived neurotrophic factor (BDNF), that are critical for neuron survival, as well as proteins that bolster efficient use of energy and prevent the accumulation of damaged molecules.

From an evolutionary standpoint, the demonstration that fasting intermittently can be beneficial should not be overly surprising. It creates a mild stress that puts the brain into a state where the protection of neurons is paramount, which would allow the animal to function at a high level and obtain food even when it is in short supply and the animal has to expend energy to find it.

Our interest in the beneficial effects of stress on brain cells eventually led us to look at the neurological effects of plants in the diet. We were intrigued by reports in journals during the 1970s that a neurotoxin in seaweed, called kainic acid, was able to bind to and cause excessive activation of receptors on the surface of brain cells that serve as docking sites for gluta-

mate, the main signaling molecule that switches on neurons.

Our group and others had already demonstrated the paradoxical effects of glutamate in fasting and exercise. Too much stimulation of the receptors can damage or destroy neurons. More moderate activation of these receptors, however, turns on a chemical pathway in neurons that plays a critical role in learning and memory and in protecting neurons. Such discoveries began to raise the question of whether low levels of plant neurotoxins in fruits and vegetables might yield beneficial health effects by inducing similar mild stresses in brain cells.

"DANGER, WILL ROBINSON!"

THE HEALTH BENEFITS of fruits and vegetables are an inadvertent offshoot of eons-long wars waged by plants against critters, mostly insects, that are intent on eating them. To survive as individuals and species, they had to develop ways of preventing their own extinction. Over the course of hundreds of millions of years of evolutionary history, they came to produce natural pesticides.

These chemicals usually do not kill the insects: a plant does not care whether predators die; it just wants them to go away and not come back. One common way that plants send pests packing is targeting their nervous systems. The plants produce chemicals that act on neurons called sensilla in the bugs' mouthparts, which are similar to the taste bud cells in the human tongue. Signals from those cells are transmitted to the brain, which then decides whether or not to eat the plant.

Although insects are plants' biggest threat, our early primate ancestors also looked for ways to make use of roots, leaves and fruits that they found in the tropical forests where they lived. Plants became food or medicine, but they could also cause nausea, vomiting or even death.

To adapt, we developed an elaborate warning system that reminds me of the behavior of a character in the old television show *Lost in Space,* which was about the adventures of nine-year-old Will Robinson and his family traveling through distant solar systems. When the Robinsons landed on a distant planet and were exploring the terrain surrounding their spaceship, their companion, a sophisticated robot, alerted them of potential dangers. In a 1968 episode called "The Great Vegetable Rebellion," the robot warned them of the threat of deadly plants.

Much like that robot, our warning system alerts our brain to the presence of toxic substances. The bitter taste of many plants tells us not to eat too much of the bad-tasting leaves, roots and fruits or to simply avoid them entirely. There seems to be some innate justification for children not wanting to eat their broccoli after all. For insects, the noxious chemicals help to drive them off, but for us they serve as a warning to limit our intake.

Traditional healers learned through trial and sometimes fatal error that these same plants had important medicinal uses. Pharmacologists, toxicologists and biochemists are now confirming that plant chemicals that are toxic when consumed at high levels can be hormetic—that is, they provide health benefits when eaten in smaller amounts.

When the effects of hormesis-inducing substances are measured, they yield what scientists call a biphasic response curve. It can be illustrated on a graph plotting effects relative to dose and by drawing a line that traces an upside-down U shape. The effect line rises at first to indicate that eating a small or moderate amount of a plant chemical has beneficial health effects. It then drops gradually to illustrate the toxicity that emerges as more of these substances are consumed. Eating too many Brazil nuts can poison the liver and lungs because of the presence of the trace element selenium. Yet eating just a few supplies an essential nutrient that is incorporated into an enzyme that may help protect against heart disease and cancer. This example illustrates how hormesis works and differentiates it from homeopathy, which claims, without valid evidence or a plausible mechanism, that vanishingly small amounts of what causes illness can be curative.

Chemicals that induce the just enough/not too much responses characteristic of hormesis seem to be ubiquitous in the plant world. Edward J. Calabrese, a professor of toxicology at the University of Massachusetts Amherst, has spent a large part of his career identifying chemicals that are responsible for hormesis. He has conducted a laborious, three-decades-long analysis of more than 10,000 published studies in the fields of biology, toxicology and medicine. On this list are caffeine, opioids and other compounds that have effects in the brain. Calabrese established a scientific society and a journal devoted to research on hormesis. Because of our common interest in how cells and organisms have evolved to respond to many types of stress and why this is important for human health, he and I co-edited a book on the subject.

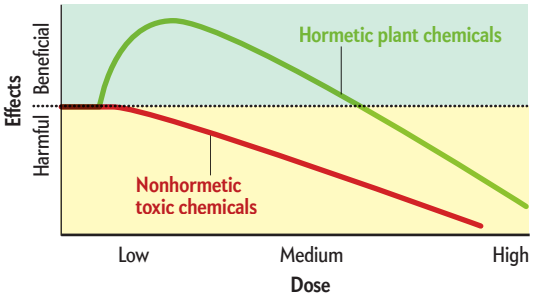
Some scientists are now reassessing earlier experiments that seemed to point to a beneficial role for fruit and vegetable antioxidants in the brain—and for general health. They are looking to see whether hormesis may have been responsible for positive results reported in their studies instead. That research and other work appear to confirm that cellular stress induced by plant chemicals may complement or, in some cases, eclipse the contribution of antioxidants. It is not that antioxidants have completely faded from the picture. Rather the biochemical processes set in motion by hormetic stress seem to control when antioxidants are available to be used by brain cells.

One example of the new line of research comes from Gregory M. Cole, a neuroscientist at the University of California, Los Angeles, who more than a decade ago used an ingredient in curries, curcumin, to perform an experiment that he thought might lead

TOXICOLOGY

First Good, Then Bad

Fruits and vegetables often contain low levels of toxic chemicals that provide health benefits when consumed in modest amounts but become increasingly noxious at high levels, a process called hormesis. The disparity in effects—traced on a biphasic response curve—contrasts with mercury and other nonhormetic toxic substances that are harmful at even low amounts.

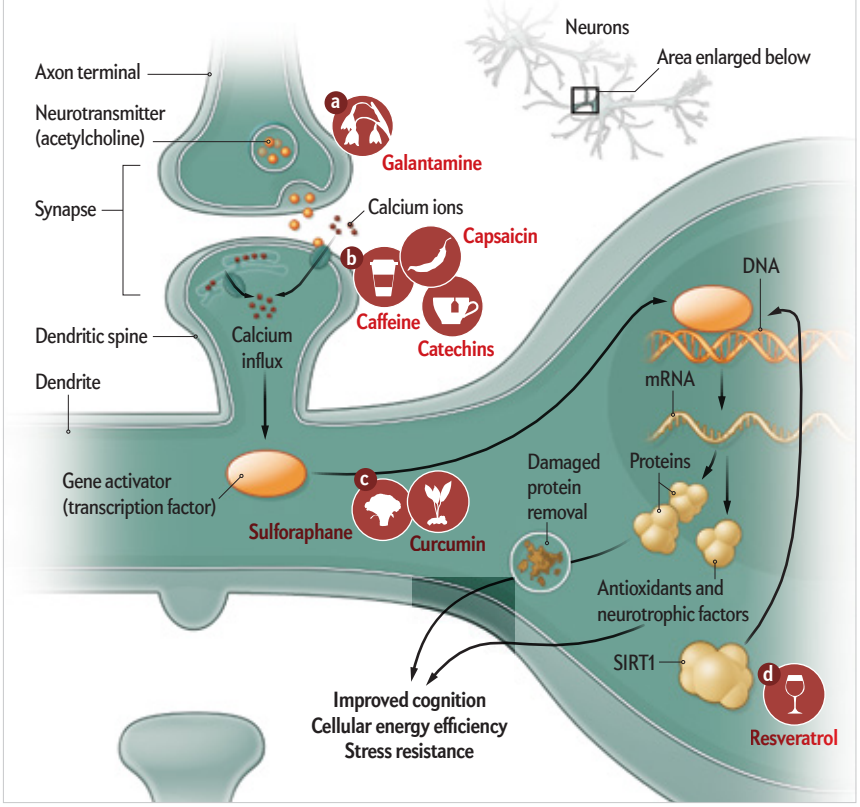


Graphic by Jen Christiansen

HOW PLANT CHEMICALS HELP

Building Brain Resilience

Investigators have traced the ways that various hormetic chemicals in plants act on signaling pathways to enhance the functioning of neurons. Galantamine, extracted from snowdrops, increases levels of acetylcholine (*a*), which is deficient in Alzheimer's disease. Once released from the tip of one neuron, acetylcholine stimulates another neuron by binding to a receptive site known as a dendritic spine. Caffeine, capsaicin from hot peppers and catechins from tea (*b*) act on channels in the cell membrane to allow entry of calcium ions that turn on the cell's protein-making machinery (DNA and RNA). Inside the cell, sulforaphane from broccoli, curcumin from turmeric (*c*) and resveratrol from grapes (*d*) also trigger activity of genes or a gene-regulating protein (SIRT1). These chains of biochemical events produce antioxidants or neurotrophic factors and eliminate damaged proteins—all of which bolster stress resistance, regulate cellular energy efficiency and, most important, improve overall cognition.



to a treatment for Alzheimer's. When mice genetically engineered to develop the pathological signs of Alzheimer's consumed curcumin, they experienced less damage to brain cells from free radicals and a diminished buildup of beta-amyloid. At first, Cole thought curcumin worked by removing free radicals. Later experiments in my lab and by others showed, however, that curcumin actually causes a mild stress in brain cells. Stress triggers the production of antioxidant enzymes that tamp down both free radicals and the accumulation of toxic proteins. The health benefits of curcumin on the brain appear to be wide-ranging. Other animal studies with curcumin suggest that it may reduce damage from stroke and may even help alleviate depression and anxiety.

Still more ingredients in curry may be good for the three-pound organ inside our skull. Garlic and hot peppers both contain chemicals that open a channel in the outer membrane of neurons to let calcium ions enter. The opening of these channels causes higher than normal levels of electrical activity in neurons, a stress that in animal models seems to protect the cells from the hyperactivity that occurs during a stroke. People living in countries where garlic or hot peppers are widely consumed tend to maintain excellent brain function as they age, although it still remains to be seen whether these plant chemicals or other aspects of their diet and way of life are responsible.

Hormesis seems to be at work in all these studies—and this insight creates an increasingly complex picture of the interaction of free radicals with antioxidants. Curcumin does not function to directly neutralize free radicals. Instead it calls in enzymes and other reserve troops that protect against these molecules. This carefully synchronized process may explain why antioxidant supplements often prove ineffective or even harmful.

Dousing the body with supplements may inhibit the natural stress response throughout the body. In one 2009 study researchers at Friedrich Schiller University Jena in Germany and their colleagues showed that after a month of exercising and taking antioxidant supplements, a group of men had no improvement in regulation of blood glucose and other health indicators, whereas men who only exercised did benefit. The implication is that antioxidant supplements may actually negate the health effects of exercise by impeding hormesis.

The biochemical pathways that bolster the body's resistance to plant chemicals are becoming clearer. One of them involves two proteins, called Nrf2 and Keap1, that are normally bound together in the cytoplasm, the area outside the cell nucleus. When exposed to plant chemicals such as curcumin or the sulforaphane in broccoli, Keap1 releases Nrf2, which then moves into the cell nucleus. There it activates genes that encode antioxidant enzymes that eliminate free radicals. Sulforaphane stimulates the Nrf2 pathway to rid the body of an overabundance of free radicals. In a petri dish, it can protect cells in the eye from the ultraviolet light damage that causes macular degeneration.

This connection between plant chemicals and the Nrf2 pathway has also motivated my own work. About seven years ago I happened across a book entitled *Insect Antifeedants,* by Opender Koul, an Indian scientist and expert on natural pesticides produced by plants. Koul catalogued more than 800 chemicals that have been isolated from plants and shown to prevent insects from feeding on them. My lab obtained about 50 such insect antifeedant chemicals and tested their ability to activate one or

SCIENTIFIC AMERICAN ONLINE Watch Mattson talk about fasting and brain health at ScientificAmerican.com/jul2015/mattson

Illustration by Tami Tolpa

more stress adaptation signaling pathways in cultured neural cells. Several of the chemicals activated the Nrf2 pathway and exhibited the classic biphasic response curve characteristic of hormesis. Particularly effective was a chemical called plumbagin, which is present in a type of tropical flowering plant and in black walnuts. We found that plumbagin was very effective in reducing brain damage and improving the prognosis for recovery in mice that model stroke. The next step we and others are contemplating is to test neuroprotective chemicals such as sulforaphane and plumbagin in human patients.

Another key cellular defense involves a family of proteins called sirtuins. Leonard Guarente of the Massachusetts Institute of Technology found that one of the sirtuins, SIRT1, can increase the life span of yeast cells and plays a key role in the extension of life span by caloric restriction. Resveratrol, found in red grapes and wine, appears to activate SIRT1, which then switches on multiple chemical pathways that mediate hormetic effects. In animal studies, resveratrol guarded the brain and spinal cord against damaging effects from the cutting off of blood flow that occurs in some types of stroke. Not all of the research is uniformly positive. Scientists still need to determine whether one of the pathways activated by resveratrol may actually speed the death of some neurons.

These studies have been complemented by other research showing that timing of the stress response in a cell is critical to whether the cell benefits from it. Just as vigorous exercise—another source of hormetic effects—needs to be interspersed with periods of rest for growth and repair of cells, so apparently does consumption of plant chemicals. When consuming fruits and vegetables, the body enters a so-called stress-resistance mode, characterized by an overall reduction in the making of new proteins, an increase in the removal of damaged molecules and the production of proteins specifically needed for cell survival.

Cells can endure in this state for only so long before they need to make new proteins for other purposes, become overstressed and begin to deteriorate. When the stress is removed, protein synthesis increases, and the cells grow and repair molecular damage that may have occurred. In the case of neurons, new connections among cells can form during the recovery period. Findings suggest consumption of fruits and vegetables or adopting an exercise regimen—followed by a period of rest—can stimulate the production of new neurons from stem cells located in a structure deep within the brain called the hippocampus. The new neurons then grow and form connections with existing neurons, effectively increasing learning and memory capacity. In practice, a normal period of sleep at night may be sufficient for cells to recover from exercise or exposure to plant chemicals consumed during the day.

DRUG LEAD FROM UWHANGCHUNGSIMWON

HORMESIS MAY OPEN THE WAY to look for new drugs—and may explain the mechanism of some already approved drugs. Snowflake and snowdrop flowers produce galantamine, a chemical that can improve memory by increasing levels of acetylcholine, a brain-signaling molecule in synapses, the connecting points between neurons. Galantamine, now a prescribed drug that has a modest beneficial effect on Alzheimer's symptoms, creates a mild stress in neurons that appears to protect them against neurodegeneration while improving their ability to use chemical and electrical signals to communicate with other neurons.

New leads for hormetic drugs may come from delving into the lore of herbal medicine. A substance known as uwhangchungsimwon, used in the traditional Korean pharmacopoeia to treat stroke, may protect neurons by inducing a stress response that results in the making of proteins, such as Bcl-xl, that prevent cells from dying. Chemicals from hallucinogenic plants may offer leads as well; when administered in moderate doses in a controlled clinical setting, they have shown promise for treating anxiety, depression and drug addiction.

The concept of hormesis has not escaped its share of controversy. Some researchers question whether scientists have developed adequate methods for distinguishing when a beneficial effect ends and a toxic one begins. The exact threshold for when a toxic reaction starts may vary by individual, making it difficult to use hormesis as a basis for drug therapies. Skepticism arises, too, when the basic concept is extended to ionizing radiation, such as x-rays, for which low doses have been shown to have beneficial effects on healthy lab animals. Various scientific advisory bodies, however, have rejected radiation as unsafe for humans even at the lowest levels.

Evaluating the potential health benefits of hormesis will require careful randomized clinical trials because many herbs are marketed with unsubstantiated claims about their efficacy. The National Center for Complementary and Integrative Health was established in 1998 in part to help fund studies of such compounds.

These challenges should not preclude continuing research on hormesis. Plant chemicals that induce a cellular stress may have advantages over traditional pharmaceuticals, which cause side effects by disrupting the normal functioning of nerve cells. Diazepam (Valium) acts on brain cells in ways that reduce anxiety but also cause drowsiness. The drug switches off a neural circuit, and that circuit stays off until the effects of the drug wear off. At the proper dose, drugs that rely on hormesis would not adversely affect circuit activity and so would be expected to have fewer side effects.

Some labs, including my own, are pursuing development of hormetic drugs and have generated encouraging results in animals genetically engineered to mimic several neurodegenerative diseases in humans. Early research shows that these drugs protect nerve cells from dying and that the cells become better able to resist an onslaught of free radicals and molecular damage that wreak havoc in the brain. Perhaps apple skins, walnuts and curry powder will become the raw materials for a radically new generation of treatments for brain disease. SA

MORE TO EXPLORE

Recruiting Adaptive Cellular Stress Responses for Successful Brain Ageing. Alexis M. Stranahan and Mark P. Mattson in *Nature Reviews Neuroscience*, Vol. 13, pages 209–216; March 2012.

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FROM OUR ARCHIVES

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BIOLOGY

Life at Hell's Gate

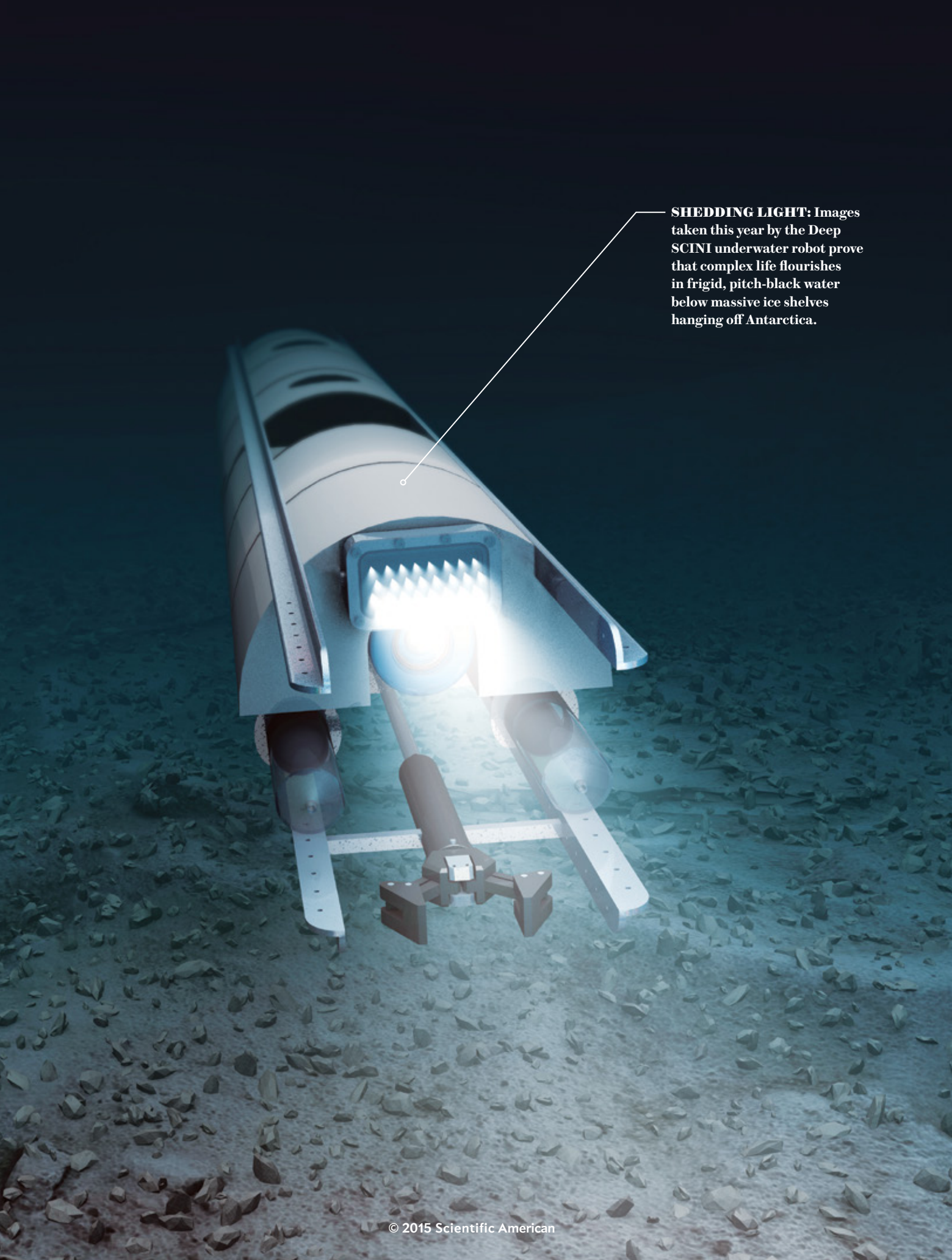
An astonishing discovery is forcing scientists to reconsider whether life can exist in the most extreme places on Earth and in space

By Douglas Fox

IN BRIEF

In January glaciologists drilled down through 740 meters of ice where the Antarctic continent meets the sea. A robot sent down the hole discovered fish and other animals living in just 10 meters of seawater, 850 kilometers from the open ocean and sunlight. Conventional wisdom held that this remote spot would be almost lifeless. **Fish eat** tiny amphipods that in turn eat microbes. Microbes at this isolated place may be fed by debris falling from the underside of the ice as it slides into the water. Without sunlight and photosynthesis, the microbes obtain energy from that debris in unusual ways. **The discovery** opens the possibility of life in places on Earth thought to be uninhabitable and on planets and moons such as Europa.

Illustration by Bryan Christie



SHEDDING LIGHT: Images taken this year by the Deep SCINI underwater robot prove that complex life flourishes in frigid, pitch-black water below massive ice shelves hanging off Antarctica.

The coast of the West Antarctic

landmass is one of the most desolate places on the planet. For 1,000 kilometers, it is buried under the West Antarctic Ice Sheet, a series of interconnected glaciers the size of western Europe that slowly slides off the continent into the sea. As the ice crosses the end of the buried land, it becomes a flat shelf hundreds of meters thick that extends hundreds of kilometers farther out to sea, floating on the water. The shelf is the size of Spain, so vast that it could take three to 10 years for an ocean current far below to carry a speck of plankton from the open sea, where sunlight and food are abundant, to the forbidding darkness way back at the submerged shoreline.

Douglas Fox is a science journalist whose work has also appeared in *Discover, Esquire, National Geographic* and *Nature*. Research for his stories has taken him to Antarctica four times since 2007.

COLD START: Researchers camping on the Ross Ice Shelf in January drilled through 740 meters of ice to see what existed at the grounding zone far below.

RACHEL MURRAY

Ocean life was the last thing Robert Zook and a dozen or so scientists expected to see this past January when they undertook a glaciological mission to the grounding zone, where the ice sheet transitions to the Ross Ice Shelf. They had traveled to this remote place to figure out how the underbelly of the slowly creeping West Antarctic Ice Sheet was responding to climate change. They brought several biologists who studied rudimentary microbes but no one who studied anything larger.

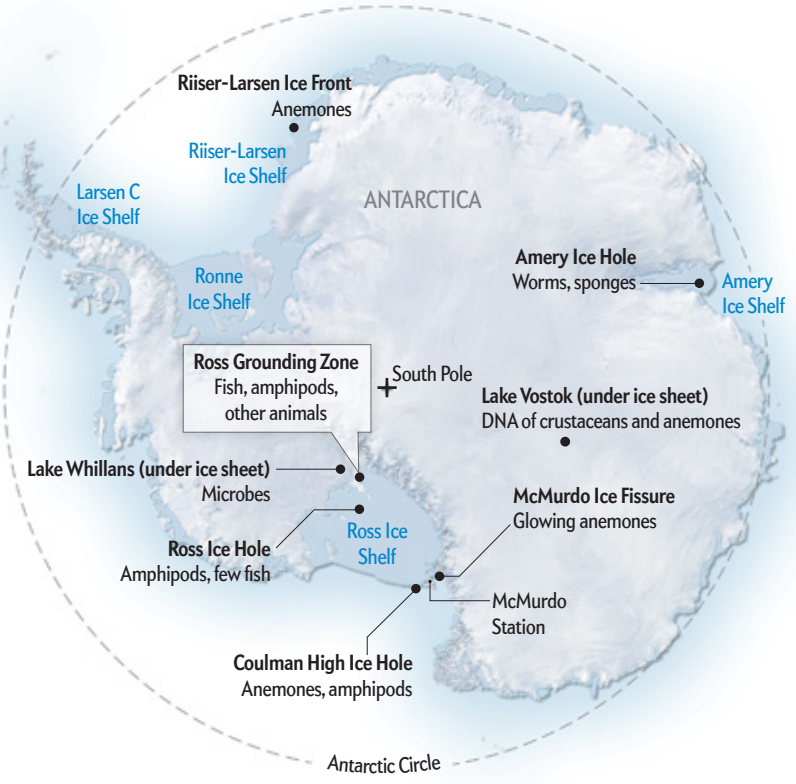
On January 16 the group crowded around video monitors in a darkened room on top of the ice—an improvised control center built inside a metal shipping container. For days tractors had dragged the cramped box, mounted on four giant skis, along with half a million kilograms of equipment and supplies, to this spot, 850 kilometers back from the shelf's front edge on the sea. They had used a hot-water drill to bore a hole slightly wider than a basketball hoop down through 740 meters of ice to reach a tiny wedge of water below, along the buried shoreline. They had then hung a robot, called Deep SCINI, on a cable and had begun to painstakingly lower it down the borehole, as a tether unfurled to keep it electronically connected to the control room.

Zook had scrambled to quickly design and build Deep SCINI to withstand the severe cold and high pressure of the depths. But he had only had time to test the remotely operated vehicle, or ROV, in a swimming pool. The crew watched nervously for 40 minutes as the narrow, two-meter-long robot descended deeper and deeper into the void. A light on the robot's nose reflected brightly off each white ripple in the icy walls of the shaft, giving the impression of a cosmic wormhole leading to another world.

The researchers in the crowded room collectively exhaled as the walls of the hole suddenly fell away into empty blackness. Deep SCINI had passed through the bottom of the ice and entered the 10-meter sliver of saltwater below. A barren seafloor rose into view, rocky and lifeless—a dark, frigid seabed humans had never seen. Water samples the crew had hoisted up the hole a few days earlier were crystal clear, lacking any obvious sign of life. Ross Powell, a glacial geologist at Northern Illinois Universi-

Surprise: Life under the Ice

This past January researchers were flabbergasted to find numerous fish and amphipods (tiny, shelled animals) living at the Ross Ice Shelf grounding zone, 850 kilometers back from the open sea and under 740 meters of ice above. Other creatures (*noted below*) had been found in the past under the front edges of ice shelves, much closer to sunlit waters, often hanging from the underside of the ice in an upside-down world.



Map by XNR Productions

ty who co-led the expedition, described the grounding zone as "pretty inhospitable" when we spoke by satellite phone after the samples had been retrieved.

The robot's pilot, Justin Burnett, slid his fingers across a touch pad to guide Deep SCINI up to the underside of the floating shelf. The ROV's lights exposed a dark, bumpy roof of ice embedded with silt. Here and there a mote of sand dislodged from the ceiling—glinting in the light as it streamed down, like a falling star. Sometimes one of these falling stars acted strangely—it appeared to dart sideways. No one could be sure, but it seemed in the video as if something had *moved*.

Burnett began to nose Deep SCINI back toward the seafloor when suddenly the video froze. The robot had shut down to avoid becoming overheated—ironic in this water, which at –2 degrees Celsius was kept liquid only by salinity and extreme pressure from the ice above. Zook called on the radio to the winch operator outside and asked him to lower the robot to the bottom while the researchers rebooted it.

When the video cameras came back on, someone inside the cold shipping container yelled, "Look, look, look. Holy sh—t!" All eyes swung left, to the monitor for the downward-looking camera. A graceful shape glided across the screen—tapered front to back like an exclamation point, its translucent body bluish, brownish, pinkish. It was a fish, as long as a butter knife. The room erupted in gasps. This team, here to investigate glaciers, had just found complex life in one of the supposedly most uninhabitable places on Earth.

The ROV stayed down six hours that day, encountering three different types of fish—20 or 30 in all. Shrimplike amphipods flitted about. The crew saw a maroon-colored jellyfish and an iridescent body swimming overhead that might have been a comb jelly. "You got a sense that they were a community living there," Powell told me shortly afterward. "It wasn't just a chance event." The barren depths, it turned out, held plenty of life.

The entire scope of the mission changed in an instant: the imperative now was to capture some of the animals, if possible, so researchers could later analyze them. Over the next several days Zook fashioned a makeshift trap on Deep SCINI with a piece of window screen and baited it with fish meat. When the robot was again lowered to the seafloor, its camera watched for four hours as dozens of amphipods crawled about the trap, like flies on a trash can. When the winch operators hoisted it back up, the trap contained more than 50 amphipods. The crew froze the tiny crustaceans and flew them back to McMurdo Station, the main U.S. logistics hub in Antarctica, as Zook and the scientists prepared to depart.

Discovering complex life in such abundance came as a complete shock. The findings are still reverberating through the scientific community, upsetting long-held assumptions about life on our planet and the potential for finding life on other worlds.

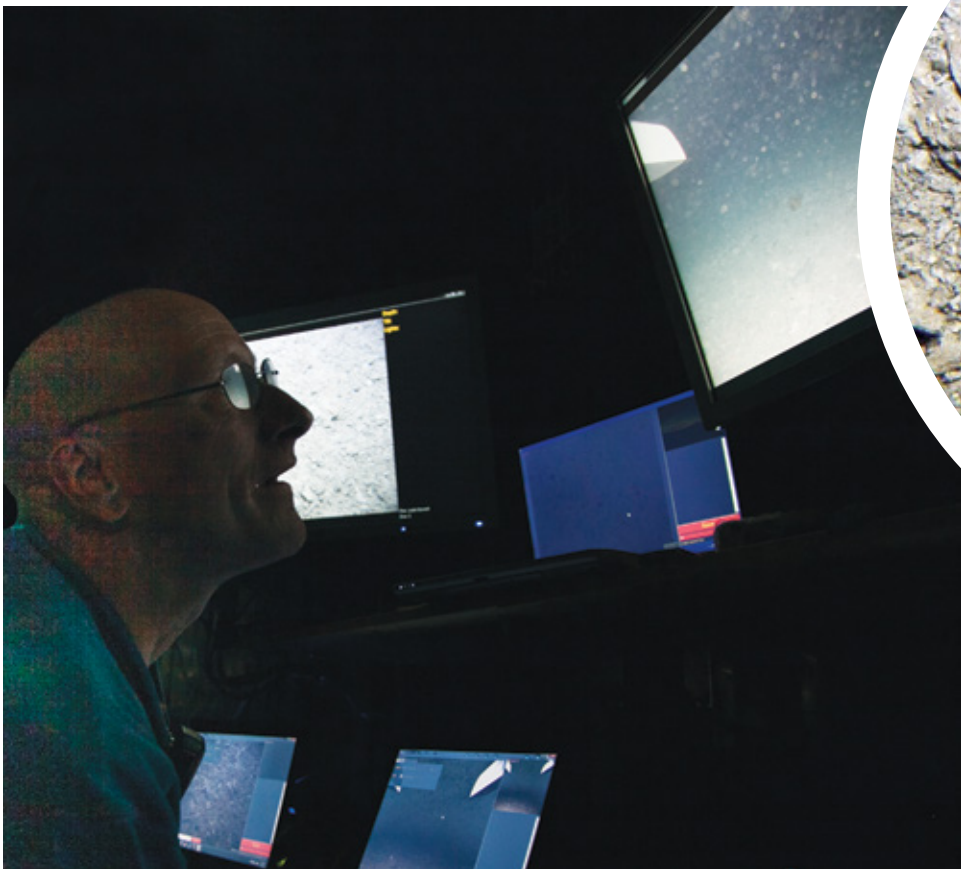
Evidence of life under Antarctica's ice has come slowly. The climate is forbidding, and expeditions are expensive, especially if they require drilling through hundreds of meters of ice. For these reasons, what little information scientists have gathered has come from the front edges of ice shelves near open water.

In the 1960s glaciologists stumbled on a colony of seals that had somehow survived despite being permanently stranded on the McMurdo Ice Shelf, 25 kilometers in from the shelf's edge—too far in for them to shimmy back to the sea. The seals congregated near a deep crack where the ice shelf buckled. They dived into the crack to hunt for food in the seawater below. The biologists wondered what the seals could possibly be eating in the dark, desolate waters—especially because they appeared to be even fatter than seals living on the open ocean—but the scientists had no way to find answers.

A clue came by chance in 1975, when low clouds forced John

Oliver's helicopter to land by a nearby crack in the ice. Oliver, then an oceanographer at the Scripps Institution of Oceanography in La Jolla, Calif., and his partner decided to dive into the crack. They descended an underwater ice wall, and 40 meters down they saw something alien: hundreds of green-glowing anemones rooted in the ice. They returned a year later to harvest some anemones but found the water swirling with ice crystals, forcing them to abandon the planned dive without collecting or even photographing the animals. All that came of their finding was a single sentence buried deep in a scientific paper on glaciers.

In 2003 Yuuki Watanabe, a biologist then at the University of Tokyo, was camped on the thin, seasonal sea ice near the Riiser-Larsen Ice Shelf 3,000 kilometers away. The ice, which forms on water off the front edge of ice shelves in winter, allowed him to stay in a hut and study the feeding habits of seals. Instruments he had attached to the animals revealed that they frequently dove 150 meters into the water; he assumed fish were congregating there. But when he attached a camera to one seal, the photographs revealed tentacle-waving animals hanging upside down from the underside of the shelf—a big surprise. Watanabe reasoned that the seals were diving under the lip of the shelf to eat whatever hung there.



FISH! Bob Zook (*left*) peers at live video sent by his robot, submerged in a pocket of water at the grounding zone. Expecting no visible life, he was shocked to find three species of fish, some of them translucent and the size of a butter knife (*right*).

RACHEL MURRAY

Few people were even aware of the glimpses Oliver and Watanabe had gained when Zook was hired in 2010 to bring an ROV to help engineers test a hot-water drill on the Ross Ice Shelf at Coulman High, a site 10 kilometers back from the shelf's front edge, where the ice was 250 meters thick. The team melted a hole through the ice, and Zook sent his robot down. As he drove it along the underside of the ice, something strange came into view on the video monitor: tentacles—phantom and ghostlike—the arms of thousands of sea anemones, which normally live rooted on the seafloor. Here they hung upside down, their stalks burrowed into the ice. Worms inhabited other ice burrows. Shrimpy amphipods and krill flitted through the water. And fish meandered about; one of them swam upside down, its belly skimming the icy ceiling. The accidental sighting was "so out of context," Zook said. "There was zero expectation that this would happen."

Marymegan Daly, an anemone specialist at Ohio State University, was stunned when she saw the first photographs. "It blew my mind. They looked like bats hanging off a cave ceiling," she says. "It never occurred to me that anemones would be living there."

No one had imagined an upside-down ecosystem on the underside of an ice shelf. But scientists could at least rationalize its existence through conventional wisdom at the time. Complex life under the front of the ice could be fed by ocean water wafting in from the sunlit sea nearby, biologists reasoned. But life would quickly dwindle farther back under the shelf—more distant from sunlight. Smaller and smaller organisms would eat the disappearing bits of food until none remained, marking the beginning of an enormous region inhabited only by microbes, reaching hundreds of kilometers back under the country-sized ice shelves toward land and ending at the grounding zone.

The isolation from sunlight and photosynthesis at the grounding zone is profound. The most barren stretches of ocean bottom that humans had previously found are dark, abyssal seafloors, out in the middle of vast oceans under 6,000 meters of water. Life at these depths depends on bits of dead plankton filtering down from the sunlit waters far above. At the grounding zone, there is no sea surface above. Stacy Kim, an Antarctic benthic ecologist at Moss Landing Marine Laboratories in California, had expected the zone to be many times more isolated than the abyss.

In 2013 the ANDRILL Science Office at the University of Nebraska–Lincoln, which funded the 2010 trip, hired Zook to build a more advanced ROV—the one that became Deep SCINI. He built its camera windows, made of sapphire, and its body, made of millions of tiny, hollow glass spheres, to withstand water pressures down to 1,000 meters so it could explore under thicker, more remote parts of the ice shelf. Zook was then invited to bring Deep SCINI on the expedition led by Powell—an unparalleled effort to drill into the grounding zone.

The 53-year-old Zook hardly fits the profile of a scientific ex-

COURTESY OF WHILLANS ICE STREAM SUBGLACIAL ACCESS RESEARCH DRILLING (WISSARD) PROJECT

plorer. He never graduated high school. He spent a few years designing early wireless phone systems before taking a job in 1997 maintaining radio repeater towers and air-navigation beacons at McMurdo Station. Zook and Burnett, a robotics graduate student at the university, rushed for six months to finish Deep SCINI, pulling 15-hour days in a sweaty brick hanger in Lincoln. Deep SCINI had been funded only as a prototype, not for real exploration. When they arrived at the drill camp on January 2, 2015, the robot still lacked a navigation system and a system to manage power consumption, making it prone to overheating.

After Deep SCINI was hoisted out of the hole following the fish discovery, the team lowered a package of oceanographic instruments belonging to Powell and parked it on the sea bottom for 20 hours. There it measured ocean currents and salinity—data that might give clues to how quickly the ice was melting. And it tracked the levels of oxygen and other chemicals in the water—suddenly crucial, given the discovery. All the while, fish and amphipods visited the package's camera.

People at the camp wracked their brains during late dinners, trying to make sense of the animals. "We have to ask what they're eating," said Brent Christner, a microbiologist at Louisiana State University who has studied Antarctic microbes for 15 years. Sunlight was way too far away, and any water from the shelf's front edge that did drift back here would have been picked clean of food during years of slow migration.

The mystery was heightened by the extravagant energy needs of animals compared with microbes. Fish require a multilevel food pyramid. At the bottom, microbes use energy from sunlight or chemicals to pluck molecules of carbon dioxide out of the water and grow. Amphipods eat the microbes and recycle their carbon. Fish, at the top, eat the amphipods. This transfer of carbon, or energy, up the food pyramid is inefficient, said John Priscu, a microbial ecologist at Montana State University who co-led this year's expedition. About 100 kilograms of microbes are needed to support one kilogram of fish.

Mystery also surrounds the million square kilometers of land hidden under the West Antarctic Ice Sheet. Glaciologists have drilled a few holes through the ice into the mud below. It is rich in the microscopic shells of diatoms that lived 20 million to five million years ago—evidence that a shallow sea covered the area in warmer times. Remote seismic mapping shows ancient sediment layers hundreds of meters thick, containing billions of tons of decomposing marine organisms that died and settled to the bottom.

In early 2013 the same team of scientists who in January drilled to the grounding zone drilled through the ice sheet 100 kilometers inland, hitting a subglacial reservoir called Lake Whillans. (I was with them for that expedition.) Organic carbon from the ancient marine layers made up 0.3 percent of the lake's mud—a striking amount similar to that in the soil that nourishes desert grassland across the U.S. The team discovered microbes in the lake, too. Without sunlight and photosynthesis, the microbes obtained energy by using oxygen in the lake to "burn" chemicals such as ammonium and methane seeping up from the decomposing layers below.

Could it be that the fish at the grounding zone were being fed by a similar source?

As Deep SCINI went down the hole, the glassy ice walls briefly turned opaque and brown just before the robot emerged into the water cavity. The bottom 20 meters of ice was cluttered with the same kind of carbon-rich debris seen in Lake Whillans—material that froze onto the underside of the glacier as it dragged across land thousands of years ago.

Bits of that sediment dropped from the ice ceiling as Deep SCINI explored the ocean cavity—those glinting specks of dirt that descended like falling stars. About a millimeter of the ice's underside melts every day, releasing the nutrient-rich crumbs. Priscu noticed that amphipods swarmed greedily about the clouds of debris that billowed from the bottom of the hole after the walls there were disturbed by the robot. He wondered if the ice that cut this place off from sunlight might also feed it by supplying organic detritus that sustains microbes at the bottom of the food pyramid. The fish "are getting their food from above," he said. "I am almost 100 percent sure."

In Priscu's mind, glaciers flowing from land to sea over the grounding zone provide a slow conveyor belt of debris-rich ice that begins to melt as it contacts seawater, sprinkling out its detritus. The dirty ice melts quickly enough that it drops its entire load by the time it moves 40 kilometers out over the sea. This local rain of sediment "can help fertilize the seawater, which helps to create [a] habitable zone" at the very back of the ice shelf, said Slawek Tulaczyk, a glaciologist at the University of California, Santa Cruz, who co-led this year's expedition with Powell and Priscu.

These isolated habitats could be widespread. More than 20,000 kilometers of grounding zones, hidden under floating ice, encircle Antarctica's coast. Imagine looking down on Antarctica from space and peering through the ice to find a ring of fish and other animals 40 kilometers wide around the entire coastline—a vast, thriving ecosystem, not a lifeless hell.

The vast stretches of dark ocean under the ice between this oasis and the open water may also contain at least some animals. In 1977 a single hole was drilled through the Ross Ice Shelf, 475 kilometers back from the open sea, into a water column that was 240 meters deep. A camera lowered through the hole shot several hundred photographs of the seafloor, and two appeared to show fish. Amphipods were also seen. "People

didn't pay a lot of attention," Kim says. But that old observation seems more noteworthy now that fish have been found in the far more isolated environment of the grounding zone.

This vision of life spread under ice shelves becomes even more enthralling. Recent images taken by ice-penetrating radar from planes, which can map the three-dimensional structure of the ice sheets, show that water melted from the ice, which is lighter than the seawater because it has less salt, flows out from the grounding zone along the underside of the shelf in well-defined plumes for hundreds of kilometers. "You're talking about an upside-down river," says David Holland, an oceanographer at New York University. The inverted rivers melt channels into the ice that can be 500 to 3,000 meters wide and 200 meters up into the ice itself. If the rivers carry debris that has melted free from the ice, they may feed organisms along those channels.

UPSIDE-DOWN WORLD: Surprising creatures had also been found under the front edge of the Ross Ice Shelf (*top*) in 2010. Instead of being rooted in the seafloor, anemones (*right*) were rooted in the underside of the ice, growing downward; other animals flitted about, including an unknown creature nicknamed "egg roll" (*left*).

The sense of intrigue about how remote life can be on Earth has only deepened as biologists examine the photographs and specimens that Zook caught, as well as the upside-down anemones collected in 2010 at Coulman High (the data were released only in 2013 after a long delay). A striking realization is emerging: these species, living in places so extreme, are surprisingly unremarkable. "The habitat is so bizarre," Daly says. "But the animals are really vanilla."

The anemones, for example, belong to a well-known family that lives worldwide. "There's nothing unexpected about them, anatomically," Daly says—no novel gland or other organ to explain how they burrow into the ice while avoiding freezing. They might survive by concentrating salt around their bodies, which can act as antifreeze. Daly did notice one adaptation: their eggs are extremely fatty, so they float to the ice ceiling above rather than sinking to the seafloor below.

The red, shrimpy amphipods discovered in January appear to belong to a well-known group that inhabits the world's deep ocean floors—"voracious scavengers," according to Kathleen Conlan, a marine biologist at the Canadian Museum of Nature in Ottawa. In Antarctica, she says, "if there's an organic source coming from that debris [in the ice above] and stimulating the growth of microbes, then the amphipods could be picking that off."

The blue-brown-pink fish were also recognized in photographs. Arthur DeVries, an ichthyologist at the University of Illinois at Urbana-Champaign who has studied Antarctic fish for almost 50 years, identified them as Antarctic silverfish, one of the most abundant species around the continent's coastal waters. Ironically, the fish are vulnerable to death by freezing.

Finding such humdrum creatures in strange places suggests a profound truth: that Earth's most remote, unexplored environments may not be as extreme as we thought. "We always think we've got a good handle on this planet," observes Britney Schmidt, a planetary scientist at the Georgia Institute of Technology. The January discovery "tells us how naive we are," she says. "For me, that's where the real lesson is."

Indeed, complex life might exist in all kinds of places we have dismissed as uninhabitable. We often define habitability in terms of liquid water, both on Earth and on other planets and moons. Schmidt sees it differently: "I'm looking for geologic sources of energy," where plate tectonics or sliding glaciers, for example, can bring long-buried carbon back up to where it can be eaten once again. "These cycles can feed life," she says.

Other recent discoveries bolster this way of thinking. Swarms of worms were found on the Gulf of Mexico seafloor, in upwelling patches of methane ice—an exotic, solid form of natural gas that develops at high pressure. Despite inhabiting such a weird place, the worms eat a typical diet: bacteria, which in turn consume the methane ice. Different worms have been found in water gurgling through bedrock fractures three kilometers below Earth's surface, feeding on microbes that eat minerals in the bedrock. Some deep-living microbes are even nuclear-powered, in a sense, consuming hydrogen that is produced by the decay of uranium and other radioactive elements.

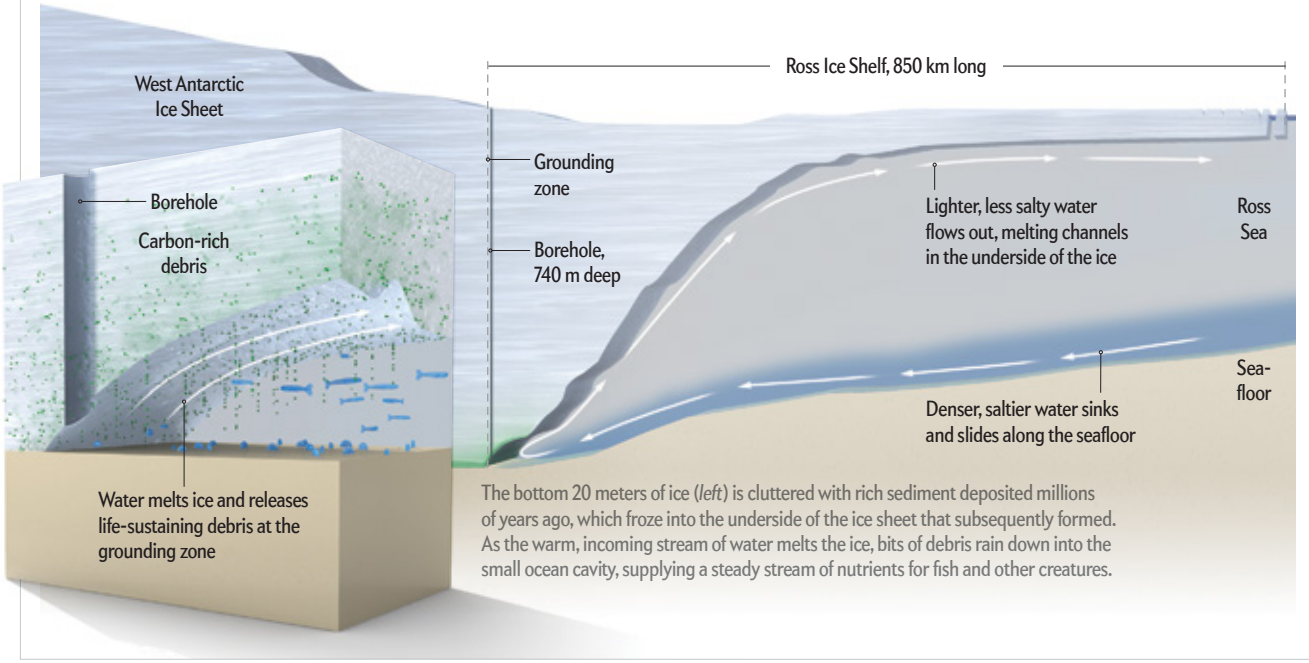
Then there is subglacial Lake Vostok, located in East Antarctica, 1,500 kilometers inland from the January drill site. Vostok sits under 3,700 meters of ice, cut off from air and sunlight for 15 million years. In the 1990s Russian scientists drilled down

BEN CRANKE *Getty Images (ice shelf)*; COURTESY OF ANDRILL SCIENCE MANAGEMENT OFFICE, UNIVERSITY OF NEBRASKA–LINCOLN (*egg roll and sea anemones*)

SCIENTIFIC AMERICAN ONLINE For more on the landmark discovery at the Ross Ice Shelf grounding zone, see ScientificAmerican.com/jul2015/fox

Fish Feed on Million-Year-Old Debris

The massive West Antarctic Ice Sheet (*left*) slowly oozes off land to the sea, where it becomes a floating ice shelf (*right*). The transition point is called the grounding zone. Dense saltwater slides back to the grounding zone, where it melts the ice, creating a small cavity of water that stays liquid at –2 degrees Celsius because of enormous pressure from 740 meters of ice above. Scientists assumed the pitch-black cavity would be virtually lifeless because it is 850 kilometers from sunlight, needed by microorganisms to sustain a food web. But in January researchers found fish and other complex life there, which seemed to feed on sediment falling from the ice (*inset, bottom left*).



The bottom 20 meters of ice (*left*) is cluttered with rich sediment deposited millions of years ago, which froze into the underside of the ice sheet that subsequently formed. As the warm, incoming stream of water melts the ice, bits of debris rain down into the small ocean cavity, supplying a steady stream of nutrients for fish and other creatures.

and, without puncturing the lake itself, retrieved ice that had frozen along the upper edge of the water in the lake. Well-respected polar biologists reacted with skepticism and ridicule in 2013, when Scott Rogers, a biologist at Bowling Green State University, analyzed the DNA trapped in this ice. He reported finding DNA evidence of aquatic animals that might inhabit the lake, including anemones and crustaceans.

"I think it's good to keep an open mind" about Rogers's analysis, Tulaczyk says. Despite being so deeply buried, Vostok probably contains substantial amounts of oxygen, injected into the lake as ancient air bubbles melt out of the ice above.

A similar process could exist on Europa—an ice-covered moon orbiting Jupiter, thought to harbor an internal ocean of liquid water underneath 10 to 20 kilometers of ice. Schmidt and others have found evidence of strong ocean currents inside Europa, powered by the gravitational tides and frictional heating from Jupiter. If those currents warm and melt the underside of the ice, that could fuel an ecosystem similar to the one found in subglacial Lake Whillans or at the grounding zone. The warm currents could drive a kind of plate tectonics, in which ice on Europa's surface is recycled to the interior ocean, bringing with it a steady flow of oxygen and other compounds.

The discovery of animals at the grounding zone poses plenty of questions. Powell will estimate the ocean currents and heat reaching this place, which will reveal the rate at which melting ice can sprinkle out new food. A string of instruments that Tulaczyk lowered into the ice hole as it froze shut will provide further information on currents by monitoring the changing tilt of the ice shelf that occurs with daily tides, beaming this information back weekly via satellite link. Priscu and Christner will dissect amphipods and DNA-fingerprint the contents of their guts to see what the animals eat. They will also analyze DNA from microbes in the water and mud to determine what energy source powers this food web—ammonium, sulfur or other chemicals.

Powell hopes to return to the grounding zone with a larger ROV that can explore farther under the ice, capture video and measure chemicals in the water. Zook hopes to harvest some live fish and other animals. But right now he feels lucky with how Deep SCINI performed. "The rule of thumb [in Antarctica] is that any new, major technological project doesn't work on its first year," he told me while packing up in January. Deep SCINI's success "was a minor miracle." SA

MORE TO EXPLORE

A Microbial Ecosystem Beneath the West Antarctic Ice Sheet. Brent C. Christner et al. in *Nature*, Vol. 512, pages 310–313; August 21, 2014.

Ongoing findings about life under the Antarctic ice can be found at the Whillans Ice Stream Subglacial Access Research Drilling program site: www.wissard.org

FROM OUR ARCHIVES

Witness to an Antarctic Meltdown. Douglas Fox; July 2012.

scientificamerican.com/magazine/sa

Illustration by Bryan Christie

GOLD ELECTRODES adorn a red perovskite solar cell, made by the Massachusetts Institute of Technology, that is the size of a postage stamp but much thinner.

ENERGY

outshining silicon

An upstart material—perovskite—could finally make solar cells that are cheaper and more efficient than the prevailing silicon technology

By Varun Sivaram, Samuel D. Stranks and Henry J. Snaith

Photographs by Plamen Petkov

Varun Sivaram is a fellow at the Council on Foreign Relations and researches energy, technology and national security.

Samuel D. Stranks is a fellow at the Massachusetts Institute of Technology and investigates the optical and electronic applications of perovskites.

Henry J. Snaith is a professor of physics at the University of Oxford and is chief scientific officer at Oxford Photovoltaics, which he co-founded.

SITTING IN A DIMLY LIT BAR IN JAPAN, THEN GRADUATE STUDENT MICHAEL LEE WAS scribbling on a beer coaster as night fell, jotting down a list of chemical ingredients before he forgot them. Earlier that day scientists at Toin University of Yokohama had generously shared their groundbreaking recipe for making solar cells from a new material called perovskite rather than the usual silicon. The cells were only 3.8 percent efficient in converting sunlight to electricity, so the world had not taken notice. But Lee was inspired. After the 2011 fact-finding mission, he returned to Clarendon Laboratory at the University of Oxford, where all three of us worked at the time, and made a series of tweaks to the recipe. The changes yielded the first perovskite cell to surpass 10 percent efficiency. His invention sparked the clean-energy equivalent of an oil rush, as researchers worldwide raced to push perovskite cells even higher.

The latest record, set at 20.1 percent by the Korea Research Institute of Chemical Technology in November 2014, marked a fivefold increase in efficiency in just three years. For comparison, after decades of development state-of-the-art silicon solar cells have plateaued at about 25 percent, a target that perovskite researchers like us have squarely in our sights. We are also anticipating a commercial debut, perhaps through a spin-off company such as Oxford Photovoltaics, which one of us (Snaith) co-founded.

Perovskites are tantalizing for several reasons. The ingredients are abundant, and researchers can combine them easily and inexpensively, at low temperature, into thin films that have a highly crystalline structure similar to that achieved in silicon wafers after costly, high-temperature processing. Rolls of perovskite film that are thin and flexible, instead of thick and rigid like silicon wafers, could one day be rapidly spooled from a special printer to make lightweight, bendable, and even colorful solar sheets and coatings.

Still, to challenge silicon's dominance, perovskite cells will have to overcome some significant hurdles. The prototypes today are only as large as a fingernail; researchers have to find ways to make them much bigger if the technology is to compete with silicon panels. They also have to greatly improve the safety and long-term stability of the cells—an uphill battle.

WINNING THE EFFICIENCY RACE

TODAY THE BEST SILICON CELLS are 25.6 percent efficient. Why can't solar cells convert 100 percent of the sun's light energy? And why should perovskites be able to surpass the silicon record?

The answers to these questions are found in the excitable and errant electron. When a solar cell is in the dark, electrons in the material stay bound to their respective atoms. No electricity flows. But when sunlight strikes a cell, it can liberate some of the electrons. Infused with energy, the "excited" electrons careen drunkenly through the crystal lattice of the cell until they either exit one end of the cell—whisked away by an electrode as useful current—or run into an obstacle or a trap, losing their energy in the form of waste heat.

The higher the crystal quality, the fewer defects there are to

IN BRIEF

Crystalline silicon has dominated the solar cell market for decades, but prototype cells made from a different crystalline material, perovskite, are rapidly approaching the same efficiency levels.

Perovskite could become cheaper than silicon because it can be made at much lower temperatures. The perovskite cells can be rolled out as flexible, colorful films, leading to a wider variety of products than silicon cells, which are rigid.

Big challenges remain, however. Techniques to reliably seal water out of perovskite are needed to prevent the cells from degrading in a matter of hours.

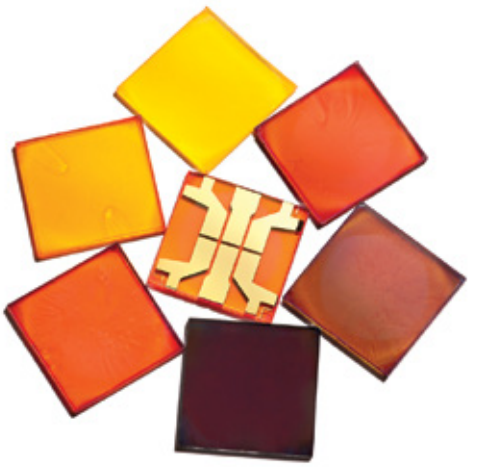
Lead, used in small quantities in each cell, must be permanently sealed in for safety. Cells must get much larger, too; right now the high-efficiency versions are only as big as a fingernail.

derail the electron's journey. Silicon cells are typically heated to as much as 900 degrees Celsius to remove defects. Perovskites are largely free of such defects even though they are processed at much lower temperatures, around 100 degrees C. As a result, electrons excited by light are just as successful in exiting perovskite cells, and they are unlikely to lose as much energy along the way when colliding with obstacles. Because the electrical power of a cell is the product of the flow of electrons exiting that cell (the current) and the energy that those electrons carry (the voltage), the efficiency of perovskites can rival silicon, with much less processing effort.

But there is a ceiling to how much of the sunlight's energy a solar cell made of semiconductors such as silicon and perovskites can convert into electrical power. That is primarily because of a property of semiconductors called the bandgap—a minimum level of energy needed to liberate electrons. Sunlight includes all wavelengths of light, but only certain wavelengths exceed the energy bandgap. Other wavelengths will simply pass through the material, doing nothing.

The bandgap is different for different semiconductors, and it sets up a fundamental trade-off: the lower the bandgap, the more of the sun's spectrum a cell can absorb to excite electrons, but the lower the energy each electron will have. Because electrical power depends on both the number and energy of electrons, even a cell with the ideal bandgap can convert only around 33 percent of the sun's energy.

Silicon has a fixed bandgap that is not ideal, but it commands the solar industry because effective ways to manufacture the technology are well understood. When making perovskites, however, researchers can adjust the bandgap at will by tweaking the mix of ingredients, which raises the prospect of exceeding silicon efficiencies. Researchers can also layer different perovskites with different bandgaps on top of one another. Double-decker perovskites should be able to break through the nominal 33 percent ceiling; some projections indicate they could put 46 percent of the sun's energy to work.



PEROVSKITE FILMS can be many colors and could be applied to windows or walls, creating a tint in addition to generating electricity.

TEACHING AN OLD MATERIAL NEW TRICKS

MINERALOGISTS HAVE KNOWN about the natural forms of perovskite in the earth's crust since the 19th century. The crystals graced a 1988 cover of this magazine when scientists thought they could form high-temperature superconductors (some work continues today). During the past two decades engineers also made experimental electronics with man-made perovskites, but they overlooked the material's potential use in solar cells.

Finally, in 2009, a group at Toin University turned a man-made version—a lead halide perovskite first synthesized in 1978—into a solar cell. The researchers dissolved selected chemicals in solution, then spun and dried that solution on a glass slide. The drying left behind a film of nanometer-scale perovskite crystals on top of the slide, much the way salt crystals emerge from evaporating tidal pools. This film generated electrons when it absorbed sunlight but not very well. The researchers added thin layers of material on either side of the perovskite nanocrystals to help them transfer the electrons to an external electrical circuit, supplying useful power.

The first tiny cells were only 3.8 percent efficient, and they were highly unstable, deteriorating within hours. Lee altered the perovskite's composition and replaced a problematic layer in the cell, pushing the efficiency beyond 10 percent. Another set of investigators, led jointly by Michael Grätzel of the Swiss Federal Institute of Technology in Lausanne and Nam-Gyu Park of Sungkyunkwan University in Korea, made a similar advance.

The recent march to 20 percent has been driven by some clever innovations. Creating a defect-free crystalline film requires tricky deposition methods, so a group headed by Sang Il Seok of the Korea Research Institute of Chemical Technology devised a multistep process that forced a more orderly crystal film to drop out of the spinning solution. By optimizing processing, Seok marched through three consecutive record efficiencies in 2014, from 16.2 to 20.1 percent.

Other scientists simplified the layering of added materials; the newest perovskite cells look more like a silicon cell—a simple stack of flat layers. In silicon's case, this design has made low-cost mass production possible. Recently perovskite researchers have also heated up the solution and the glass slide on which it is deposited, resulting in crystals that are several orders of magnitude bigger than those in the initial cells, an encouraging sign that the crystallinity is still improving.

Scientists are devising some novel traits, too. Varying the chemical ratio can create cells that have a gentle shade of yellow or a blush of crimson. Depositing perovskite on glass in islands instead of one thin layer can create films that are opaque or transparent or degrees in between. Together these options—refreshing choices over rigid, opaque, blue-black silicon cells—could help architects design skylights, windows and building facades that incorporate colorful perovskite solar films. Imagine a skyscraper with perovskite-tinted windows that shade the interior from hot sunlight by converting it into electricity, reducing the cooling bill while also providing power.

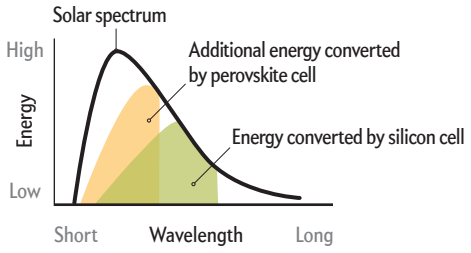
LONG ROAD TO COMMERCIALIZATION

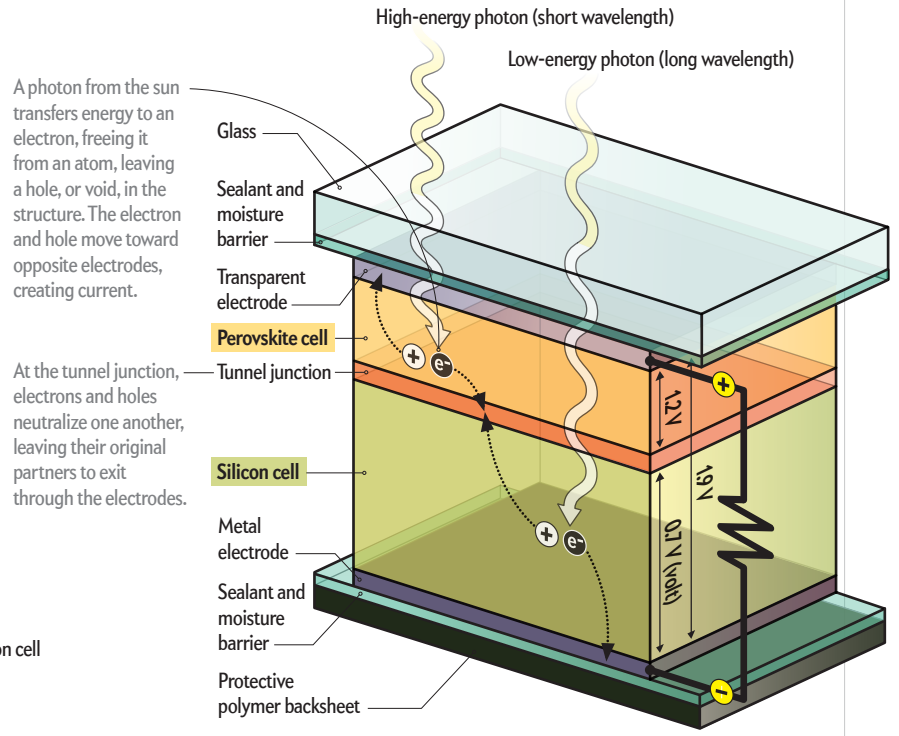
PEROVSKITES HAVE A LONG WAY TO GO before they fulfill such visions. Although Korean and Australian researchers recently demonstrated printable cells that are 10 by 10 centimeters—large enough for commercially competitive products—the most efficient cells are still small prototypes. As labs and start-up companies scale up the devices, they must accomplish three prerequisites for commercialization: ensure that the cells are stable enough to produce

PAGE 54 AND THIS PAGE: SAMPLES SUPPLIED BY MATTHEW T. KLUG *Belcher Group* AND ANNA OSHEROV *Bulović Group, Massachusetts Institute of Technology*

Two Are Better Than One

Rather than competing commercially, silicon and perovskite solar cells could operate together, converting sunlight into electricity with greater efficiency than the technologies achieve alone. In a tandem cell (*right*), a perovskite layer and silicon layer connect, generating electrons that have higher voltage and more energy than either material creates on its own. Perovskite and silicon also convert different wavelengths of sunlight (*below*), putting more of the spectrum to work.





electricity for decades, design a product that customers feel is safe to put in their homes and buildings, and satisfy critics who caution that the claims for perovskite efficiency levels are inflated.

The stability of the perovskite solar cell is arguably its Achilles' heel. Perovskites can degrade rapidly because they are sensitive to moisture, so they must be encased in a watertight seal. Cells fabricated by us in an inert atmosphere and encapsulated in epoxy have performed stably for more than 1,000 hours when exposed continuously to light. Researchers at the Huazhong University of Science and Technology in China, in collaboration with Grätzel, have also reached 1,000 hours even without encapsulation, and in recently published work they have deployed test panels outdoors in Saudi Arabia to show that their design will function in real-world conditions. At a recent Materials Research Society meeting in San Francisco, we disclosed results from Oxford Photovoltaics that demonstrate that perovskite cells can generate stable power output for more than 2,000 hours under full sunlight.

The industry convention for solar panels is a 25-year warranty, however. That equates to about 54,000 hours under constant, bright sunlight. Finding an effective moisture barrier that works for that long, over a wide temperature range, is crucial. Silicon manufacturers solved the problem by laminating the cells between glass sheets. This is perfect for large, ground-based installations. But because perovskite cells can be made as films that are much lighter and more flexible than cells on glass, alternative encapsulation strategies may open up broader applications, such as veneers for walls or windows that can generate electricity.

Fortunately, some progress has been made by companies trying to commercialize other flexible solar materials, such as the semiconductor made of copper indium gallium selenide. The encapsulation technologies work well, yet businesses have struggled to gain market share from silicon because the cells are less efficient and cost more. Perovskites, which should have higher efficiencies and lower processing costs, may be able to exploit the encapsulation advances.

Just as important as sealing *out* moisture is sealing *in* the cells' contents because of the tiny amount of lead added to the perovskite recipe. Lead is toxic, so the market will demand a high burden of proof that perovskite power is safe. For inspiration, researchers can again look to an alternative solar material, the only one besides silicon that has achieved significant commercial success: cadmium telluride.

Manufactured by First Solar, cadmium telluride panels have been deployed around the world and have exceeded safety standards despite the presence of an element far more toxic than lead: cadmium. First Solar has convinced communities that its panels are so well sealed that no cadmium could escape, even in a desert wildfire at 1,000 degrees C. The panels use a glass substrate, however, which precludes the flexibility and lower weight that perovskites promise. Yet perovskite companies can learn from First Solar's success in sealing and rigorously testing products.

An encouraging development related to lead recently emerged from the Massachusetts Institute of Technology as well: Angela Belcher and her colleagues demonstrated that lead-acid car batteries can be recycled safely, with the lead content recovered to make perovskite cells. This result could be an environmental plus. Belcher estimates that the lead in a single car battery could enable production of around 700 square meters of perovskite

SCIENTIFIC AMERICAN ONLINE For more on tandem solar cells, see ScientificAmerican.com/jul2015/sivaram

Illustration by Jen Christiansen

cells, which at 20 percent efficiency would be enough to power 30 houses in a warm but sunny climate such as that in Las Vegas.

A different route would be to eliminate the lead altogether. Both our group and another one at Northwestern University have published preliminary reports on cells that use tin instead of lead. The efficiency and stability are worse, however, because tin tends to cause the perovskite to lose its crystalline structure over time, hampering an electron's ability to get out of the cells. A major advance would be needed for tin to match lead's long-term performance.

In addition to the issues listed here, researchers have to solve a smaller, quirkier problem. Critics have claimed that the efficiency numbers for perovskite cells might be inflated because of hysteresis—a jitter in the measurement that is likely caused by charged molecules migrating from one side of a cell to the other, which could create the appearance of greater current. This ion migration is very brief, however. Scientists are looking for ways to halt it, but in the near term, there is a simple remedy: wait out the migration and measure efficiency over a longer period. In most cases, this process renders efficiency readings that are similar to quick, initial measurements, but researchers may be tempted to report the higher of the readings. We are working with investigators worldwide to standardize the measurement process so that our results meet a high standard of scrutiny.

Finally, to succeed commercially, perovskite innovators need to provide a compelling economic narrative to attract the investment dollars required for scaling up production. Although materials for perovskites are abundant and cells can be processed at low temperatures into films that roll off inexpensive equipment, perovskite solar companies should not fall into the trap of competing on silicon's terms. There is little room to undercut silicon panels because most of the cost of an installation is not related to the panels but to what is called the "balance of system," which includes installation materials and labor, permits and inspections, and other expenses related to system installation. An average U.S. residential solar installation in 2014 was priced at $3.48 per watt of electricity-generating capacity, yet the cost of the actual solar panel was only 72 cents per watt. Even if perovskite panels achieve the dirt-cheap 10 to 20 cents per watt that researchers think is possible, the improvement would reduce the final installed price by only a small percentage.

Perovskite companies can build on those small savings, though, by devising products that beat silicon's efficiencies. A highly efficient perovskite solar panel reduces the total installed cost per watt by requiring less land or roof space and therefore less labor and equipment. An even more imaginative example of changing the rules would be to sell perovskite products for applications that silicon cannot compete in, such as films that could be integrated right into building materials for walls, roofs and windows.

THE HYBRID SOLUTION

FOR NOW PEROVSKITES MIGHT HAVE the best chance to reach the market as an ally rather than a competitor of silicon. Perovskites could literally piggyback off silicon's success, gaining entry to a $50-billion market.

An alliance could happen by adding a perovskite layer right on top of a silicon layer, creating a "tandem" solar cell. Perovskites are good at harnessing the higher-energy colors of sunlight, such as blue and ultraviolet, which silicon fails to capture, generating a much higher voltage in electrons. Researchers at Stanford University and M.I.T. recently stacked a perovskite cell on top of a sealed silicon cell, raising efficiency from the silicon's original 11 to 17 percent. They also assembled a tandem cell by layering perovskite on top of unsealed silicon, creating a single structure. The combination achieved just 14 percent efficiency, but that figure could surely go up with manufacturing refinements. Based on the two experiments, the researchers sketched out a scenario by which a tandem cell made with a state-of-the-art silicon component and a state-of-the-art perovskite device, combined using clever engineering, could surpass 30 percent efficiency without any radical change in either technology.

If a tandem solar panel could reach 30 percent efficiency, the impact on the balance-of-system cost could be enormous: only two thirds of the number of panels would be needed to produce the same amount of power as panels that are 20 percent efficient, greatly reducing the amount of roof space or land, installation materials, labor and equipment. Oxford Photovoltaics, Snaith's spin-off company, is partnering with traditional silicon manufacturers to boost silicon's efficiency with a perovskite coating over the silicon cell; the company is targeting prototypes of the tandem cells this year. Down the line, cheap solar coatings integrated into roofing or glazing materials could transform the entire cost structure of a solar-powered building.

RUNNING IN REVERSE

THE QUICK RISE OF PEROVSKITE SOLAR CELLS has inspired scientists and engineers to fabricate other types of prototype products that also might one day make it to market. Working with our colleagues at the University of Cambridge, we recently created light-emitting diodes (LEDs) and lasers using metal halide perovskites, which efficiently emit light (instead of absorbing it) through a process called luminescence.

This turnabout is not really surprising; when run in reverse, the world's most efficient solar cell, gallium arsenide, acts as an LED. Cheap, printable LEDs and lasers could lead to intriguing applications, from large-scale lighting to medical imaging.

Research into these novel products is very early, of course, but we think the work will become more popular. Perovskites make scientists feel like children in a candy shop; we have found a material whose properties fill almost every checkoff box on our wish list, including high efficiency, low cost, light weight, flexibility and aesthetic appeal. It will take a concerted, global effort by academia, industry and government to fully realize the potential perovskites have to move beyond the silicon era. But given the prize—cheap, clean energy and the next generation of electronics—we think perovskites are a good bet. SA

MORE TO EXPLORE

The Emergence of Perovskite Solar Cells. Martin A. Green, Anita Ho-Baillie and Henry J. Snaith in *Nature Photonics,* Vol. 8, pages 506–514; July 2014.

Compositional Engineering of Perovskite Materials for High-Performance Solar Cells. Nam Joong Jeon et al. in *Nature,* Vol. 517, pages 476–480; January 22, 2015.

Metal-Halide Perovskites for Photovoltaic and Light-Emitting Devices. Samuel D. Stranks and Henry J. Snaith in *Nature Nanotechnology*, Vol. 10, pages 391–402; May 2015.

FROM OUR ARCHIVES

Solar Wars. David Biello; November 2014.

scientificamerican.com/magazine/sa

EVOLUTION

FROM WOLF

Scientists are racing to solve the enduring mystery of how a large, dangerous carnivore evolved into our best friend *By Virginia Morell*

Photographs by Peter Rigaud

TO DOG

Virginia Morell is a science writer based in Oregon. She covers evolution and animal behavior for *Science* and *National Geographic*, among other publications. Her latest book is *Animal Wise* (Crown, 2013).

WHEN YOU HAVE CARED FOR DOGS AND WILD WOLVES FROM THE TIME they are little more than a week old and have bottle-fed and nurtured them day and night, you are wise to their differences. Since 2008 Zsófia Virányi, an ethologist at the Wolf Science Center in Austria, and her colleagues have been raising the two species to figure out what makes a dog a dog—and a wolf a wolf. At the center, the researchers oversee and study four packs of wolves and four packs of dogs, containing anywhere from two to six animals each. They have trained the wolves and dogs to follow basic commands, to walk on leashes and to use their nose to tap the screen of a computer monitor so that they can take cognition tests. Yet despite having lived and worked with the scientists for seven years, the wolves retain an independence of mind and behavior that is most undoglike.

"You can leave a piece of meat on a table and tell one of our dogs, 'No!' and he will not take it," Virányi says. "But the wolves ignore you. They'll look you in the eye and grab the meat"—a disconcerting assertiveness that she has experienced on more than one occasion. And when this happens, she wonders yet again how the wolf ever became the domesticated dog.

"You can't have an animal—a large carnivore—living with you and behaving like that," she says. "You want an animal that's like a dog; one that accepts 'No!'"

Dogs' understanding of the absolute no may be connected to the structure of their packs, which are not egalitarian like those of the wolves but dictatorial, the center's researchers have discovered. Wolves can eat together, Virányi notes. Even if a dominant wolf flashes its teeth and growls at a subordinate, the lower-ranked member does not move away. The same is not true in dog packs, however. "Subordinate dogs will rarely eat at the same time as the dominant one," she observes. "They don't even try." Their studies also suggest that rather than expecting to cooperate on tasks with humans, dogs simply want to be told what to do.

How the independent-minded, egalitarian wolf changed into the obedient, waiting-for-orders dog and what role ancient humans played in achieving this feat baffle Virányi: "I try to imagine how they did it, and I really can't."

Virányi is not alone in her bafflement. Although researchers have successfully determined the time, location and ancestry of nearly every other domesticated species, from sheep to cattle to chickens to guinea pigs, they continue to debate these questions for our best friend, *Canis familiaris*. Scientists also know why humans developed these other domesticated animals—to have food close at hand—but they do not know what inspired us to allow a large, wild carnivore into the family homestead. Yet dogs were the first domesticated species, a status that makes the mystery of their origin that much more perplexing.

As inscrutable as the mystery is, scientists are piecing it together. In the past few years they have made several breakthroughs. They can now say with confidence that contrary to received wisdom, dogs are not descended from the gray wolf species that persists today across much of the Northern Hemisphere, from Alaska to Siberia to Saudi Arabia, but from an unknown and extinct wolf. They are also certain that this domestication event took place while humans were still hunter-gatherers and not after they became agriculturalists, as some investigators had proposed.

At what time and in what location wolves became dogs and whether it was only a one-time event are questions that a large research team, composed of once competing scientists, has just started to tackle. The researchers are visiting museums, universities and other institutions around the world to study collections of canine fossils and bones, and they are readying genetic samples from ancient and modern dogs and wolves for the most comprehensive comparison to date. When they are finished, they will be very close to knowing when and where—if not exactly how—wolves first began down the path toward becoming our trusted companions. Answers to these questions will complement

IN BRIEF

The dog was the first domesticated species. Yet despite years of research, scientists have struggled to figure out when, where and how it originated. **Recent DNA studies** have thrown new light on the dog's wolf ancestor and an ambitious project is now under way to nail down the timing and location of dog domestication. **Such insights** will complement clues to how the human-dog relationship shifted in the millennia that followed.

the growing body of evidence for how humans and dogs influenced one another after that relationship was first forged.

MIXED SIGNALS

WHEN MODERN HUMANS arrived in Europe perhaps 45,000 years ago, they encountered the gray wolf and other types of wolves, including the megafaunal wolf, which pursued large game such as mammoths. By that time wolves had already proved themselves among the most successful and adaptable species in the canid family, having spread across Eurasia to Japan and into the Middle East and North America. They were not confined to a single habitat type but flourished in tundra, steppelands, deserts, forests, coastal regions and the high altitude of the Tibetan Plateau. And they competed with the newly arrived humans for the same prey—mammoths, deer, aurochs, woolly rhinoceroses, antelopes and horses. In spite of this competition, one type of wolf, perhaps a descendant of a megafaunal wolf, apparently began living close to people. For many years scientists concurred on the basis of small portions of the genome that this species was the modern gray wolf (*Canis lupus*) and that this canid alone gave rise to dogs.

But last January geneticists discovered that this long-held "fact" was wrong. Repeated interbreeding between gray wolves and dogs, which share 99.9 percent of their DNA, had produced misleading signals in the earlier studies. Such consorting between the two species continues today: wolves with black coats received the gene for that color from a dog; shepherd dogs in Georgia's Caucasus Mountains mate so often with the local wolves that hybrid ancestors are found in both species' populations, and between 2 and 3 percent of the sampled animals are first-generation hybrids. (Building on the admixture theme, in June researchers writing in *Current Biology* reported on the sequencing of DNA from a 35,000-year-old wolf fossil from Siberia. This species appears to have contributed DNA to high-latitude dogs such as huskies through ancient interbreeding.)

Analyzing whole genomes of living dogs and wolves, last January's study revealed that today's Fidos are *not* the descendants of modern gray wolves. Instead the two species are sister taxa, descended from an unknown ancestor that has since gone extinct. "It was such a long-standing view that the gray wolf we know today was around for hundreds of thousands of years and that dogs derived from them," says Robert Wayne, an evolutionary geneticist at the University of California, Los Angeles. "We're very surprised that they're not." Wayne led the first genetic studies proposing the ancestor-descendant relationship between the two species and more recently was one of the 30 co-authors of the latest study, published in *PLOS Genetics,* that debunked that notion.

SIT AND STAY: A dog at the Wolf Science Center outside Vienna, Austria, awaits permission to eat. Wolves, even those raised by people, lack such respect for human authority.

More surprises may come from renewed efforts to nail down the timing and location of dog domestication. Previous studies left a confusing trail. The first analysis, carried out in 1997, focused on the genetic differences between dogs and gray wolves and concluded that dogs may have been domesticated some 135,000 years ago. A later study by some members of the same group indicated that dogs originated in the Middle East. But another analysis, which examined the DNA of 1,500 modern dogs that was published in 2009, argued that dogs were first domesticated in southern China less than 16,300 years ago. Then, in 2013, a team of scientists compared the mitochondrial genomes of ancient European and American dogs and wolves with their modern counterparts. It concluded that dogs originated in Europe between 32,000 and 19,000 years ago.

Evolutionary biologist Greger Larson of the University of Oxford, who is co-leading the recently launched multidisciplinary dog-domestication project, says the previous studies, while important, have shortcomings. He faults the 1997 and 2009 studies for relying solely on DNA from modern dogs and the last one for its geographically limited samples. "You can't solve this problem by using modern animals alone as windows to the past," Larson says. The studies of modern dog DNA are not sufficiently informative, he explains, because people have moved and interbred dogs around the world numerous times, blurring their genetic heritage. Any regional signatures that might have helped identify where they were domesticated has long since been lost.

To further muddy the picture, "wolves have a ridiculously broad distribution across the world," Larson explains. In contrast, he points out, the ancestors of most other domesticated species, such as sheep and chickens, had much smaller geographical ranges, making it far easier to trace their origins.

Larson suspects that several geographically disparate populations of the ancestral wolf species may have contributed to the making of today's dog. It would not be the first time such a thing happened: Larson has shown that pigs were domesticated twice—once in the Near East and once in Europe. Intriguingly, enigmatic fossils from Belgium, the Czech Republic and southwestern Siberia that date to between 36,000 and 33,000 years ago and exhibit a mix of wolf and dog features hint at the possibility of at least three independent instances of domestication attempts from an ancestral wolf. But the anatomical characteristics of these fossils alone cannot answer the question of where dogs came from.

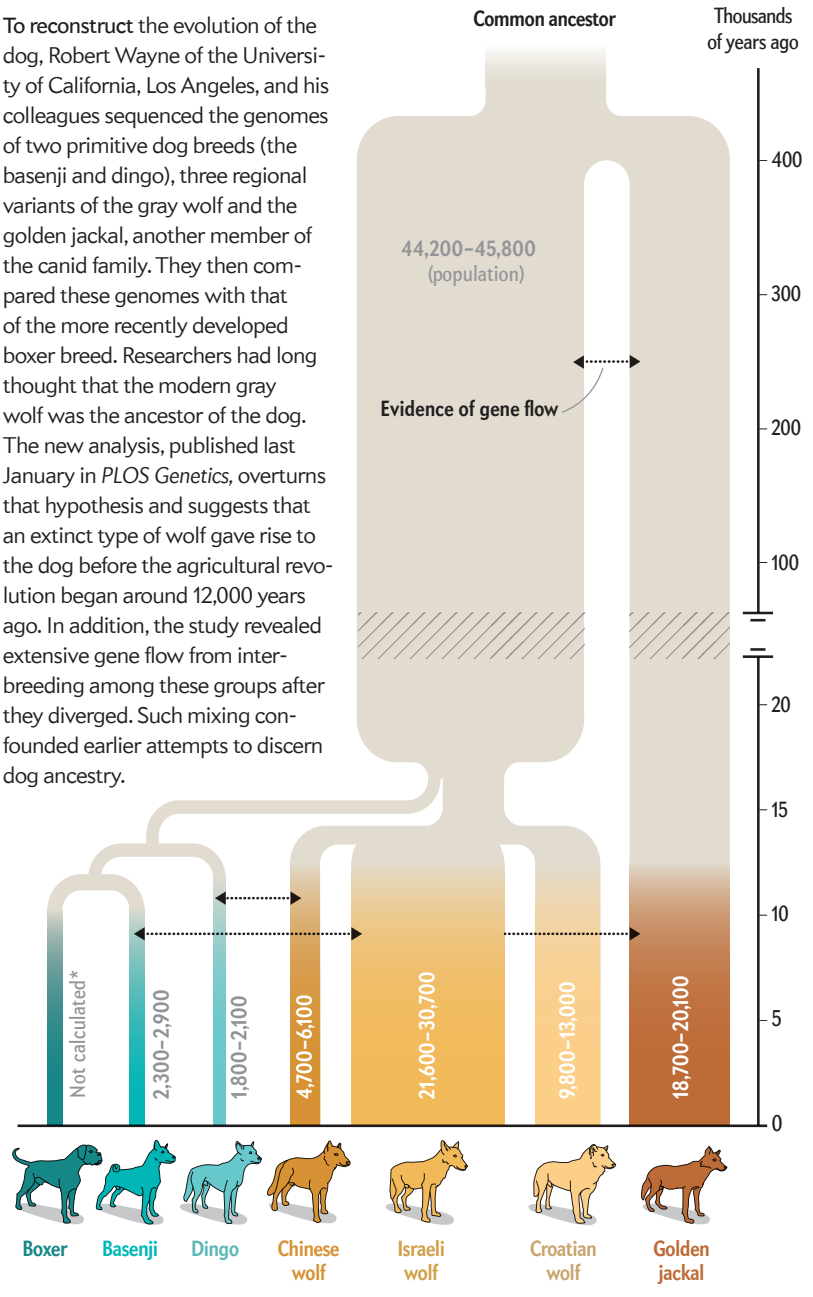
To solve the dog-domestication puzzle,

Larson and his collaborators are using two key techniques employed in the pig study: they are undertaking a more thorough analysis of thousands of modern and ancient samples of dog and wolf DNA from individuals across the globe and are using a fairly new technique for measuring bones. Called geometric morphometrics, this method enables scientists to quantify certain traits, such as the curves of a skull, and so better compare the bones of individuals. Previously researchers relied primarily on the length of a canid's snout and the size of the canine teeth to distinguish dogs from wolves. Dogs' snouts are generally shorter, their canines are smaller, and their teeth are on the whole more crowded than those of wolves. The new method should identify other, perhaps more telling differences. Together these techniques should yield a far more detailed picture of dog domestication than any other approach has to date.

FINDINGS

A Complex History

To reconstruct the evolution of the dog, Robert Wayne of the University of California, Los Angeles, and his colleagues sequenced the genomes of two primitive dog breeds (the basenji and dingo), three regional variants of the gray wolf and the golden jackal, another member of the canid family. They then compared these genomes with that of the more recently developed boxer breed. Researchers had long thought that the modern gray wolf was the ancestor of the dog. The new analysis, published last January in *PLOS Genetics*, overturns that hypothesis and suggests that an extinct type of wolf gave rise to the dog before the agricultural revolution began around 12,000 years ago. In addition, the study revealed extensive gene flow from interbreeding among these groups after they diverged. Such mixing confounded earlier attempts to discern dog ancestry.



*Boxer population size could not be estimated based on the available data.

CLOSE ENCOUNTERS

ALTHOUGH THE WHEN and where of dog domestication remain open questions, scientists now have a general idea of which kind of human society was the first to establish a close relationship with dogs. Perhaps not surprisingly, this question, too, has generated debate over the years. Some investigators have argued that settled agriculturalists had that distinction. After all, the other domesticated animal species all entered the human realm after people started farming and putting down roots. But other researchers credited earlier hunter-gatherers with being the first to have dogs. Wayne says that his team's latest DNA study has at last ended this part of the debate. "The domestication of the dog occurred prior to the agricultural revolution," he asserts. "It happened when people were still hunter-gatherers," sometime between 32,00 and 18,800 years ago. (Agriculture is thought to have begun in a big way roughly 12,000 years ago in the Middle East.)

And that finding leads back to the questions Virányi and most everyone who owns and loves a dog has: How did these hunter-gatherers do it? Or did they? What if the first dogs—which, it is important to remember, would have at first been more wolf than dog—showed up on their own?

The genus *Canis* goes back about seven million years, and although some members of that group, such as jackals and the Ethiopian wolf, lived in Africa, the birthplace of humanity, there is no evidence that the earliest humans tried to domesticate any of these species. Only after modern humans spread out from Africa and into Europe 45,000 years ago did the wolf-dog-human triad begin to form.

Hints about the evolving relationship between canids and early modern humans have come from the paleontological and archaeological records. Take the canid remains unearthed between 1894 and 1930 at Předmostí, a roughly 27,000-year-old settlement in the Bečva Valley in what is now the Czech Republic. The ancient people who lived and died there are known to us as the Gravettians, after a site with

SOURCE: "GENOME SEQUENCING HIGHLIGHTS THE DYNAMIC EARLY HISTORY OF DOGS." BY ADAM H. FREEDMAN ET AL., IN *PLOS GENETICS*, VOL. 10, NO. 1, ARTICLE NO. e1004016; JANUARY 16, 2014

Graphic by Tiffany Farrant-Gonzalez, Illustration by Portia Sloan Rollings (dogs)

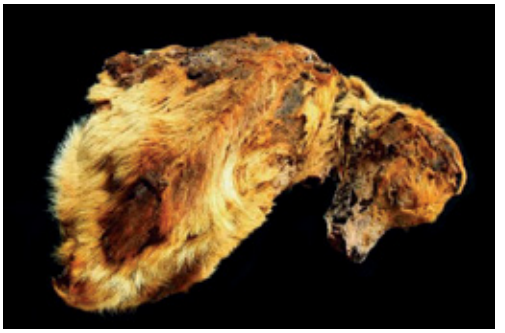
similar cultural artifacts in La Gravette, France. The Czech Gravettians were mammoth hunters, killing more than 1,000 of the great creatures at this one site alone. They ate the behemoths' meat, used their shoulder blades to cover human remains and decorated their tusks with engravings. They also killed wolves. Canids are the most abundant type of mammal at the site after mammoths, and their remains include seven complete skulls.

But some of the canid skulls do not look exactly like those of wolves. Three in particular stand out, says Mietje Germonpré, a paleontologist at the Royal Belgian Institute of Natural Sciences in Brussels. Compared with the wolf skulls found at Předmostí, the three unusual ones "have shorter snouts, broader braincases and crowded teeth," she notes.

These kinds of anatomical changes are the first signs of domestication, Germonpré and others say. Similar changes are found in the skulls of the silver foxes that are the focus of a famous, long-running experiment at Novosibirsk State University in Russia. Since 1959, researchers there have selected the foxes for tameness and bred them. Over the generations their coats have become spotted, their ears floppy, their tails curly, their snouts shorter and wider—even though the scientists have been selecting only for behavior. Similar changes are seen in other domesticated species, including rats and mink. Investigators have yet to explain why docile animals are consistently altered in these ways. They do know that the tame silver foxes have smaller adrenal glands and much lower levels of adrenaline than their wild counterparts.

Last year other scientists came up with a testable hypothesis: tame animals may have fewer or defective neural crest cells. These embryonic cells play a key role in the development of the teeth, jaws, ears and pigment-producing cells—as well as the nervous system, including the fight-or-flight response. If they are right, then all those cute domestic traits—spotted coats, curly tails, floppy ears—are a side effect of domestication.

Germonpré suspects that the apparent domestication at Předmostí was a dead-end event; she doubts that these animals are related to today's dogs. Nevertheless, to Germonpré, "they are dogs—Paleolithic dogs." She says these early dogs probably looked very much like today's huskies, although they would have been larger, about the size of a German shepherd. Germonpré calls the Předmostí specimens "dogs" because of what she interprets as some type of relationship between the canids and the Gravettians. For instance, a dog's lower jaw was found near a child's skeleton, according to the diary of the original excavator.



DOG LIVES: Dogs from the roughly 27,000-year-old site of Předmostí, Czech Republic, were seemingly bred for sacrifice (*skull, top*); dogs bred by the Chiribaya in Peru 1,000 years ago were revered herders (*mummy, bottom*).

The dogs were also included in rituals in ways that other species were not. In one case, a Gravettian tucked what is most likely a piece of mammoth bone between the front teeth of one of the dog skulls after the animal died and arranged its jaws so that they clamped together on the bone. Germonpré suspects that an ancient mammoth hunter placed the bone there as part of a ritual related to hunting, or to help sustain in death an animal the hunter revered, or to enable the dog to assist a human in the afterlife. "You see this kind of thing in the ethnographic record," she says, citing, as one example, a Chukchi ceremony in Siberia for a deceased woman in the early 20th century. A reindeer was sacrificed and its stomach placed in the mouth of a dead dog's head, which was then positioned to protect the woman on her death journey.

Many researchers imagine that these early people set about making the wolf into the dog to help us hunt big game. In her book *The Invaders,* published by Harvard University Press earlier this year, anthropologist Pat Shipman argues that the first dogs (or wolf-dogs, as she calls them) were like a new and superior technology and helped the mammoth-hunting modern humans outcompete the Neandertals. But she, Wayne, Larson and others think that wolves joined forces with humans on their own; that the canny, adaptable canids identified us as a new ecological niche they could exploit. The alternative scenario—people brazenly raiding wolf dens to steal pups young enough for taming—would have been a dangerous undertaking. And raising wolves in camps with young children would have presented another serious risk.

"We didn't do [domestication] deliberately; not at first," Larson surmises. Instead wolves most likely started following people for the same reason that ants trail into our kitchens—"to take advantage of a nutritional resource, our trash." Over time, some of these camp-following wolves increasingly lost their fear of people—and vice versa—and a mutually beneficial relationship developed. Wolf-dogs would sniff out prey for us, and we would share the resulting meat with them. (Circumstantial evidence for this scenario comes from the silver fox experiment. By selecting foxes that were less fearful of humans, the researchers at Novosibirsk eventually developed a silver fox that runs to greet people. Most silver foxes in captivity hide in the back of their cage.)

There is just one problem with this imagined event, at least at Předmostí: Germonpré's early dogs were not eating mammoth meat even though that is what the humans were dining on; isotopic analysis of the Paleolithic dogs' bones indicates that they were eating reindeer, which was not a favored food of the people who inhabited the site. The Předmostí dogs also had broken teeth and severe facial inju-

MIETJE GERMONPRÉ Royal Belgian Institute of Natural Sciences (*skull*); MARIANA BAZO Reuters (*mummy*)

WILD AT HEART: Exactly how the dog's wolf ancestor first began down the path to becoming our trusted companion may remain a mystery.

ries, many of which had healed. "Those could be signs of fighting with other dogs," Germonpré says, "or of being hit with sticks." She pictures the human-dog bond developing via the mammoth hunters' canid rituals. In this scenario, the hunter-gatherers brought pups to their camps, perhaps after killing the adult wolves, just as many modern nomadic peoples bring baby or young animals to their settlements. The mammoth bones at Předmostí show no signs of being gnawed by canids, which suggests they were not free to roam and scavenge people's scraps. Rather humans probably tied the canids up, fed them what appears to have been second-rate food, given that the humans were not eating it, and even bred them—all to ensure a ready supply of victims for their ritualistic sacrifices.

Breeding wolves in captivity would lead to the anatomical changes that Germonpré has documented in the Předmostí dogs and could even produce a less fearful and independent animal as seen in the Novosibirsk silver foxes.

Confined, beaten, fed a restricted diet, the dogs at Předmostí would likely have understood the meaning of "No!" There is no evidence at Předmostí or other comparably old sites where dog remains have been uncovered that the ancient hunter-gatherers there regarded the canines as their friends, companions or hunting pals, Germonpré observes. "That relationship came later."

SHIFTING FORTUNES

IF GERMONPRÉ IS RIGHT, then dog domestication may have begun quite early and under circumstances that were not favorable for the dogs. Not every scientist agrees that Germonpré's dogs are dogs, however. Some prefer the wolf-dog designation or simply "wolf" because their taxonomic status is not clear either from their morphology or genetics. (Larson expects to resolve this question over the course of his mega project.)

The earliest undisputed dog on record, a 14,000-year-old specimen from a site called Bonn-Oberkassel in Germany, tells a very different story of dog domestication, evincing a much more affectionate bond between humans and canines. In the early 1900s archaeologists excavating the site found the dog's skeleton interred in a grave with the remains of a man about 50 years old and a woman about 20 to 25. When researchers see such associations, they know they are looking at a fully domesticated animal—one that is treasured and regarded so highly that it is given a burial as if it, too, were a member of its human family.

The Bonn-Oberkassel dog is not the only ancient hound to have received such honors. In Israel, at Ain Mallaha, a hunter-gatherer site dating to 12,000 years ago in the upper Jordan Valley, archaeologists discovered what is perhaps the most famous dog-human burial. The skeleton of an elderly person lies curled on its right side, its left arm stretched out under the head, with the hand resting gently on a puppy. The dog was about four to five months old and was placed there, archaeologists think, to be a companion to the deceased. Unlike the Předmostí dogs, this puppy was not battered; its remains were arranged lovingly with someone who may have cared for it.

Although such touching dog-human scenes are rare during this period, dog burials are not. And after about 10,000 years ago, the practice of entombing dogs increased. No other animal species is so

SCIENTIFIC AMERICAN ONLINE Read more about the relationship between people and dogs at ScientificAmerican.com/jul2015/dogs

consistently included in human mortuary rituals. People had come to see dogs in a different light, and this shift in attitude had a profound effect on dogs' evolution. Perhaps during this period dogs acquired their human social skills, such as abilities to read our facial expressions, understand our pointing gestures and gaze into our eyes (which increases oxytocin—the love hormone—in both dog and owner).

"Dog burials happen after hunting moves away from the open plains and into dense forests," says Angela Perri, a zooarchaeologist at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, and a specialist on these burials. "Dogs in open environments might be good for helping you transport meat from killed mammoths but wouldn't necessarily help you hunt them," she says, noting that elephant hunters do not use dogs. "But dogs are excellent for hunting smaller game, such as deer and boar," that live in forests.

Beginning at least 15,000 years ago and probably somewhat earlier, Perri says, hunter-gatherers in Europe, Asia and the Americas began depending on their dogs' hunting skills for survival. Researchers cannot trace a direct genetic line from those animals to our pet pooches; nevertheless, they say, these animals were unquestionably dogs. "Good hunting dogs can find fresh tracks, and guide the hunters to the prey, and hold them at bay," says Perri, who has joined traditional hunters and their dogs in Japan and the U.S. "When people start using dogs for hunting, you see a switch in how people view them, and you start finding dog burials across the world." Such burials are not rituals or sacrifices, she emphasizes. "These are burials of admiration, where the dogs are interred with ocher, stone points and blades—male tools of hunting."

One of the most elaborate dog burials comes from Skateholm, Sweden, and is dated to about 7,000 years ago. Several dogs were found interred in the same area with dozens of humans. One was particularly celebrated and given the finest treatment there of anyone, human or dog. "The dog was laid on its side, flint chips were scattered at its waist, and red deer antlers and a carved stone hammer were placed with it, and it was sprinkled with red ocher," Perri says. There is no indication of why this dog was so revered, but she suspects it must have been an excellent hunter and that its human owner mourned its death. "You see this relationship among hunters and their dogs today and in the ethnographic record," Perri observes, noting that Tasmanian hunter-gatherers in the late 19th century were quoted as saying, "Our dogs are more important than our children. Without them, we couldn't hunt; we wouldn't survive."

Early dogs provided other important services, too. The first known attempt at the kind of intentional selection that has shaped the evolution of *C. familiaris* comes from a site in Denmark dating to 8,000 years ago. The ancient hunter-gatherers there had three sizes of dogs, possibly bred for certain tasks. "I didn't expect to see something like dog breeds," Perri says, "but they had small, medium and large dogs." It is not clear what they used the small dogs for, but the medium-sized animals had the build of hunting dogs, and the larger ones, which were the size of Greenland sled dogs (about 70 pounds), most likely transported and hauled goods. With their warning barks, all the dogs would have served as camp sentinels, too.

The dog's status plunged when people developed farming. In early agricultural settlements, dog burials are rare. "The difference is so strong," Perri says. "When people are living as hunter-gatherers, there are tons of dog burials." But as agriculture spreads, the burials end. "Dogs are no longer as useful." That fall from grace, though, did not doom them to extinction—far from it. In many places, they began to turn up on the dinner table, providing a new reason to keep dogs around.

Not all agricultural cultures consigned Fido to the menu, however. Among those groups that tended livestock, dogs were sometimes bred for herding. Those that proved their worth could still end up pampered in the afterlife. In 2006 archaeologists discovered 80 mummified dogs buried in graves next to their human owners at a 1,000-year-old cemetery near Lima, Peru. The dogs had protected the Chiribaya people's llamas and, in return for their service, were well treated in life and death. Nearly 30 of the dogs were wrapped in finely woven llama-wool blankets, and llama and fish bones were set close to their mouth. The region's arid climate mummified the dogs' remains, preserving their fur and tissue. Unwrapped, the mummies resemble the small street dogs that roam Lima today, looking for a human to take them in and tell them what—and what not—to do. (That resemblance notwithstanding, the Chiribaya herding dogs are not related to Lima's modern-day mutts. Nor is there any evidence to support claims linking any of the breeds of antiquity anywhere to the modern, standard breeds of the American Kennel Club.)

Although the Chiribaya dogs and other dog burials in the Americas hail from the wrong place and time to represent the earliest stages of domestication, Larson and his colleagues are happily measuring their bones and sampling their DNA. That is because these early North American dogs descended from ancient European or Asian dogs; their bones and genes will help the scientists determine how many dog-domestication events occurred and where they took place. Thus far in their attempt to study as many ancient canids as possible, the researchers have analyzed upward of 3,000 wolves, dogs and other specimens that do not readily fall into either box. More than 50 scientists worldwide are helping with the effort. They expect to have a paper ready on their initial findings by this summer.

Will we then finally know where and when the dog became domesticated? "I expect we'll be very close to an answer," Larson says. But we still won't know exactly how some long-lost type of wolf managed to become a creature that respects "No." SA

MORE TO EXPLORE

Palaeolithic Dog Skulls at the Gravettian Předmostí Site, the Czech Republic. Mietje Germonpré et al. in *Journal of Archaeological Science,* Vol. 39, No. 1, pages 184–202; January 2012.

Rethinking Dog Domestication by Integrating Genetics, Archeology, and Biogeography. Greger Larson et al. in *Proceedings of the National Academy of Sciences USA,* Vol. 109, No. 23, pages 8878–8883; June 5, 2012.

Genome Sequencing Highlights the Dynamic Early History of Dogs. Adam H. Freedman et al. in *PLOS Genetics,* Vol. 10, No. 1, Article e1004016; January 16, 2014.

FROM OUR ARCHIVES

The Taming of the Cat. Carlos A. Driscoll, Juliet Clutton-Brock, Andrew C. Kitchener and Stephen J. O'Brien; June 2009.

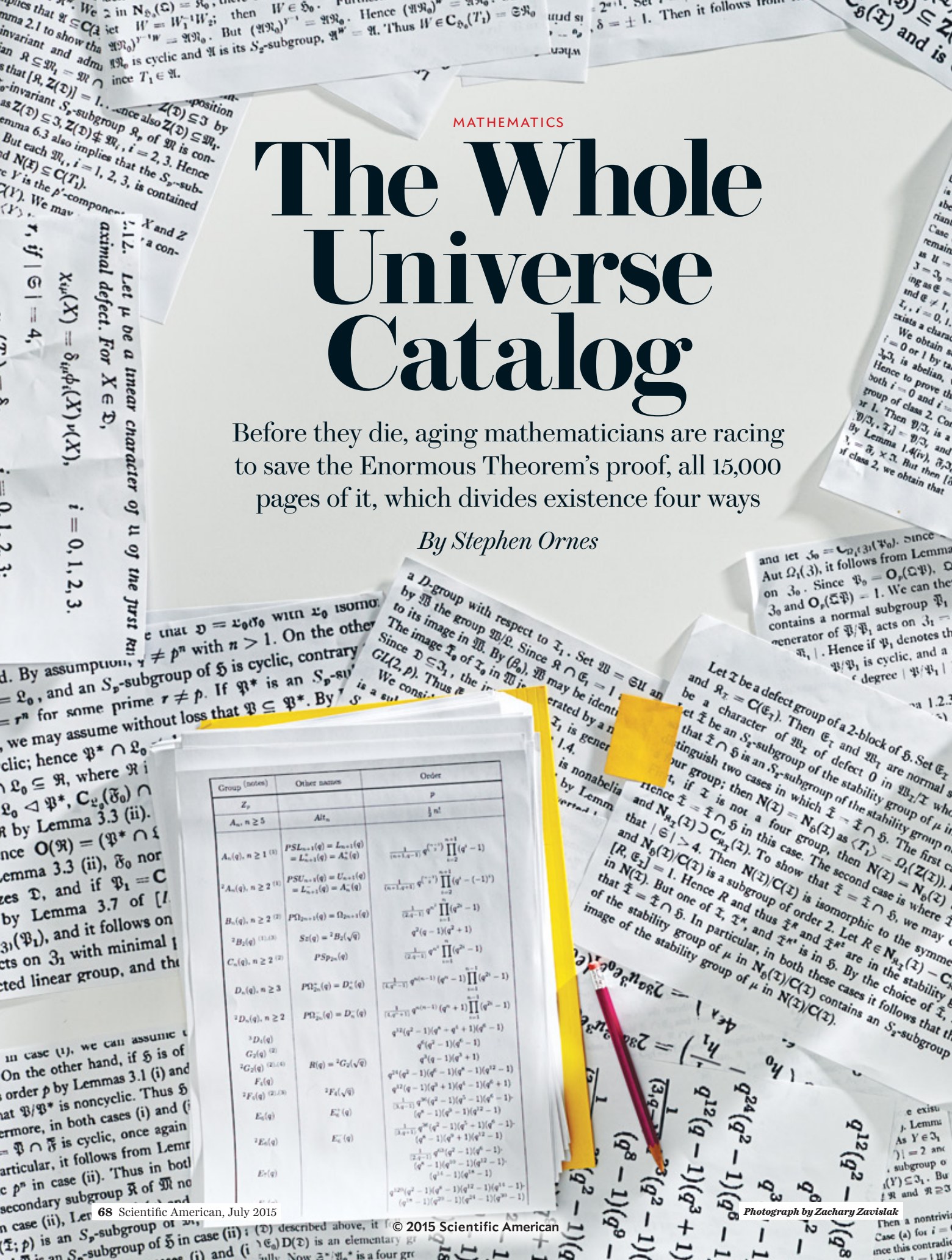
scientificamerican.com/magazine/sa

MATHEMATICS

The Whole Universe Catalog

Before they die, aging mathematicians are racing to save the Enormous Theorem's proof, all 15,000 pages of it, which divides existence four ways

By Stephen Ornes



Photograph by Zachary Zavislak

Group	Other names	Order
M_{11}		$2^4 \cdot 3^2 \cdot 5 \cdot 11$
M_{12}		$2^6 \cdot 3^3 \cdot 5 \cdot 11$
M_{22}		$2^7 \cdot 3^2 \cdot 5 \cdot 7 \cdot 11$
M_{23}		$2^7 \cdot 3^2 \cdot 5 \cdot 7 \cdot 11 \cdot 23$
M_{24}		$2^{10} \cdot 3^3 \cdot 5 \cdot 7 \cdot 11 \cdot 23$
J_1		$2^3 \cdot 3 \cdot 5 \cdot 7 \cdot 11 \cdot 19$
J_2	HJ	$2^7 \cdot 3^3 \cdot 5^2 \cdot 7$
J_3	HJM	$2^7 \cdot 3^5 \cdot 5 \cdot 17 \cdot 19$
J_4		$2^{21} \cdot 3^3 \cdot 5 \cdot 7 \cdot 11^3 \cdot 23 \cdot 29 \cdot 31 \cdot 37 \cdot 43$
HS		$2^9 \cdot 3^2 \cdot 5^3 \cdot 7 \cdot 11$
He	$HHM = F_7$	$2^{10} \cdot 3^3 \cdot 5^2 \cdot 7^3 \cdot 17$
Mc		$2^7 \cdot 3^6 \cdot 5^3 \cdot 7 \cdot 11$
Suz	Sz	$2^{13} \cdot 3^7 \cdot 5^2 \cdot 7 \cdot 11 \cdot 13$
Ly	LyS	$2^8 \cdot 3^7 \cdot 5^6 \cdot 7 \cdot 11 \cdot 31 \cdot 37 \cdot 67$
Ru		$2^{14} \cdot 3^3 \cdot 5^3 \cdot 7 \cdot 13 \cdot 29$
$O'N$	$O'S$	$2^9 \cdot 3^4 \cdot 5 \cdot 7^3 \cdot 11 \cdot 19 \cdot 31$
Co_1	$\cdot 1$	$2^{21} \cdot 3^9 \cdot 5^4 \cdot 7^2 \cdot 11 \cdot 13 \cdot 23$
Co_2	$\cdot 2$	$2^{18} \cdot 3^6 \cdot 5^3 \cdot 7 \cdot 11 \cdot 23$
Co_3	$\cdot 3$	$2^{10} \cdot 3^7 \cdot 5^3 \cdot 7 \cdot 11 \cdot 23$
Fi_{22}	$M(22)$	$2^{17} \cdot 3^9 \cdot 5^2 \cdot 7 \cdot 11 \cdot 13$
Fi_{23}	$M(23)$	$2^{18} \cdot 3^{13} \cdot 5^2 \cdot 7 \cdot 11 \cdot 13 \cdot 17 \cdot 23$
Fi'_{24}	$M(24)'$	$2^{21} \cdot 3^{16} \cdot 5^2 \cdot 7^3 \cdot 11 \cdot 13 \cdot 17 \cdot 23 \cdot 29$
F_5	HN	$2^{14} \cdot 3^6 \cdot 5^6 \cdot 7 \cdot 11 \cdot 19$
F_3	Th	$2^{15} \cdot 3^{10} \cdot 5^3 \cdot 7^2 \cdot 13 \cdot 19 \cdot 31$
F_2	$B = BM$	$2^{41} \cdot 3^{13} \cdot 5^6 \cdot 7^2 \cdot 11 \cdot 13 \cdot 17 \cdot 19 \cdot 23 \cdot 31 \cdot 47$
		$2^{46} \cdot 3^{20} \cdot 5^9 \cdot 7^6 \cdot 11^2 \cdot 13^3 \cdot 17 \cdot 19 \cdot 23 \cdot 29 \cdot 31 \cdot 41 \cdot$

Stephen Ornes writes on subjects ranging from mathematics to cancer research. His biography of mathematician Sophie Germain for young adults was published in 2008. He is based in Nashville, Tenn.

A SEEMINGLY ENDLESS VARIETY OF FOOD WAS SPRAWLED OVER SEVERAL TABLES at the home of Judith L. Baxter and her husband, mathematician Stephen D. Smith, in Oak Park, Ill., on a cool Friday evening in September 2011. Canapés, homemade meatballs, cheese plates and grilled shrimp on skewers crowded against pastries, pâtés, olives, salmon with dill sprigs and feta wrapped in eggplant. Dessert choices included—but were not limited to—a lemon mascarpone cake and an African pumpkin cake. The sun set, and champagne flowed, as the 60 guests, about half of them mathematicians, ate and drank and ate some more.

The colossal spread was fitting for a party celebrating a mammoth achievement. Four mathematicians at the dinner—Smith, Michael Aschbacher, Richard Lyons and Ronald Solomon—had just published a book, more than 180 years in the making, that gave a broad overview of the biggest division problem in mathematics history.

Their treatise did not land on any best-seller lists, which was understandable, given its title: *The Classification of Finite Simple Groups*. But for algebraists, the 350-page tome was a milestone. It was the short version, the CliffsNotes, of this universal classification. The full proof reaches some 15,000 pages—some say it is closer to 10,000—that are scattered across hundreds of journal articles by more than 100 authors. The assertion that it supports is known, appropriately, as the Enormous Theorem. (The theorem itself is quite simple. It is the proof that gets gigantic.) The cornucopia at Smith's house seemed an appropriate way to honor this behemoth. The proof is the largest in the history of mathematics.

And now it is in peril. The 2011 work sketches only an outline of the proof. The unmatched heft of the actual documentation places it on the teetering edge of human unmanageability. "I don't know that anyone has read everything," says Solomon, age 66, who studied the proof his entire career. (He retired from Ohio State University two years ago.) Solomon and the other three mathematicians honored at the party may be the only people alive today who understand the proof, and their advancing years have everyone worried. Smith is 67, Aschbacher is 71 and Lyons is 70. "We're all getting old now, and we want to get these ideas down before it's too late," Smith says. "We could die, or we could retire, or we could forget."

That loss would be, well, enormous. In a nutshell, the work brings order to group theory, which is the mathematical study of symmetry. Research on symmetry, in turn, is critical to scientific areas such as modern particle physics. The Standard Model—the cornerstone theory that lays out all known particles in existence, found and yet to be found—depends on the tools of symmetry provided by group theory. Big ideas about symmetry at the smallest scales helped physicists figure out the equations used in experiments that would reveal exotic fundamental particles, such as the quarks that combine to make the more familiar protons and neutrons.

Group theory also led physicists to the unsettling idea that mass itself—the amount of matter in an object such as this magazine, you, everything you can hold and see—formed be-

IN BRIEF

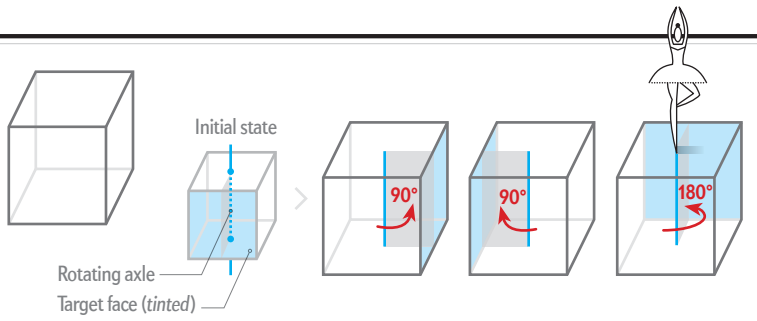
The largest proof in mathematics supports the notion that symmetry in the universe can be divided into four categories. Its 15,000 pages provide the crucial evidence behind something called the Enormous Theorem.

The few aging people who understand the proof fear they will die before a younger generation takes over.

Mathematicians have launched a rescue project to streamline the proof and save it before the knowledge vanishes.

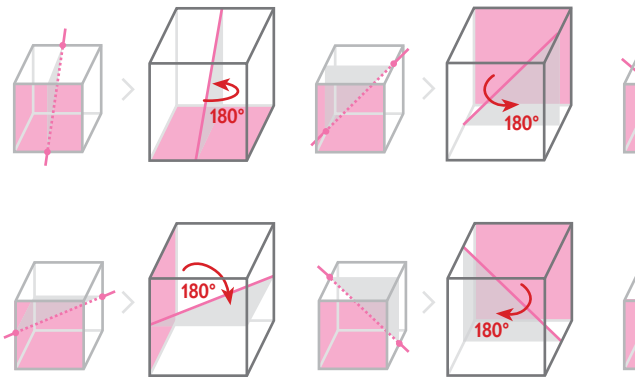
Turn, Turn, Turn

To understand group theory—and how symmetry is a part of it—turn to a cube. The cube has six faces, and you can rotate any one of them and the cube will look the same—as long as you do not paint the faces—when you are finished. There are 24 possible rotations that preserve the cube's symmetry. The limited number makes this symmetry, mathematically, a finite group. To see why there are 24 turns, follow the steps in this diagram. To show the turns, we have placed an imaginary axle between each pair of opposite, or symmetrical, features of the cube: faces, edges and corners. In the initial state, or position one, the target face is closest to you. Then the cube rotates around each axle (as shown by a flap inside the cube and an arrow) to illustrate every new position that keeps the cube's symmetry. There are 23 such moves that can be added to the initial one.



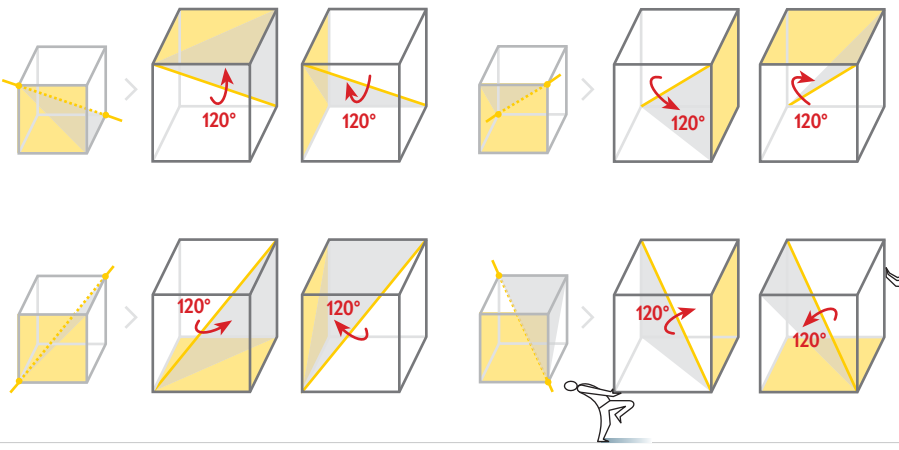
Faces

There are three pairs of opposite faces. For each axle connecting a pair, there are three possible rotations: 90° one way, 90° the other and one going 180°, for a total of nine symmetrical rotations.



Edges

Because the cube has 12 edges, there are six pairs of opposite edges. An axle connecting each of these pairs can rotate only 180° and maintain symmetry, thereby producing six rotations.



Corners

The cube has eight corners, so there are four opposite pairs. Each connecting axle has two possible rotations to keep the cube symmetrical: 120° one way or 120° the other way. This means eight more rotations.

Illustration by Nigel Holmes

cause symmetry broke down at some fundamental level. Moreover, that idea pointed the way to the discovery of the most celebrated particle in recent years, the Higgs boson, which can exist only if symmetry falters at the quantum scale. The notion of the Higgs popped out of group theory in the 1960s but was not discovered until 2012, after experiments at CERN's Large Hadron Collider near Geneva.

Symmetry is the concept that something can undergo a series of transformations—spinning, folding, reflecting, moving through time—and, at the end of all those changes, appear unchanged. It lurks everywhere in the universe, from the configuration of quarks to the arrangement of galaxies in the cosmos.

The Enormous Theorem demonstrates with mathematical precision that any kind of symmetry can be broken down and grouped into one of four families, according to shared features. For mathematicians devoted to the rigorous study of symmetry, or group theorists, the theorem is an accomplishment no less sweeping, important or fundamental than the periodic table of the elements was for chemists. In the future, it could lead to other profound discoveries about the fabric of the universe and the nature of reality.

Except, of course, that it is a mess: the equations, corollaries and conjectures of the proof have been tossed amid more than 500 journal articles, some buried in thick volumes, filled with the mixture of Greek, Latin and other characters used in the dense language of mathematics. Add to that chaos the fact that each contributor wrote in his or her idiosyncratic style.

That mess is a problem because without every piece of the proof in position, the entirety trembles. For comparison, imagine the two million-plus stones of the Great Pyramid of Giza strewn haphazardly across the Sahara, with only a few people who know how they fit together. Without an accessible proof of the Enormous Theorem, future mathematicians would have two perilous choices: simply trust the proof without knowing much about how it works or reinvent the wheel. (No mathematician would ever be comfortable with the first option, and the second option would be nearly impossible.)

The 2011 outline put together by Smith, Solomon, Aschbacher and Lyons was part of an ambitious survival plan to make the theorem accessible to the next generation of mathematicians. "To some extent, most people these days treat the theorem like a black box," Solomon laments. The bulk of that plan calls for a streamlined proof that brings all the disparate pieces of the theorem together. The plan was conceived more than 30 years ago and is now only half-finished.

If a theorem is important, its proof is doubly so. A proof establishes the honest dependability of a theorem and allows one mathematician to convince another—even when separated by continents or centuries—of the truth of a statement. Then these statements beget new conjectures and proofs, such that the collaborative heart of mathematics stretches back millennia.

Inna Capdeboscq of the University of Warwick in England is one of the few younger researchers to have delved into the theorem. At age 44, soft-spoken and confident, she lights up when she describes the importance of truly understanding how the

TYPES OF SYMMETRY

Four Enormous Families

Symmetries can be broken down into basic pieces. Called finite simple groups, they function like elements, coming together in different combinations to form larger, more complicated symmetries.

The Enormous Theorem organizes these groups into four families. Although its proof is huge, the theorem itself is just one sentence that lists all four: "Every finite simple group is cyclic of prime order, an alternating group, a finite simple group of Lie type, or one of the twenty-six sporadic finite simple groups."

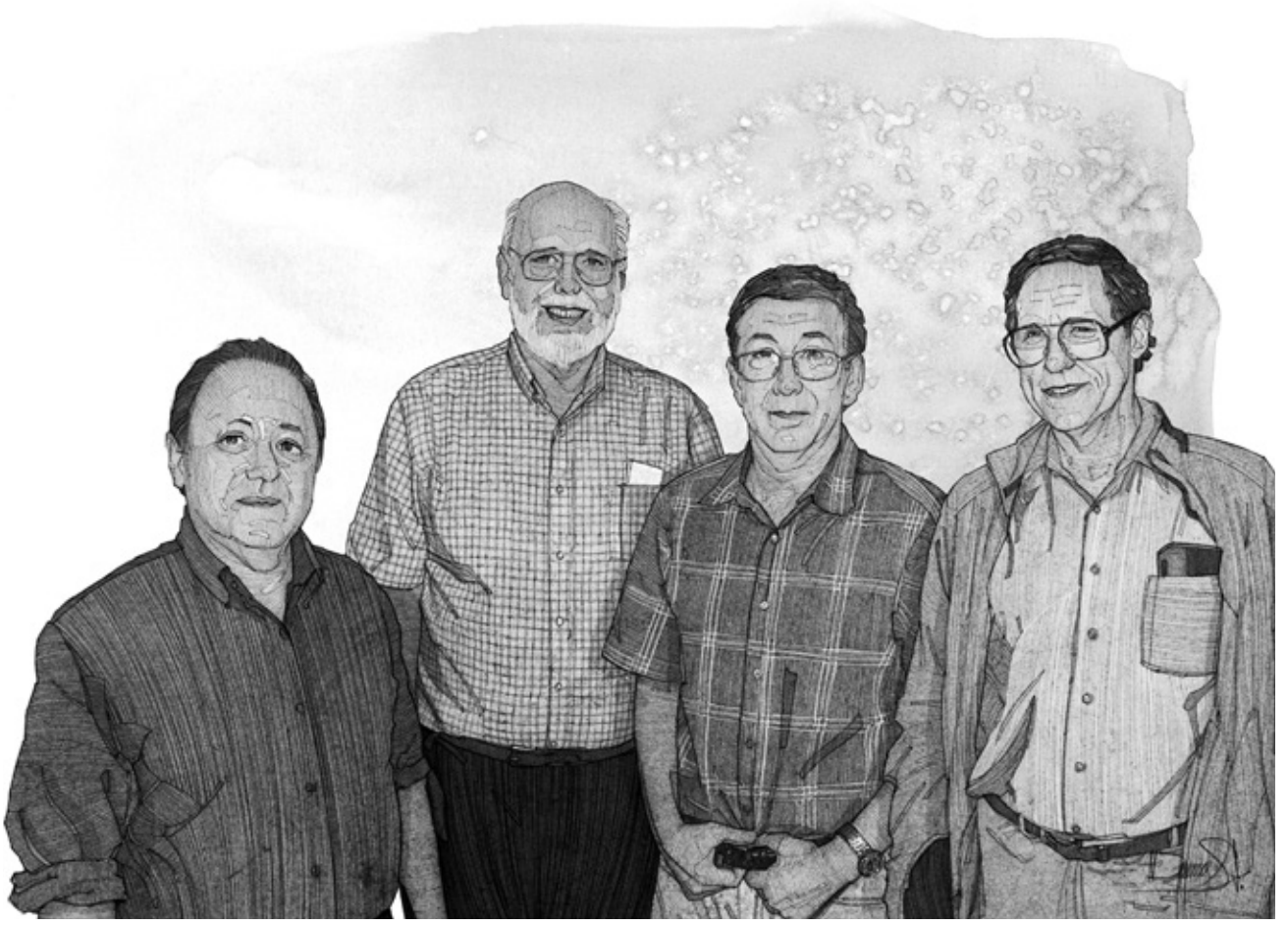
Here is a brief rundown of those families:

Cyclic groups were among the first building blocks to be categorized. Turn a regular pentagon through one fifth of a circle, or 72 degrees, and it looks unchanged. Turn it five times, and you are back at the beginning. Cyclic groups repeat themselves. The cyclic finite simple groups each have a prime number of members. Cyclic groups with more than two even numbers of members can be broken down further, so they are not simple.

Alternating groups come from switching around the members of a set. A full group of symmetries contains all the permutations, or switches. But an alternating group contains only half of them—the ones that have an even number of switches. For example, let us say you had a set of three numbers: 1, 2 and 3. There are six different ways to write that set: (1, 2, 3), (1, 3, 2), (2, 1, 3), (2, 3, 1), (3, 1, 2), and (3, 2, 1). The alternating group contains three of those. In terms of symmetry, each of these arrangements might correspond to a sequence of symmetries (that is, turn the cube up, then on its side, and so on).

Lie-type groups, named for 19th-century mathematician Sophus Lie, start to get more complicated. They are related to things called infinite Lie groups. The infinite groups include the rotations of a space itself that do not change the volume. For example, there are infinitely many ways to spin a doughnut without changing the doughnut itself. The finite analogues of these infinite groups are the Lie-type groups—in other words, the doughnut in a Lie-type group permits only a finite number of rotations. Most finite simple groups fall into this family. Neither infinite Lie groups nor Lie-type groups are limited to our pedestrian three dimensions. Ready to talk about the symmetries that arise in 15-dimensional space? Then look to these groups.

Sporadic groups make up the family of rogues. They include 26 outliers that do not line up neatly in the other families. (Imagine if the periodic table of elements had a column for "miscreants.") The largest of these sporadic groups, called the Monster, has more than 10^{53} elements and can be faithfully represented in 196,883 dimensions. It is baffling and bizarre, and no one really knows what it means but it is tantalizing to think about. "I have a sneaking hope, a hope unsupported by any facts or any evidence," physicist Freeman Dyson wrote in 1983, "that sometime in the twenty-first century physicists will stumble upon the Monster group, built in some unsuspected way into the structure of the universe." —*S.O.*



TO THE RESCUE (*from left*)**: Mathematicians Ronald Solomon, Richard Lyons, Michael Aschbacher and Stephen D. Smith fear they may be the last people to understand the Enormous Theorem's rambling proof unless they create a streamlined version.**

Enormous Theorem works. "What is classification? What does it mean to give you a list?" she ponders. "Do we know what every object on this list is? Otherwise, it's just a bunch of symbols."

REALITY'S DEEPEST SECRETS

MATHEMATICIANS FIRST BEGAN DREAMING of the proof at least as early as the 1890s, as a new field called group theory took hold [*see box on opposite page*]. In math, the word "group" refers to a set of objects connected to one another by some mathematical operation. If you apply that operation to any member of the group, the result is yet another member.

Symmetries, or movements that do not change the look of an object, fit this bill. Consider, as an example, that you have a cube with every side painted the same color. Spin the cube 90 degrees—or 180 or 270—and the cube will look exactly as it did when you started. Flip it over, top to bottom, and it will appear unchanged. Leave the room and let a friend spin or flip the cube—or execute some combination of spins and flips—and when you return, you will not know what he or she has done. In all, there are 24 distinct rotations that leave a cube appearing unchanged. Those 24 rotations make a *finite* group.

Simple finite groups are analogous to atoms. They are the basic units of construction for other, larger things. Simple finite groups combine to form larger, more complicated finite groups. The Enormous Theorem organizes these groups the way the periodic table organizes the elements. It says that every simple finite group belongs to one of three families—or to a fourth family of wild outliers. The largest of these rogues, called the Monster, has more than 10^{53} elements and exists in 196,883 dimensions. (There is even a whole field of investigation called monsterology in which researchers search for signs of the beast in other areas of math and science.) The first finite simple groups were identified by 1830, and by the 1890s mathematicians had made new inroads into finding more of those building blocks. Theorists also began to suspect the groups could all be put together in a big list.

Mathematicians in the early 20th century laid the foundation for the Enormous Theorem, but the guts of the proof did not materialize until midcentury. Between 1950 and 1980—a period which mathematician Daniel Gorenstein of Rutgers University called the "Thirty Years' War"—heavyweights pushed the field of group theory further than ever before, finding finite simple groups and grouping them together into families. These mathematicians wielded 200-page manuscripts like algebraic machetes, cutting away abstract weeds to reveal the deepest foundations of symmetry. (Freeman Dyson of the Institute for Advanced Study in Princeton, N.J., referred to the onslaught of discovery of strange, beautiful groups as a "magnificent zoo.")

Those were heady times: Richard Foote, then a graduate student at the University of Cambridge and now a professor at the University of Vermont, once sat in a dank office and witnessed

Illustration by Stavros Damos

two famous theorists—John Thompson, now at the University of Florida, and John Conway, now at Princeton University—hashing out the details of a particularly unwieldy group. "It was amazing, like two Titans with lightning going between their brains," Foote says. "They never seemed to be at a loss for some absolutely wonderful and totally off-the-wall techniques for doing something. It was breathtaking."

It was during these decades that two of the proof's biggest milestones occurred. In 1963 a theorem by mathematicians Walter Feit and John Thompson laid out a recipe for finding more simple finite groups. After that breakthrough, in 1972 Gorenstein laid out a 16-step plan for proving the Enormous Theorem—a project that would, once and for all, put all the finite simple groups in their place. It involved bringing together all the known finite simple groups, finding the missing ones, putting all the pieces into appropriate categories and proving there could not be any others. It was big, ambitious, unruly and, some said, implausible.

GROUP THEORY

The Math of Making Connections

The origins of group theory are inextricably linked to tragedy. They began in the 19th century, with Évariste Galois, a hotheaded French revolutionary whose passion for overthrowing his country's monarchy matched his passion for pushing mathematics as far as it could go. In his teenage years, Galois explored innovative ways to solve equations, which led him to find bridges between disparate fields of mathematics—when he was not in prison.

Galois was brilliant, but he was not lucky. He died at the age of 20 in 1832, the victim of a gunshot wound to the stomach that he received during a duel over a love interest. Historians have speculated that the duel might have been a murder attempt, or a staged suicide, or a simple tragic example of the perils of unrequited love. But recent scholarship suggests only one pistol was loaded, and it was not the one held by the young genius. "I die the victim of an infamous coquette and her two dupes," he wrote in a letter the night before the duel. In another letter penned that night, he laid out many of his ideas about groups. Over the next century and a half, group theory blossomed

THE MAN WITH THE PLAN

YET GORENSTEIN was a charismatic algebraist, and his vision energized a new group of mathematicians—with ambitions neither simple nor finite—who were eager to make their mark. "He was a larger than life personality," says Lyons, who is at Rutgers. "He was tremendously aggressive in the way he conceived of problems and conceived of solutions. And he was very persuasive in convincing other people to help him."

Solomon, who describes his first encounter with group theory as "love at first sight," met Gorenstein in 1970. The National Science Foundation was hosting a summer institute on group theory at Bowdoin College, and every week mathematical celebrities were invited to the campus to give a lecture. Solomon, who was then a graduate student, remembers Gorenstein's visit vividly. The mathematical celebrity, just arrived from his summer home on Martha's Vineyard, was electrifying in both appearance and message.

"I'd never seen a mathematician in hot-pink pants before," Solomon recalls.

In 1972, Solomon says, most mathematicians thought that the proof would not be done by the end of the 20th century. But within four years the end was in sight. Gorenstein largely credited the inspired methods and feverish pace of Aschbacher, who is a professor at the California Institute of Technology, for hastening the proof's completion.

One reason the proof is so huge is that it stipulates that its list of finite simple groups is complete. That means the list includes every building block, and there are not any more. Oftentimes proving something does not exist—such as proving there cannot be any more groups—is more work than proving it does.

In 1981 Gorenstein declared the first version of the proof finished, but his celebration was premature. A problem emerged with a particularly thorny 800-page chunk, and it took some debate to resolve it successfully. Mathematicians occasionally claimed to find other flaws in the proof or to have found new groups that broke the rules. To date, those claims have failed to topple the proof, and Solomon says he is fairly confident that it will stand.

Gorenstein soon saw the theorem's documentation for the sprawling, disorganized tangle that it had become. It was the product of a haphazard evolution. So he persuaded Lyons—and in 1982 the two of them ambushed Solomon—to help forge a revision, a more accessible and organized presentation, which would become the so-called second-generation proof. Their goals were to lay out its logic and keep future generations from having to reinvent the arguments, Lyons says. In addition, the effort would whittle the proof's 15,000 pages down, reducing it to a mere 3,000 or 4,000.

Gorenstein envisioned a series of books that would neatly collect all the disparate pieces and streamline the logic to iron over idiosyncrasies and eliminate redundancies. In the 1980s the proof was inaccessible to all but the seasoned veterans of its forging. Mathematicians had labored on it for decades, after all, and wanted to be able to share their work with future generations. A second-generation proof would give Gorenstein a way to assuage his worries that their efforts would be lost amid heavy books in dusty libraries.

Gorenstein did not live to see the last piece put in place, much less raise a glass at the Smith and Baxter house. He died of lung cancer on Martha's Vineyard in 1992. "He never stopped working," Lyons recalls. "We had three conversations the day before he died, all about the proof. There were no good-byes or anything; it was all business."

PROVING IT AGAIN

THE FIRST VOLUME of the second-generation proof appeared in 1994. It was more expository than a standard math text and included only two of 30 proposed sections that could entirely span the Enormous Theorem. The second volume was published in 1996, and subsequent ones have continued to the present—the sixth appeared in 2005.

SCIENTIFIC AMERICAN ONLINE Watch a video of 24 symmetries of a cube at ScientificAmerican.com/jul2015/cube-symmetry

from those last words of a dying man. Within decades it became a mature field.

A group, in mathematics, is an unspecified collection of objects that are connected through some operation. The integers, for example, make up a group linked through addition. Turns of a geometric shape that preserve its appearance also form a group [*see main article*]. Chemistry uses group theory to describe symmetries of a crystal or a molecular structure, which is key to understanding the physical properties of a material. And some of the mathematics used in devising—and breaking—codes such as public-key cryptography depend on group theory.

After Galois's death, mathematicians raced to construct, deconstruct and study groups. At first, it may have seemed like an abstract pursuit, but in the early 20th century German mathematician Emmy Noether found a connection between symmetry—that is, group theory—and the conservation laws of physics. (Energy cannot be destroyed or created, for example.) Her brilliant work paved the way for theoretical physicists to use group theory to better understand the symmetry underlying fundamental particles—and to predict the existence of many that had not yet been discovered. Group theory grew beyond the boundaries of arcana and became a powerful tool for understanding the fabric of reality. —*S.O.*

Foote says the second-generation pieces fit together better than the original chunks. "The parts that have appeared are more coherently written and much better organized," he says. "From a historical perspective, it's important to have the proof in one place. Otherwise, it becomes sort of folklore, in a sense. Even if you believe it's been done, it becomes impossible to check."

Solomon and Lyons are finishing the seventh book this summer, and a small band of mathematicians have already made inroads into the eighth and ninth. Solomon estimates that the streamlined proof will eventually take up 10 or 11 volumes, which means that just more than half of the revised proof has been published.

Solomon notes that the 10 or 11 volumes *still* will not entirely cover the second-generation proof. Even the new, streamlined version includes references to supplementary volumes and previous theorems, proved elsewhere. In some ways, that reach speaks to the cumulative nature of mathematics: every proof is a product not only of its time but of all the thousands of years of thought that came before.

In a 2005 article in the *Notices of the American Mathematical Society,* mathematician E. Brian Davies of King's College London pointed out that the "proof has never been written down in its entirety, may never be written down, and as presently envisaged would not be comprehensible to any single individual." His article brought up the uncomfortable idea that some mathematical efforts may be too complex to be understood by mere mortals. Davies's words drove Smith and his three co-authors to put together the comparatively concise book that was celebrated at the party in Oak Park.

The Enormous Theorem's proof may be beyond the scope of most mathematicians—to say nothing of curious amateurs—but its organizing principle provides a valuable tool for the future. Mathematicians have a long-standing habit of proving abstract truths decades, if not centuries, before they become useful outside the field.

"One thing that makes the future exciting is that it is difficult to predict," Solomon observes. "Geniuses come along with ideas that nobody of our generation has had. There is this temptation, this wish and dream, that there is some deeper understanding still out there."

THE NEXT GENERATION

THESE DECADES of deep thinking did not only move the proof forward; they built a community. Judith Baxter—who trained as a mathematician—says group theorists form an unusually social group. "The people in group theory are often lifelong friends," she observes. "You see them at meetings, travel with them, go to parties with them, and it is really is a wonderful community."

Not surprisingly, these mathematicians who lived through the excitement of finishing the first iteration of the proof are eager to preserve its ideas. Accordingly, Solomon and Lyons have recruited other mathematicians to help them finish the new version and preserve it for the future. That is not easy: many younger mathematicians see the proof as something that has already been done, and they are eager for something different.

In addition, working on rewriting a proof that has already been established takes a kind of reckless enthusiasm for group theory. Solomon found a familiar devotee to the field in Capdeboscq, one of a handful of younger mathematicians carrying the torch for the completion of the second-generation proof. She became enamored of group theory after taking a class from Solomon.

"To my surprise, I remember reading and doing the exercises and thinking that I loved it. It was beautiful," Capdeboscq says. She got "hooked" on working on the second-generation proof after Solomon asked for her help in figuring out some of the missing pieces that would eventually become part of the sixth volume. Streamlining the proof, she says, lets mathematicians look for more straightforward approaches to difficult problems.

Capdeboscq likens the effort to refining a rough draft. Gorenstein, Lyons and Solomon laid out the plan, but she says it is her job, and the job of a few other youngsters, to see all the pieces fall into place: "We have the road map, and if we follow it, at the end the proof should come out." SA

MORE TO EXPLORE

The Classification of the Finite Simple Groups: A Personal Journey: The Early Years. Daniel Gorenstein in *A Century of Mathematics in America,* Part I. Edited by Peter Duren, with the assistance of Richard A. Askey and Uta C. Merzbach. American Mathematical Society, 1998. www.ams.org/samplings/math-history/hmath1-gorenstein33.pdf

A Brief History of the Classification of the Finite Simple Groups. Ronald Solomon in *Bulletin of the American Mathematical Society,* Vol. 38, No. 3, pages 315–352; 2001. www.ams.org/journals/bull/2001-38-03/S0273-0979-01-00909-0

The Equation That Couldn't Be Solved: How Mathematical Genius Discovered the Language of Symmetry. Mario Livio. Simon & Schuster, 2005.

Symmetry and the Monster: One of the Greatest Quests in Mathematics. Mark Ronan. Oxford University Press, 2006.

FROM OUR ARCHIVES

The Enormous Theorem. Daniel Gorenstein; December 1985.

scientificamerican.com/magazine/sa

MORE TO EXPLORE For an interview with science-fiction authors Daniel Abraham and Ty Franck, go to ScientificAmerican.com/jul2015/recommended

Predictive Visions

Four novelists weave together credible science and literary storytelling to imagine very different futures

Seveneves

by Neal Stephenson.
William Morrow, 2015 ($35)

A cataclysm on the moon dooms Earth in this near-future epic tale by famed science-fiction author Stephenson. With less than two years to prepare before the planet becomes unlivable, humanity scrambles to devise a plan to live long-term in space. Nations join forces to augment the International Space Station to serve as a life raft for a sampling of the human species. Relatable heroes rise to the occasion, finding creative ways to acquire rocket fuel and battle space debris, and nefarious actors attempt sabotage in this scientifically rich and realistic picture of how people manage to endure. Later in the story, readers fast-forward 5,000 years to follow the races and cultures of the survivors' descendants, who are grappling with their history as they ready to return to their home planet.

The Only Words That Are Worth Remembering

by Jeffrey Rotter.
Metropolitan Books,* 2015 ($26)

There is no evolution, or climate change, or even astronomy in the curriculum. In fact, there is no curriculum, because schools have become merely training grounds that educate the young in mining and other trades. In such a world, where the stars are believed to be blemishes in the night glass of the sky, what if you knew some of the secrets of Nicolaus Copernicus? That is the fate Rotter imagines for the beleaguered Van Zandt family, whose members are rescued from penal servitude and forced to become astronauts. Alternately grisly, funny, tragic and thought-provoking, Rotter explores what might happen to people trapped in a postscience world run by libertarian fiat—and what giving in to their own impulses might cost them. *—David Biello*

Aurora

by Kim Stanley Robinson.
Orbit, 2015 ($26)

Robinson has built a career crafting scientifically realistic novels that probe our deep prehistoric past, our crisis-wracked present and our possible interplanetary futures. Here he turns his talents to the final frontier, envisioning humankind's first interstellar voyage. *Aurora* is Robinson's best book yet. The action takes place on a terrariumlike spaceship in which successive generations are born and die without ever making planetfall, bound for promising worlds orbiting the nearby star Tau Ceti. Mixing equal parts ecology, sociology and astrophysics, Robinson's heart-wrenching, provocative tale makes plain that even though humanity may someday reach the stars, we can never truly escape the pull of Earth. *—Lee Billings*

Persona

by Genevieve Valentine.
Saga Press, 2015 ($24.99)

In Valentine's imagined future, war and international politics have been replaced by maneuverings in a reality television–esque "International Assembly," where a celebrity "Face" represents each country. Romantic relationships between Faces stand in for diplomatic treaties, and the beauty and popularity of a representative determine the nation's standing on the world stage. In this atmosphere, the Face of the United Amazonian Rainforest Confederation escapes an assassination attempt with the help of a paparazzo and must uncover the humanity behind other Faces to survive. The action-packed story and thorough characterization in Valentine's sardonic novel offer a view on a not so different world from our own, where a celebrity-obsessed populace can ignore the real issues affecting people around the globe.

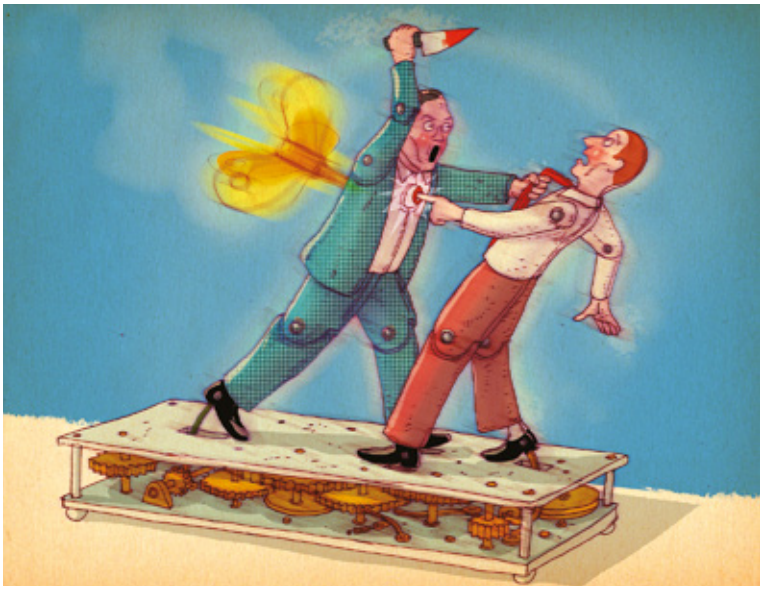
*SCIENTIFIC AMERICAN AND METROPOLITAN BOOKS ARE AFFILIATES

Illustration by Curt Merlo

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

Outrageous

Why cops kill



The ongoing rash of police using deadly force against minority citizens has triggered a search for a universal cause—most commonly identified as racism. Such soul searching is understandable, especially in light of the racist e-mails uncovered in the Ferguson, Mo., police department by the U.S. Department of Justice's investigation into the death of 18-year-old Michael Brown.

To whatever extent prejudice still percolates in the minds of a few cops in a handful of pockets of American society (nothing like 50 years ago), it does not explain the many interactions between white police and minority citizens that unfold without incident every year or the thousands of cases of assaults on police that do not end in police deaths (49,851 in 2013, according to the FBI). What in the brains of cops or citizens leads either group to erupt in violence?

An answer may be found deep inside the brain, where a neural network stitches together three structures into what neuroscientist Jaak Panksepp calls the rage circuit: (1) the periaqueductal gray (it coordinates incoming stimuli and outgoing motor responses); (2) the hypothalamus (it regulates the release of adrenaline and testosterone as related to motivation and emotion); and (3) the amygdala (associated with automatic emotional responses, especially fear, it lights up in response to an angry face; patients with damage to this area have difficultly assessing emotions in others). When Panksepp electrically stimulated the rage circuit of a cat, it leaped toward his head with claws and fangs bared. Humans similarly stimulated reported feeling uncontrollable anger.

The rage circuit is surrounded and modulated by the cerebral cortex, particularly the orbitofrontal cortex, wherein decisions are made about how you should respond to a particular stimulus—whether to act impulsively or show restraint. In her 1998 book *Guilty by Reason of Insanity,* psychiatrist Dorothy Otnow Lewis notes that when a cat's cortex is surgically detached from the lower areas of its brain, it responds to mildly annoying stimuli with ferocity and violence, not unlike a convicted killer improbably named Lucky, who had lesions between his cortical regions and the rest of his brain. Lewis suspects that Lucky's lesions were responsible for his savage stabbing of a store clerk.

In healthy brains and under normal circumstances, cortical self-control usually trumps emotional impulses. In certain conditions that call for strong emotions, such as when you feel threatened with bodily injury or death, it is prudent for the rage circuit to override the cortex, as in a case of a woman named Susan described by evolutionary psychologist David M. Buss in his 2005 book *The Murderer Next Door.* As her cocaine-fueled abusive husband advanced on her with a hunting knife screaming, "Die, bitch!" Susan kneed him in the groin and grabbed the knife. What happened next is what sociologist Randall Collins calls a "forward panic"—an explosion of violence akin to the wartime massacres at Nanking and My Lai and the beating of Rodney King by Los Angeles police officers. "I stabbed him in the head and I stabbed him in the neck and I stabbed him in the chest and I stabbed him in the stomach," Susan testified at her murder trial, explaining the 193 stab wounds resulting from her uncontrollable urge to avenge her abuse. Such emotions evolved as an adaptation to threats, especially when there is not time to compute the odds of an outcome. *Fear* causes us to pull back and retreat from risks. *Anger* leads us to strike out and defend ourselves against predators or bullies.

A charitable explanation for why cops kill is that certain actions by suspects (running away, or resisting arrest, or reaching into the squad car to grab a gun) may trigger the rage circuit to fire with such intensity as to override all cortical self-control. This may be especially the case if the officer is modified by training and experience to look for danger or biased by racial profiling leading to negative expectations of certain citizens' behavior.

Future police training should include putting cops in threatening situations and giving them techniques for diffusing the outcome. In their 2011 book *Willpower,* Roy F. Baumeister and John Tierney describe methods for suppressing such impulses. In turn, citizens should remember that cops are working to protect us from threats to our security. SA

SCIENTIFIC AMERICAN ONLINE
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Illustration by Izhar Cohen

The ongoing search for fundamental farces

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

Legionnaires' Unease

An astrophysicist's novel considers the contingency of history

Imagine a world in which this magazine never existed. In that version of existence, the chief resident at New York's biggest hospital is a homeopath, I'm selling aluminum siding and right now you're reading the *Daily Racing Form*.

This musing has been a very small exercise in what's called alternate history, or alt history, defined in its Wikipedia entry as "a genre of fiction consisting of stories that are set in worlds in which one or more historical events unfolds differently from how it did in reality."

For example, in Michael Chabon's novel *The Yiddish Policemen's Union,* Alaska rather than Israel is home to millions of the world's Jews displaced by World War II. Tensions exist between the immigrants and the native Tlingit, but everyone likes salmon. In Quentin Tarantino's movie *Inglourious Basterds,* a special-forces team kills Hitler, who still couldn't make it as a painter. In Philip K. Dick's book *The Man in the High Castle,* the Axis powers have won World War II, and a character in the book is writing an alternate-history novel in which the Allies won the war. Philip K. Dick did things like that.

Of course, alt history contemplates themes other than World War II and its aftermath. Another popular scenario is the one in which the South wins the Civil War. In such an America, black men might be incarcerated at a rate seven times higher than that of white men, or a southerly-facing Congress could forbid academic scientists from advising the Environmental Protection Agency about their research. Ahem.

To this list of alt-history works, add the new novel *Clash of Eagles,* by Alan Smale. He's an astrophysicist at the NASA Goddard Space Flight Center in Maryland, but his book is on terra firma if a bit incognita. It contemplates a world in which the Roman Empire has continued chugging along, unfallen, into the early 13th century. Having made Scandinavia a vassal state, Rome has a navy of Norse longships. And in 1218 those ships carry to the eastern shore of North America the 33rd Legion, which commences to march west under its eagle standard.

The Roman invaders figure they are going to have an easy time with any locals, until they reach Cahokia, the major city of the Mississippian culture, site of some 120 minor earthen mounds and one absolutely enormous one, now known as Monk's mound. Yes, Cahokia really existed.

"I used to go for family vacations at Hadrian's Wall when I was much younger," Smale says. "So I've been interested in the Romans for a long, long time. More recently, I was reading Charles Mann's *1491,* about the Americas before the Columbus voyage, and he has a large section on Cahokia, and I got fascinated with it." As *Scientific American*'s sister publication *Nature* recently noted in a report about evidence for a huge flood there some eight centuries ago, "Cahokia was a pretty big deal in the 1100s."

To give them a fighting chance against a steel-bearing, combat-hardened legion, Smale's Cahokians have come up with a rather advanced technology for the time. (And here's your requisite spoiler alert.) His research alerted him to "the dominance of flying imagery in Mississippian art. It was clear that they had a birdman cult. And that really got me thinking about what is the point of having these big, tall mounds if you're not going to throw yourself off them. And so the Mississippian culture in the book has developed a form of flying. Essentially they have things made of wood and deer skin that are very much like hang gliders."

With air power and incendiary devices, the Cahokians are, as Smale puts it, "able to give the Romans a run for their money." And their raptor imagery versus the Roman standard provides the clash of eagles of the title.

The book is the first volume of a trilogy that will eventually take the reader farther west and south. The saga will presumably wrap up before Robert E. Lee accepts the surrender of William Tiberius Sherman in Atlanta. SA

SCIENTIFIC AMERICAN ONLINE
Hear an interview with Alan Smale: ScientificAmerican.com/jul2015/multimedia

Illustration by Matt Collins

July 1965

House Fly: Disease Vector?

"By now flies have been found to harbor well over 100 different species of pathogenic organisms. Yet the evidence is still only circumstantial. The reputation of the domestic flies is in the position of a man charged with homicide because he is found standing beside the victim with a loaded gun in his hand. In most cases it cannot be proved conclusively that the flies in question fired the gun. The infections they are accused of spreading can actually be spread by any of four different agents: food, fingers, feces and flies."

Enzyme in 3-D

"X-ray crystallographers have succeeded for the first time in determining the three-dimensional structure of an enzyme: the protein known as lysozyme. Originally discovered in tears, where it acts as a mild antiseptic, lysozyme has the ability to dissolve the mucopolysaccharides found in the walls of certain bacteria. The determination of its structure has already led to experiments identifying the regions in the lysozyme molecule that appear to be involved in its wall-destroying activity. The work was done at the Royal Institution in London. The X-ray study provides a picture of the lysozyme molecule with a resolution of two angstrom units."

July 1915

War Work

"Women as car conductors have soon become a common feature in Berlin as well as in other German cities, with their strange accouterment—skirt, cap and tunic. Timid at first, they were not long in getting used to the role they are called upon to play in war time. In fact, they are now as bold as their male comrades in distributing the tickets, shouting the names of stoppages and answering the inquiries of passengers. Since, however, nothing in Germany is done in a haphazard way, these women had at first to undergo the same theoretical and practical training to which regular tramway guards are subjected."

BUILDING MASS TRANSIT: Workers in New York City in the subterranean gloom, 1915

Cotton for Guns

"For warring nations, cotton is king. In the past cotton has been important in war merely as raw material for textile mills, the amount of it used to make smokeless powder having been very small. Cotton is the principal ingredient by weight in all smokeless powders, which consist of nitro-cellulose. Strange as it may seem, more cotton is now being consumed in Germany for the manufacture of smokeless powder than for industrial use. The greatest surprise of the war has been the vast expenditure of artillery ammunition. The amount of cotton used for every round fired will average well over four pounds. The expenditure of cotton in Germany is about 1,000,000 pounds per day."

Railways and Subways

"Fifty years ago when the question of having a subway in New York was first agitated, Alfred V. Craven, who was the chief engineer of the Croton Aqueduct, came out flatly against the proposition. The irony of fate may be seen in the appointment of this man's nephew and namesake, Alfred Craven, to the position of the chief engineer of the Public Service Commission, which is now adding over fifty miles of new subways [*see illustration*] and above-ground tracks to the system that has already proved its success."

Take a trip back to 1915 for a look at railways, subways and the invention of mass transit at www.ScientificAmerican.com/jul2015/transit

July 1865

Steam Helicopter

"A flying machine of novel form is now in the process of construction at Hoboken, N.J., for the United States Government. A fan with blades of 20 feet diameter, revolving at a certain rate of speed, would raise six tons, and have considerable power to spare. It is only a child's toy upon a large scale. We see every day in the streets toy vendors who give a quick twirl with a string to a little fan upon a stick, and lo! it shoots into the air to a height of 20 or 30 feet, and descends slowly, still revolving as it comes down. The government toy—as some persons will probably call it—is a cigar-shaped canoe, built of copper, with iron ribs. The weight of the whole, fully equipped and manned, is about six tons."

SCIENTIFIC AMERICAN, VOL. CXIII, NO. 2, JULY 10, 1915

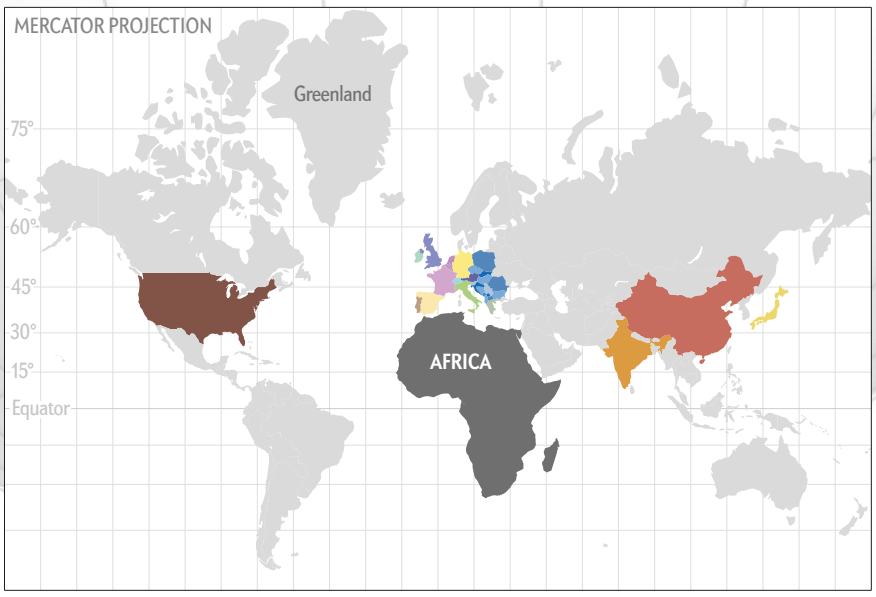
True Size of Africa

The most prevalent flat maps make Africa appear much smaller than it is

When shown in proper proportions, Africa swallows up China, India, the contiguous U.S. and much of Europe. Think of a world globe as a hollow crust: pop out the landmasses and set those slightly curved pieces onto Africa. And no, neither Russia nor Canada comes close in actual size.

On a flat map of the world, Greenland appears as big as Africa. In fact, Africa is 14 times larger. The distortion arises from a mathematical process, known as the Mercator projection, that converts the earth's spherical surface to a handy two-dimensional rectangle. The result is that the area of landmasses becomes increasingly exaggerated toward the poles. Africa should be shown to be larger than many big countries taken together. To correct widespread misconceptions, Kai Krause, a designer and author, devised a puzzle to show the true relations among landmasses (*above*). Understanding Africa's immense size helps us appreciate how difficult it may be to solve the continent's poverty and drought problems.

—Mark Fischetti



SOURCE: KAI KRAUSE

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Graphic by Bryan Christie and Kai Krause

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