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Looking after the Legacy

A Q&A with Sabine Bernschneider-Reif

Sabine Bernschneider-Reif, head of corporate history at Merck KGaA, Darmstadt, Germany, sees the strength of the company's future rising from its nearly 350-year-old foundation.

Question: How did you become Merck KGaA, Darmstadt, Germany's corporate historian and when?

Sabine Bernschneider-Reif: I studied pharmaceutical sciences and history of pharmacy, and during my postgraduate studies, I worked at Marburg University where I also did my Ph.D. The job offer from Merck KGaA, Darmstadt, Germany in 1999 had absolutely been perfect, and now my job is really a dream job.

Question: Has the company always had a historian?

Sabine Bernschneider-Reif: The first information concerning a historical archive is from 1905. At that time, the intention was to collect all of the important documents relating to the history of the family and a little bit about the "Angel-Pharmacy," as well as the pharmaceutical and chemical company at a central place. The first main emphasis was genealogical or legal interest. They began to work on a family tree and to collect information about all the members of this very widespread family.

Question: How do you describe your job?

Sabine Bernschneider-Reif: I'm in charge of preserving the history of Merck KGaA, Darmstadt, Germany. So I'm responsible for the company archives, the family archives, the historical library, the museum and an institution we call the lecture room, where people come together for discussions or talks. Thirteen people work in my department. We have to collect, select and conserve a very comprehensive range of documents and objects. Our department is also a research center in close collaboration with universities in several countries.

There is no daily routine. We are always faced with new challenges and questions. Requests for projects come from different parts of the company, from the family and to a large extent from the scientific community—scientists from a wide variety of fields from all over the world. Almost every day, scientists are researching documents here and joint publications are often possible. The topics are as varied as Merck KGaA, Darmstadt, Germany. The materials may be from the 16th century or from yesterday. The basis of all of these things is a well-run archive. We must acquire material, and we must prepare it in a form that allows us to find as many facts as possible, as soon as possible.

Question: If someone asks you about Merck KGaA, Darmstadt, Germany's historical collection, how do you describe it?

Sabine Bernschneider-Reif: Our archives, library, museum and auditorium present a holistic concept. Our work for our company is founded on four pillars. First, we maintain a family archive and an international business archive. Second, is a historical library that contains more than 8,000 books and a collection of journals. The topics range from recipe books from the 16th century to expert literature on corporate strategy of the 21st century. That facility is open to all employees. The third, is the museum presentation, and it shows the constant change of the company. Our scientific objects give a tangible understanding of this company. The fourth pillar is that we have established a forum in which we offer topics from our guests and, we present our own research.

Question: I find it fascinating that Merck KGaA, Darmstadt, Germany created a museum. What does it include and how is it used?

Sabine Bernschneider-Reif: Our collection in the exhibition focuses on the development of the company and the family since 1668. We cover scientific, economic and administrative developments of the company, as well as cultural aspects, such as changes in healing ideas. Most of the objects came directly from people who work in the company. That's very important to us. We want to have a museum created not only for employees, but also with help from employees in all countries. I think people are proud when they understand that their work will be preserved for the future.

In the museum, you will discover exhibition areas describing the work of the old pharmacy, which was operated by the Merck family in the 17th century. We have exhibits on plant-based, animal-based and mineral-based drugs. Also, all of our guests want to see our Egyptian mummies. I won't explain why we have mummies, because that would take two hours. Of course, we have some books that are very valuable.

You understand as you go through the exhibition the change from pharmacy as a handcraft to pharmacy as a science. It happened in the era of Emanuel Merck, and you'll see lots of tools and papers from this time. In the history of pharmacy, that change is a milestone, and pharmacy as a science was beginning at the end of the 18th century. Visitors will see part of the old factory, and a room focused on products, and research and development. You'll see instruments for pharmacology, for toxicology, for biotechnology and, of course, for the important part of our chemical research—liquid crystals, for example.

We have very many visitors, and most of them are employees from all over the world. Outside visitors need a special permit to come.

Question: How does Merck KGaA, Darmstadt, Germany's long history impact the way that the company works?

Sabine Bernschneider-Reif: We preserve and develop information that must be remembered for future business dealings. There are many items that people want to remember, but most of the things must be remembered. We provide the place where all employees can become acquainted with the history of their company, and that's very important when new companies come to Merck KGaA, Darmstadt, Germany. Those people have no idea what the company is, and they can come to the museum to learn and feel the spirit of Merck KGaA, Darmstadt, Germany.

We do business based on common values: courage, achievement, responsibility, respect, integrity and transparency. These values are the basis of our actions and our daily dealings with customers and business partners, as well as in our own teamwork. When you look at our historical documents, and letters and correspondence of the family, or in former times of the business, you'll see that these values have their origins in our history, and often it's easier to explain why we have such values when we show historical objects or historical letters.
Currently there are many changes in our company. I think if people know that the history and development of this company are full of changes, it will be easier to understand why changes are important.

Question: It is very unique for a company to have a historian, and that obviously speaks to the value Merck KGaA, Darmstadt, Germany puts on its legacy. Can you talk about that legacy and how it informs your outlook ahead?

Sabine Bernschneider-Reif: Future-oriented ideas have a long history at Merck KGaA, Darmstadt, Germany. Knowing about the legacy can be great for innovation for people working here now. I think that all employees at the company can be proud to create part of this exciting story. When we know that our company's innovations have such a long history, we want to do all that we can to make new innovations and be a part of this history. It's not so easy to explain, but this is my feeling. It is the spirit of Merck KGaA, Darmstadt, Germany that our people want to work together for our long-term goals.

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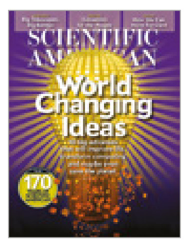
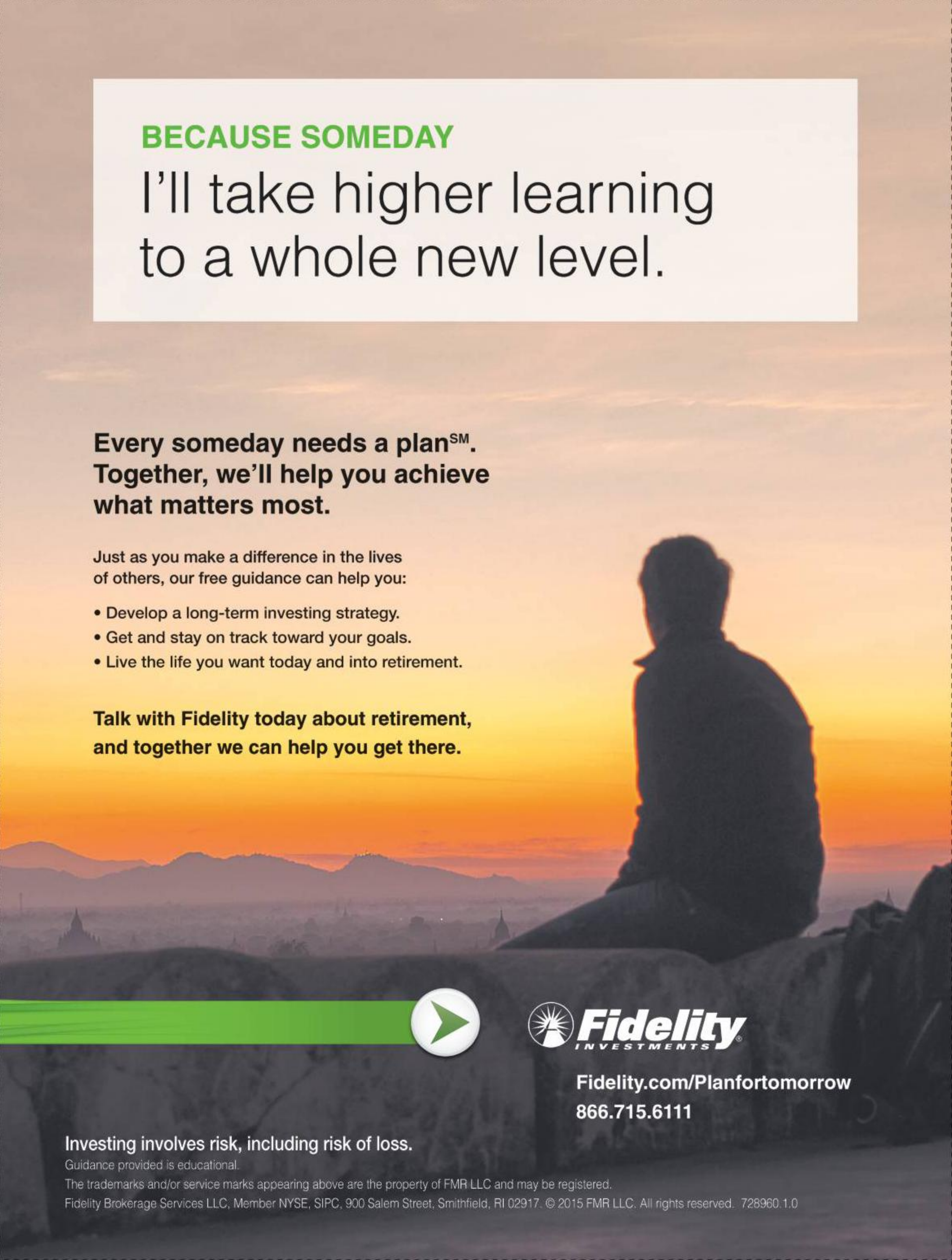


ON THE COVER
This year's edition of "World Changing Ideas," our annual roundup of advances with transformative potential, features tools that could improve brain monitoring and virus screening, networks that could make humanlike artificial intelligence a reality, methods for making genetically modified organisms self-destruct on escape from the lab, and more. **Illustration by Tavis Coburn.**

Photograph by Grant Delin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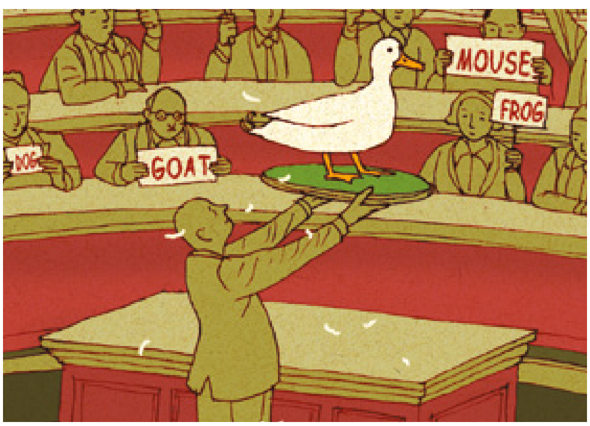

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Six scientists and writers present their varied and sometimes opposing views about the United Nations climate treaty negotiations.
Go to www.ScientificAmerican.com/dec2015/climate

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Innovation Celebration

In August we celebrated the 170th anniversary of the founding of *Scientific American,* born on a Thursday, the 28th, and let you know we were kicking off several months of activities. (See our In-Depth Report at ScientificAmerican.com/report/celebrating-170-years-of-scientific-american1.) In this issue, the editors and I are pleased to close out the year by sharing with you a special report that showcases the wonders wrought by human ingenuity.

Perhaps we're optimists by nature, but we've always found ourselves looking forward to a future powered by the basic research that is emerging from labs today. So it's only natural that we begin the feature well in this issue with our annual "World Changing Ideas," starting on page 30. In this section, you will learn about 10 advances that will help drive progress in the years ahead, including software that translates eye movements to control devices, a new method that identifies every virus in a given sample with near-perfect accuracy, and the rise of deep-learning computer networks that act more like a human brain to foster artificial intelligence, or A.I.

But *Scientific American* also grew up with the science and technologies that its editors have covered since 1845. We are unique in having scientists—Nobelists among them [*see box below*]—regularly write about their work alongside our award-winning journalists, providing a knowing and expert eye over the unfolding proceedings. Turn to page 40 to take an armchair ride through an editorial time machine. You can journey through the landmark discoveries in the cosmos, an evolving understanding of our brain and physiology, and the increasing pace of communications and computing. Want more? Please see the link below. SA

Our Nobel Honor Roll

EVERY YEAR when the Nobel Prizes are announced, we editors are not only excited to see what scientific advances get recognized, but we are also always rooting for our past authors, many of whom contributed long before receiving science's high honor. To date, 155 Nobel laureates have written a total of 249 articles for *Scientific American.* We salute three past writers who will receive medals this month:

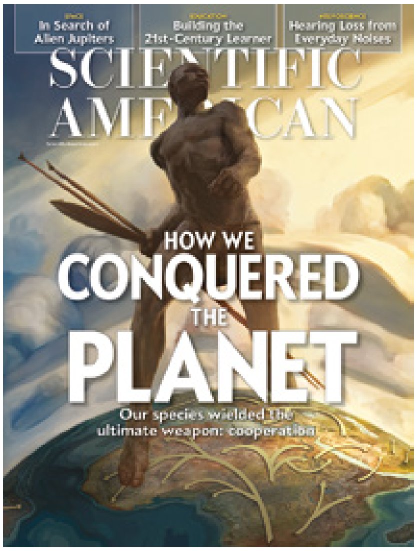
TAKAAKI KAJITA ("Detecting Massive Neutrinos," August 1999) and **ARTHUR B. McDONALD** ("Solving the Solar Neutrino Problem," April 2003) won the 2015 Nobel Prize in Physics for their work on puzzling out the riddle of the elusive neutrino.

PAUL MODRICH ("Engineering Life: Building a FAB for Biology," June 2006) shared the 2015 Nobel Prize in Chemistry for his work on how cells repair their damaged DNA.

ALL THE ARTICLES BY OUR NOBEL AUTHORS ARE AVAILABLE AT SCIENTIFICAMERICAN.COM/MAGAZINE/SA

GETTY IMAGES (*Nobel Prize medal*)

Illustration by Nick Higgins



August 2015

HOMO SAPIENS' SUCCESS

In "The Most Invasive Species of All," Curtis W. Marean includes a fanciful image of Neandertals telling boastful tales around their campfires. While this was clearly meant as a literary device, it points out a serious oversight: he left speech out of his list of current theories of why humans came to dominate the planet. And his few references to language imply that he believes speech was equally available to all human groups.

There is no scientific consensus for that, and based on anatomical differences, some researchers think speech was the key advantage modern humans had over the Neandertals. Indeed, it is hard to credit the level of cooperation Marean calls "hyperprosociality" and attributes as key to *Homo sapiens'* success as possible without speech.

Tracy Schwartz Matthews
Mountain View, Calif.

There is a questionable idea, which Marean seems to take for granted, that human success all comes down to better and better spearpoints and male activities. Why are all the allegedly successful attributes of our species male ones? It may have escaped his notice that virtually every aspect of human replication is determined by women. And according to some authors the act of gathering can provide more protein than hunting. The plentiful beds of shellfish Marean argues were highly important to human evolution would have been gathered, not hunted.

Adrian Verrinder
Bendigo, Australia

"There is a questionable idea that human evolutionary success all comes down to better and better spearpoints and male activities."
ADRIAN VERRINDER *BENDIGO, AUSTRALIA*

MAREAN REPLIES: On the issue of speech and language: I agree that the highly advanced hyperprosocial behavior exhibited by modern humans requires a reasonably advanced form of communication. We know that fully modern speech must have existed before 110,000 years ago because that is when the oldest surviving human lineage (the Khoisan peoples) originated, and that group has a fully modern language. There have been some estimates that language is as old as the shared common ancestor of modern humans and Neandertals. There is no consensus that Neandertals lacked the anatomical machinery for speech—we just do not have the relevant parts preserved.

Regarding Verrinder's objection to the overtly "male-centric" theme of my article: it is a sequel to my 2010 Scientific American *article "When the Sea Saved Humanity," in which I emphasized the importance of shellfish and plant collection to the survival of our species. The ethnographic record clearly shows that in hunter-gatherer societies, those two activities are typically the work of women. The 2010 article was about how food and shared ingenuity helped our species survive through a climate crisis, but the topic of the current article is what happens when one ethnolinguistic group invades the territory of another. Such events are penetrating, brutal, bloody affairs, and the killing and butchery that ensue is the product of weapons and men.*

SAVE OUR HEARING

In "Hidden Hearing Loss," M. Charles Liberman describes how elevated noise levels can permanently damage auditory nerve fibers. As a doctor and a member of the board of the American Tinnitus Association, I can say that Liberman's work and thousands of peer-reviewed articles have established that noise is a hazard for hearing and general health.

In the 1950s, when the medical and scientific communities became aware that smoking caused cancer and heart disease, they spoke out about it and spearheaded antismoking efforts. Such efforts eventually led to one of the great public health successes of the last quarter of the 20th century: a marked decrease in smoking and our essentially smoke-free environment. It is time for a similar effort to make our environment quieter before we are all deaf.

Daniel Fink
Beverly Hills, Calif.

SPACEFLIGHT RHETORIC

In "Space Cowboys" [Forum], Linda Billings complains that the rhetoric about space exploration in the U.S. is colonialist and marginalizes women, minorities and non-Americans.

It is true that colonialist attitudes, applied within the confines of Earth, have been very damaging. But in the realm of space exploration, who stands to be exploited? The "conception of outer space as a place of wide-open spaces and limitless resources" she criticizes is completely accurate. By encouraging support for space exploration with such frontier imagery, we can reap benefits for the species as a whole.

Her proposition that a rhetoric of exploration would appeal only to white American males is also objectionable. As a non-American female science student, a frontier is exactly how I view space, and such language is engaging to me.

Sarah Flaherty
Hamilton, Ontario

BENEFITS OF TESTING

I was interested in reading about the way retrieval practice, in which testing is used to reinforce learning rather than assess it, was being used in the classroom in "A New Vision for Testing," by Annie Murphy Paul [Building the 21st-Century Learner]. A var-

iation of this learning has been growing in popularity among many language learners for years now, with many using flashcard programs to employ "spaced repetition," in which the time periods between learning and reviewing material increase.

Traditional teaching tends to place more onus on learners to find a way to absorb the material themselves than it does on the teacher in helping them. It is also important to empower students with a method for studying at home using a framework such as retrieval practice.

Steve Warner
Glasgow, Scotland

I recall that in the 1950s and 1960s, we learned using many of the same methods as are used in "retrieval practice": weekly quizzes discussed in recitations and labs, problem sets that had to be turned in and discussed in class, end-of-chapter questions in textbooks that were handed back with corrections. That system seemed to have worked quite well in producing scientists and engineers of my generation.

Frank Heppner
University of Rhode Island

GUN CONTROL

I was disappointed that the editors decided to wade into the controversy over doctors questioning patients about gun ownership in "Docs, Glocks and Stray Bullets" [Science Agenda]. Does anyone believe that a doctor who does not even own a gun can advise on handgun safety? Doctors should stick to their area of expertise.

Bob Carney
McLean, Va.

The right to have a gun is an anathema to most of us outside the U.S. The level of gun deaths—murders, suicides and accidents—shows that allowing citizens to own them is bad for society. To silence doctors on this subject is incomprehensible. Not to have an ownership database is astonishing.

Jon Scott
via e-mail

ERRATUM

"Hidden Hearing Loss," by M. Charles Liberman, incorrectly refers to correcting myopia by laser surgery of the lens. Such surgery is performed on the cornea.

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/dec2015

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PROMOTION

The Agenda Setters

Bringing Science to Life

SCIENTIFIC AMERICAN's 170th Anniversary

One New York Plaza, New York City | August 26, 2015

We marked **SCIENTIFIC AMERICAN's 170th Anniversary** with a tweet-up celebration held at our brand new offices in the Financial District of New York. It was a great opportunity to gather some of our friends for a look at historical treasures from our archives and the beautiful views from our offices. Many science luminaries attended, including a great, great grandson of Charles Darwin, Matthew Chapman, and theoretical physicist Brian Greene. Of course, it wouldn't have been a party without a very special cake made to look like our first issue from 1845!

The Price of Pollution

Low oil and gas prices make this the right time to tax fossil fuels

By the Editors

In British Columbia, air pollution dwindles while the economy grows. The Canadian province began to tax fossil-fuel users, ranging from utility companies to car drivers, in 2008. Since then, the economy has grown by an average of nearly 2 percent a year, despite a big national recession through 2009, outpacing the rest of Canada. The use of gasoline, coal and other carbon-based fuels has dropped 16 percent during the same period, reducing greenhouse gas pollution. Today the carbon levy is $30 (Canadian) per metric ton; in exchange, both companies and individuals get income tax cuts and other savings.

British Columbia copied this idea from its oil-producing neighbor, Alberta. The time is now right for the U.S. to copy them both and put a price on carbon pollution. Coal, gas and oil are so cheap at present that even with an added tax, fuel costs will remain lower than what people and companies paid just a few years ago.

This is basic market economics: put a monetary value on the use of the sky, and people will not treat it like a free dump. The idea has a long pedigree. In 1920 economist Arthur Pigou suggested that forcing polluters to pay for the air they abuse would discourage heavy use, like sin taxes imposed on alcohol or tobacco. Years later the late economist Ronald Coase, winner of the 1991 Nobel prize for economics, refined Pigou's idea. He proposed that governments could sell companies or individuals a legal right to pollute, forming a kind of pollution market. Everyone could compete to buy these allowances, which would drive up the price of dirty air. Coase's idea convinced even the late conservative icon Milton Friedman that trading, buying or selling pollution rights was the rational way to address environmental woes.

More recently, the U.S. has used this kind of market mechanism to combat one particular pollution problem: acid rain. In the 1990s President George H. W. Bush's administration set an overall limit on the amount of sulfur dioxide—the molecule responsible for the damaging precipitation—that could come out of power plant smokestacks. Shares in that amount were divvied up among polluters. These owners of power plants could stay within their share by installing emissions-scrubbing technology or switching to less polluting fuels. Or they could spend money to enlarge their share, buying permits from other polluters who had already cut emissions.

To tackle another problem—carbon dioxide—nine northeastern states have eased in a similar cap-and-trade program for power plants, and California has even included vehicles, as has the European Union. But attempts to expand this scheme to a national level in the U.S. have failed, derided by opponents as a hidden tax on companies that would cost jobs.

The more straightforward approach, a carbon tax, can have direct benefits for business and does not mean a higher overall tax bill. As it does in British Columbia, a carbon tax could replace other taxes. For example, a carbon tax of $25 per ton levied on coal, gas and oil might raise more than $100 billion that could offset payroll taxes, boost earned income tax credits, fund innovation research or pay to improve infrastructure, or any combination of the above. This is why the proposal has drawn support from all kinds of economists, including N. Gregory Mankiw, who advised Republican president George W. Bush, and Lawrence Summers, who advised Democratic president Barack Obama. The tax would not pain consumers either. In British Columbia today, the share of the tax at the gas pump is only about seven extra Canadian cents per liter.

If the word "tax" remains too frightening for politicians, there is another way, albeit a less direct one, to make an honest carbon market: stop spending tax dollars on subsidies for fossil fuels. More than half a trillion dollars are spent around the world making coal, gas and oil cheaper for businesses to find or consumers to burn, according to the International Monetary Fund. These gifts make fossil fuels appear falsely inexpensive. Any approach that stops obscuring the real price, whether it be a tax, a cap or a subsidy reform, would help clear the air. SA

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COMMENT ON THIS ARTICLE AT
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Illustration by Thomas Fuchs

Michael E. Mann is Distinguished Professor of Meteorology at Pennsylvania State University. His most recent book, with Lee R. Kump, is *Dire Predictions: Understanding Climate Change* (second edition, Pearson/DK Publishing, 2015).

Two Degrees of Freedom

The world can still avoid dangerous global warming if it acts fast

By Michael E. Mann

It is a steep hill to climb if the world is to avoid warming the earth's surface by no more than two degrees Celsius (3.6 degrees Fahrenheit), the limit beyond which we will seriously harm the planet. That number is driving the commitments many nations will make at the 2015 United Nations climate change conference in Paris (COP21) to reduce their greenhouse gas emissions.

Yet some critics have declared that the so-called 2° C target is impossible, saying we cannot deploy the technologies needed to decarbonize the economy in time. But we can. The obstacle is not a physical one—it is one of political and societal will.

Nobody has said it will be easy. More than 70 climate experts who advised the U.N. Framework Convention on Climate Change said limiting global warming to below 2° C "necessitates a radical transition … not merely a fine tuning of current trends."

We can emit only 300 billion more tons (270 billion more metric tons) of carbon into the atmosphere and keep warming below 2° C. At the current emissions rate of more than 10 billion tons a year, we will burn through this "carbon budget" in just three decades. According to one recent analysis, staying below 2° C would require that a third of all proved reserves of oil, half of all natural gas and 80 percent of coal remain in the ground.

That's a big ask. It means we have to phase out coal now and walk away from most if not all the Canadian tar sands (good-bye, Keystone XL pipeline). It also means that we cannot burn increasing amounts of natural gas as a "bridge" to a cleaner climate future powered by renewable energy sources.

The 2° C threshold is often equated with keeping the atmospheric concentration of carbon dioxide below 450 parts per million (ppm). The challenge is made tougher as we use less coal. When it burns, coal releases sulfate aerosol particulates into the atmosphere that reflect some of the sun's incoming energy back into space. For a 2014 *Scientific American* article, "False Hope," I calculated that to compensate for the drop to zero sulfur emissions by the end of the century, we have to meet a CO_2 target of about 405 ppm—just slightly above current levels.

Can we do it? Climate scientist James E. Hansen has made a compelling case that we could pull 100 billion tons of carbon from the air by massive reforestation—limiting land use enough to allow forests to grow back to their extent before human deforestation. That, along with reducing carbon emissions by several percent a year, which is challenging but doable, could meet the 2° C stabilization target.

History is replete with preemptive declarations of infeasibility that proved misguided. As Joe Romm of the Center for American Progress said in response to climate critics, "Thank goodness these pundits weren't around when we had to do something *really* difficult, like suffer millions of casualties and remake our entire economy almost overnight to win World War II." An inspired agreement at the COP21 climate summit in Paris this month could kick-start an ambitious but entirely feasible effort.

The key factor is that there are technological innovations and economies of scale that emerge only in the course of actually *doing* something. The price of solar cells globally, for example, has dropped by more than 50 percent over the past several years as China has ramped up production. Those who say "no we can't" are engaging in self-fulfilling prophecy. The U.S. has never been a nation of no-we-canters.

Even with innovation and scaling up, we may at some point have to deploy "direct-air capture" technology, which pulls carbon dioxide out of the atmosphere. That would be expensive, but Klaus Lackner, an engineering professor at Arizona State University, is confident that the cost could be brought down to $30 a ton with volume manufacturing.

The cost of taking action is only half as much as the cost of inaction. This is not the conclusion of the Intergovernmental Panel on Climate Change. It comes from ExxonMobil, which has pegged the true cost of carbon to society at $60 a ton. Other estimates are even higher. Can we afford to stabilize planetary warming below two degrees C? We can't afford *not* to. SA

SCIENTIFIC AMERICAN ONLINE
COMMENT ON THIS ARTICLE AT
SCIENTIFICAMERICAN.COM/DEC2015

Illustration by Andrew J. Nilsen

ADVANCES

The Indian cobra, *Naja naja,* opens its hood when threatened. It is one of the deadliest snakes on the Indian subcontinent.

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INSIDE

- Streets re-created in virtual reality elucidate why kids cross even when there is danger
- How volcanic hotspots arise
- An expert at diagnosing bad smells
- A glimpse of neutrinos from the beginning of time

HEALTH

Defanging Snakebites

New antivenom research could help tackle an ancient danger

Modern medicine can grow kidneys from scratch, halt the spread of infectious diseases such as Ebola and diagnose the cause of a cough with a smartphone, yet snakebites still thwart us. Every year venom from snakes kills nearly 200,000 people and leaves hundreds of thousands disfigured or disabled, making these legless squamates the second deadliest animal. Only mosquitoes may kill more people every year (by spreading the protozoa that cause malaria).

Venomous snakes recently slithered their way back into the news when it came to light that leaders in the pharmaceutical world had ceased developing antidotes. French drug company Sanofi Pasteur, for example, made headlines in September, when Doctors Without Borders pointed out that the final batch of FAV-Afrique—the only antivenom proved to effectively treat snakebite victims in sub-Saharan Africa—expires in June 2016. Sanofi, its sole manufacturer, had ended production in 2014 because the drug was not making enough money. Others in the industry had already made similar moves, including Behringwerke and Wyeth Pharmaceuticals (now part of Pfizer).

The treatment situation has become so dire that Doctors Without Borders now describes snakebites as "one of the world's

Antivenom development is stuck in the 19th century because the field is underfunded.

most neglected public health emergencies." And in October dozens of experts at the 18th World Congress of the International Society on Toxinology in Oxford, England, called for the World Health Organization to relist snakebite as a neglected tropical disease. Most bites occur in Africa and Southeast Asia.

Antivenom development is stuck in the 19th century because the field is underfunded, says David Williams, a clinical toxinologist and herpetologist who heads the Australian Venom Research Unit at the University of Melbourne and is also CEO of the Australian nonprofit Global Snakebite Initiative. To isolate compounds for treatment, researchers typically inject subtoxic levels of venom into animals, collect the antibodies formed by the immune response and purify the result. Antivenom must be tailored to an array of toxins across different regional snake species. No universal antidote exists.

Despite constraints, small research groups around the world are quietly working away at new, exciting solutions—waiting for a windfall of money and momentum. The most innovative of them is a targeted antivenom designed for sub-Saharan Africa that could serve as a blueprint for making cheaper compounds to counter bites from snakes found in other regions. Researchers from the U.K., Costa Rica and Spain started with proven "base antivenom" for three snakes and have begun screening it against toxins from additional snakes. Venom proteins that fail to bind to the base antivenom are screened for toxicity; only proteins identified as dangerous toxins become part of the immunizing mixture used to make the next antivenom batch more effective.

Such selective screening and iterative testing of specific proteins make for a stronger, targeted antidote compared with conventional antivenoms, which indiscriminately neutralize both toxic and nontoxic venom proteins. The group also plans to cut costs with a method pioneered in Costa Rica that requires fewer manufacturing steps. "Our goal is to make a product for sub-Saharan Africa that is cheaper or as cheap as $35 a vial," says Robert Harrison, head of the Alistair Reid Venom Research Unit at the Liverpool School of Tropical Medicine in England. Sanofi's product costs $150 per vial.

Other animals—and bacteria—may provide alternative antivenom. An opossum protein first identified in the 1990s has since been shown to protect mice from snake toxins that can cause widespread internal bleeding. Moreover, the protein neutralized hemorrhagic toxins from venomous snakes in both the U.S. and Pakistan. The finding suggests that the protein might possibly defend against all hemorrhagic snake toxins, says Claire Komives, a chemical engineer at San José State University. Komives has already demonstrated that she can engineer *Escherichia coli* bacteria to make the protein—which could reduce the cost of treatment to around $10 a dose. "I'm trying to make it in bacteria because we can scale [up production] cheaply," she says. To fund her research, Komives has turned to the crowdfunding service Experiment.com.

Research groups elsewhere have turned away from traditional antidote development altogether. Matthew Lewin, director of the Center for Exploration and Travel Health at the California Academy of Sciences, has begun screening existing FDA-approved drugs for chemical ingredients that could form the basis of an injection or pill that stabilizes people bitten in the field or at least gives them time to reach a hospital. "If you had a pharmaceutical antidote, you could have it on your person," Lewin says. Many snakebite deaths happen when victims cannot reach hospitals or clinics to receive an intravenous antivenom treatment.

Similarly, Sakthivel Vaiyapuri, a pharmacology researcher at the University of Reading in England, is screening for molecules that block the effects of snake venom. He also hopes to eventually develop a cocktail of chemical inhibitors that could lead to a universal antidote.

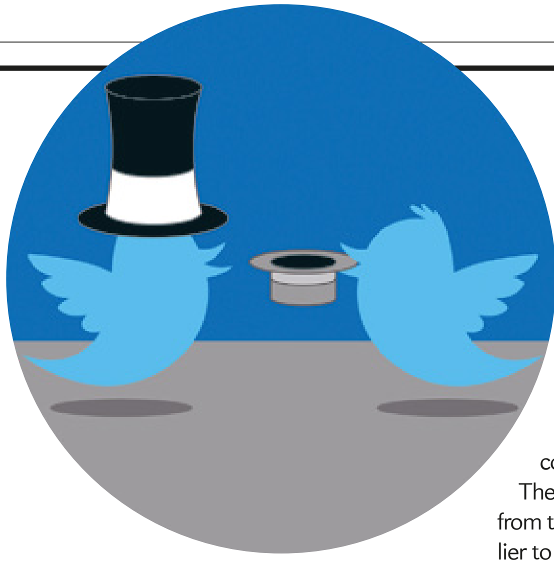
Modernized antivenom treatments would represent a solid first step toward reducing deaths from snakebites. Yet in the end, the best treatments in the world will fail without funding and distribution. "If the ministries of health responsible for health and well-being don't prioritize snakebite treatment," says Williams of the Global Snakebite Initiative, "you're banging your head against a brick wall." *—Jeremy Hsu*

PRECEDING PAGES: SURESH SHARMA *Getty Images*

MACHINE LEARNING

Money Talks—and Tweets

An analysis of more than 10 million posts to Twitter shows that users unknowingly tip their socioeconomic status



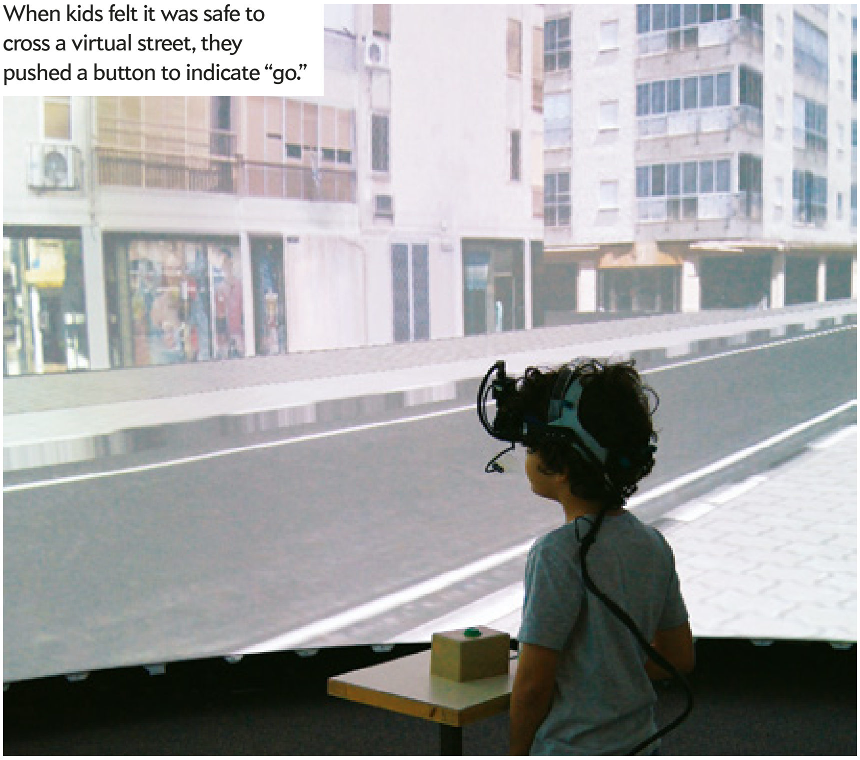
Like sex, money is a topic that most people avoid discussing publicly. Yet we regularly leave digital traces of our economic standing—even when expressing ourselves within Twitter's 140-character limit.

In an analysis of roughly 10.8 million tweets posted by more than 5,000 users of the online social media network, the pithy messages were found to provide enough information to reveal a user's income bracket. Daniel Preoţiuc-Pietro, a postdoctoral researcher in natural language processing at the University of Pennsylvania, and his colleagues relied on self-identified profession to sort 90 percent of their sample into corresponding income groups. They then used a machine-learning model, which can learn from data and make predictions based on them, to identify features unique to each group. When they tested the savvy model on the remaining 10 percent of subjects, it successfully predicted the financial means of those users.

As the researchers described this fall in the journal *PLOS ONE,* those with higher incomes tended to discuss business, politics and nonprofit work. People in lower brackets stuck mostly to personal subjects, such as beauty tips and experiences. "Higher-income people are using Twitter as a means of disseminating information; lower-income people use it more for social communication," Preoţiuc-Pietro says. The analysis also revealed that tweets from those who make more money are likelier to express fear or anger.

In previous machine-learning studies, Preoţiuc-Pietro and his colleagues were able to predict Twitter users' gender, age and political leaning. They could even detect signs of postpartum depression and post-traumatic stress disorder in tweets. The team continues to develop its model, but in the end "machine learning is only as powerful as the data we can get access to," Preoţiuc-Pietro says. "People should be aware of how much they inadvertently disclose about themselves." —*Rachel Nuwer*

Illustrations by Thomas Fuchs



When kids felt it was safe to cross a virtual street, they pushed a button to indicate "go."

COURTESY OF ANAT MEIR ET AL.

TECHNOLOGY

Kids Can Do Better in the Crosswalk

Training could bolster children's street-crossing skills

"Look both ways before you cross the street!" "Look left, right and left again!" These classic childhood safety lessons span generations and cultures. Yet traffic accidents remain one of the most common sources of injuries and fatalities for children around the world. In the European Union, children younger than 14 years account for a higher proportion of pedestrian mortalities than any other age group except the elderly; in the U.S., among children killed by cars, nearly a quarter were on foot. The numbers are particularly chilling in Israel, where kids account for 20 percent of pedestrian deaths.

COMMENT AT ScientificAmerican.com/dec2015

Past studies have found that youngsters are less adept at identifying road hazards than adults, but Anat Meir, a lecturer in industrial engineering and management at Ben-Gurion University of the Negev and the Holon Institute of Technology in Israel, wanted to pinpoint exactly which behaviors lead to accidents, with the goal of finding ways to correct them.

> **Children aged seven to nine exhibited the least caution when crossing, typically deciding to step into the virtual road with little or no hesitation.**

To do that without putting anyone in danger, she turned to virtual reality. In 2013 Meir and her colleagues simulated 18 prototypical streets in Israel and used an eye-tracking device to study how 46 adults and children (ranging in age from seven to 13) evaluated when it was safe to cross. Children aged seven to nine, they found, exhibited the least caution when crossing, typically deciding to step into the virtual road with little or no hesitation, even when their field of vision was restricted. "We had parents looking on who were like, 'Wow, I cannot believe my child just crossed there!'" Meir says. "It caused them to reassess their child's road-crossing abilities." The older children did not perform much better, though for different reasons. They often lingered on the curb for an inordinate amount of time—an indication that they are less able to distinguish between safe and hazardous situations than adults—and in interviews did not express an understanding of how factors such as car speed and field of vision affect crossing safety.

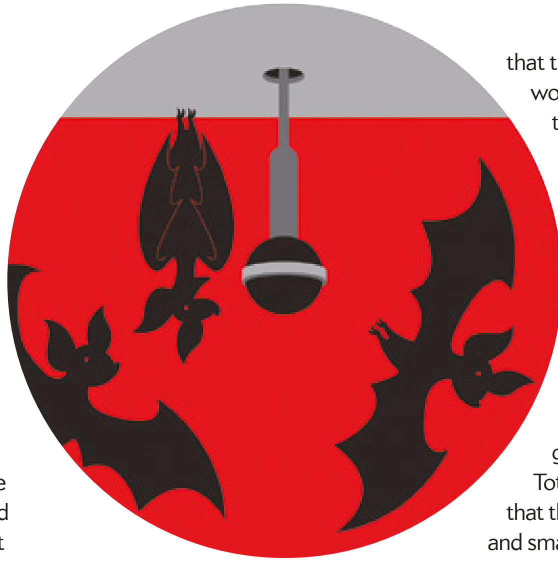
Interventions do seem to improve crossing success. In Meir's most recent study, described in *Accident Analysis & Prevention,* two dozen seven- to nine-year-olds underwent 40 minutes of hazard-detection training. Afterward, Meir and her colleagues compared trainees' and control kids' performances in the virtual road-crossing task. The children who received safety instructions were significantly better at crossing than the control subjects—to the point that their crossing skills resembled those of adults.

Next, Meir and policy makers aim to figure out how to translate these findings into the real world. "These kind of results are important because you cannot build interventions without an understanding of the problem," says Joseph Kearney, a professor of computer science and associate dean of research and infrastructure at the University of Iowa, who was not involved in the work. "Now it's up to people with their feet on the ground to determine how they can develop training programs for children and for parents about good road-crossing habits." *—Rachel Nuwer*

ANIMAL BEHAVIOR

Batty Performers

When courting lovers, males in one bat species rotate who gets the mic



When day draws to a close in New Zealand, the forests echo with screeches. There the male lesser short-tailed bat sings up to 100,000 songs a night—more than any other animal—to woo a mate. He serenades from a special singing roost used solely for the purpose of sexual display. But not every one of these Romeos is a one-man show. After a three-year study of the nocturnal mammals' habits, Cory Toth of the University of Auckland found that males in nearly half the 12 singing roosts he observed in North Island turned the stages into time-shares. “One male will be singing, will leave, and as little as three seconds later, another male will enter the roost and start singing,” Toth says. In total, two to five males perform every night in one roost, singing for a few hours each.

Overall, the shared roosts broadcast more songs than those occupied by only one bat all night, increasing the chances that a passing female will stop by. The behavioral ecologist initially hypothesized that the time-share bats were related and worked together to ensure reproductive success for their specific gene pool. But when males in three of four singing roosts turned out to be unrelated or only distantly related, Toth's attention turned to bat size: the males that took turns on the stage were significantly larger than those who sang alone. Larger males expend more energy in the daily tasks of survival and thus might save energy at night by taking shifts singing, Toth says. In fact, DNA testing revealed that the reproductive success for larger and smaller bats within the colony was about the same, suggesting that the joint ownership arrangement helps the big guys compete with little ones.

The lesser short-tailed bat is one of only two remaining endemic land mammals in the country (the second is the long-tailed bat) and is endangered. Knowledge of the reproductive habits of the species could inform conservation efforts. *—David Godkin*

COMMENT AT ScientificAmerican.com/dec2015

GEOLOGY

The Molten Mechanics of Inner Earth

Dozens of exceptionally active volcanic sites dot the earth. But geologists have debated the cause of these so-called hotspots for decades. Do they originate in mantle plumes—vast upwellings of superhot rock from the earth's core—or in shallower reservoirs of heat in the upper mantle? Seismologists at the University of California, Berkeley, and Lawrence Berkeley National Laboratory recently took an unprecedented look at what lies below the earth's surface to depths of thousands of kilometers. After performing MRI-like tomographies of the planet's innards, they found more than two dozen mantle plumes rising continuously from the core to the surface—many of them directly feeding hotspots. The plumes, reported in *Nature,* provide the first direct evidence that these columns of heat generate volcanic hotspots, such as Iceland and the island chain of Hawaii. —*Shannon Hall*

28

Number of mantle plumes rising continuously from the earth's core.

600–800 kilometers

Average width of plumes, three to five times larger than computer models predicted.

44 terawatts
(44 trillion joules per second)

Internal heat the earth sheds by way of mantle plumes.

GETTY IMAGES (*lava flow*); SOURCES: "BROAD PLUMES ROOTED AT THE BASE OF THE EARTH'S MANTLE BENEATH MAJOR HOTSPOTS," BY SCOTT W. FRENCH AND BARBARA ROMANOWICZ, IN *NATURE,* VOL. 525; SEPTEMBER 3, 2015 (*first item*); "MANTLE PLUMES SEEN RISING FROM EARTH'S CORE," BY ERIC HAND, IN *SCIENCE,* VOL. 349; SEPTEMBER 4, 2015 (*second and third items*)

ENVIRONMENT

Banking on Groundwater

Hydrologists experiment with a farming technique that could ease drought pains

Intentional flooding of farmland, such as the walnut orchard above, has the potential to recharge California's aquifers.

California is parched. Rivers that usually surge now trickle, and once large reservoirs stand as puny pools. Those most critically affected by the state's four-year drought are the Central Valley's farmers, whose livelihoods are threatened. Without rain to irrigate croplands, growers repeatedly turn to underground aquifers, but the overpumping has taken a toll, causing water tables to drop dramatically.

Fortunately, this winter's forecast in California calls for plenty of rain, most likely amplified by strong El Niño conditions. Storm drainage systems typically redirect most floodwater out to sea, but given the region's intense water deficit, hydrology scientists at the University of California, Davis, are experimenting with so-called groundwater banking, which involves sending storm water to flood fallow fields where it can percolate into the soil and replenish aquifers. Storm water absorbed in the winter can then serve as a reservoir of summer refreshment for growing crops, says U.C. Davis's Helen Dahlke.

For two months this winter Dahlke and her team will flood almond orchards in the Central Valley near Davis to a depth of two feet by redirecting rainfall through a network of ditches originally designed to divert floodwater away. To measure success, they will then monitor how much water filters into the water table over the course of two years. They will also test the quality of the infiltrated water and check trees for root rot, which could be detrimental to crop yield. If the method pans out, pear, plum and walnut tree orchards might also benefit from intentional flooding, according to a recent study led by Anthony O'Geen of the University of California's Division of Agriculture and Natural Resources.

Previous tests of the technique have proved successful. In 2011 Terranova Ranch manager Don Cameron diverted Kings River floodwater in Fresno County onto 240 acres of vineyards and other farmland, inundating them for five months. "They looked like rice fields, but the grapes did fine," Cameron says. Seventy percent of the water percolated into the water table, where it was available for pumping back onto fields during the next growing cycle.

Questions remain about groundwater banking's effects on tree physiology and the extent to which salts and nitrates from fertilizers could migrate into drinking water. The costs of storm water diversion and legal issues, including who owns the captured water, also need to be sorted out. Still, some 3.6 million acres of agricultural land statewide could eventually serve as receptacles for groundwater recharge. And with climatologists expecting the state's rainfall deficit to continue long after a single season of strong winter storms, a growing number of ranchers are more than intrigued by the possibilities for their land. Says Cameron: "Drought makes people more creative." —*Jane Braxton Little*

COURTESY OF UNIVERSITY OF CALIFORNIA BOARD OF REGENTS

COMMENT AT ScientificAmerican.com/dec2015

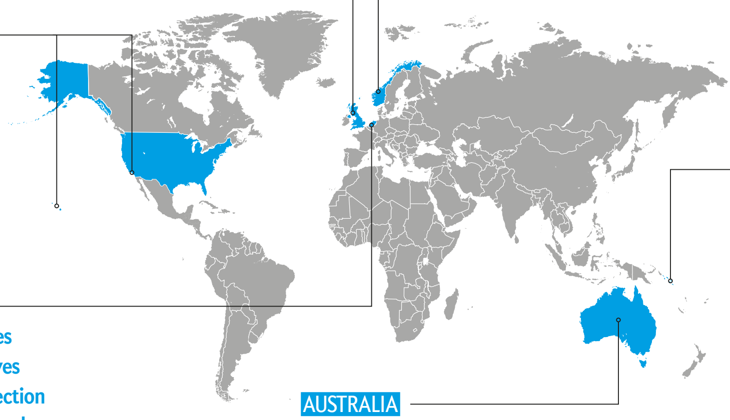
IN THE NEWS

Quick Hits

U.K.
A clinical trial investigating a treatment for blindness is under way this winter to evaluate the safety and efficacy of replacing diseased eye cells with stem cells.

NORWAY
After a local seed bank in Syria was damaged in the country's civil war, researchers have made the first-ever withdrawal from the Svalbard Global Seed Vault. The master vault holds more than 860,000 seed samples collected from around the world in an effort to ensure against their loss in the wild. The replacement seeds will be stored in Lebanon and Morocco.

U.S.
Following a federal court hearing, the U.S. Navy has agreed to limit its use of sonar in specified areas around the Hawaiian Islands and southern California. Sonar activity has been shown to harm marine animals.



SOLOMON ISLANDS
Biologists captured underwater footage of a glow-in-the-dark sea turtle, the first reptile known to exhibit biofluorescence.

NETHERLANDS
Delta Flume, a facility that produces the world's largest man-made waves to study and improve coastal protection systems, opened in Delft. Waves reach as high as 4.5 meters.

AUSTRALIA
The government approved a new curriculum for elementary school students, who will now learn computer coding and programming in place of history and geography.

For more details, visit
www.ScientificAmerican.com/dec2015/advances

ODD JOBS

Ned the Nose

An odor scientist and engineer knows how to snuff out bad aromas

Ned Ostojic's nose has led him to sites that range from odd to repugnant. He has inhaled the air of tuna canneries in American Samoa, whiffed gooey kibble at pet-food factories in Canada and sniffed sewage tanks in Brooklyn. Worldwide, there are only a handful of people like him: experts at diagnosing offensive odors. His clients are usually desperate to eliminate a stench that bothers neighbors or presents a hazard to workers. Trained as an analytical chemist, his job is to find the source of a smell and then figure out how to fix it.

Scientific thinking on olfaction posits that there are hundreds of odor receptors in the human nose, each responsible for detecting different odor molecules. Smells are the perception of combinations of these molecules and as such are tricky to manipulate and record. The act of smelling itself has long been an "orphan sense," especially compared with a more dominant faculty such as sight, Ostojic says. "We can represent the whole world on our TVs using just three colors, we can see to the end of the observable universe and we can see a single atom," he asserts, but smell remains elusive.

As a result, Ostojic approaches his job with a mix of science and art. In the field, he employs an olfactometer with an aggressive brand name: Nasal Ranger. Held up to his face, it works like a gas mask at first. Once his nose adjusts to that confined odorless environment, Ostojic adds controlled amounts of the surrounding air to map the intensity and spread of a stink.

Thousands of New Yorkers can thank Ostojic and his Nasal Ranger for rendering the city's largest sewage treatment plant scent-free (*above*). "We had a horrendous record," says Jim Pynn, who recently retired as the superintendent of Newtown Creek Wastewater Treatment Plant in Brooklyn. "We had such a disgusting, putrid smell that even I was left to retch by some of the odors in the plant." In this case, everyone knew where the stench was coming from: aeration tanks. So Ostojic developed a way to cover the tanks and then ventilate the fetid air through wide cylinders of porous carbon, which absorbs odor. Now the site smells neutral enough to serve as a shooting location for movies, such as *Salt,* starring Angelina Jolie; film crews have had no idea they were shooting at a sewage plant, Pynn says. "When someone has to ask me what goes on here, we've met out goal," says Pynn, who calls Ostojic a "silent hero."

Ostojic's next projects include mapping the odor footprints of paint fumes at car factories in Michigan and of decomposing garbage buried in landfills in Kentucky. Advances in gas chromatography now allow him and other engineers to separate odor compounds and quantify them, but those data shed no light on whether people will tolerate particular nasal assaults. After all, an odor only becomes a problem when people complain about it. "It all leads back to the human nose," Ostojic says.

—Megan Gannon

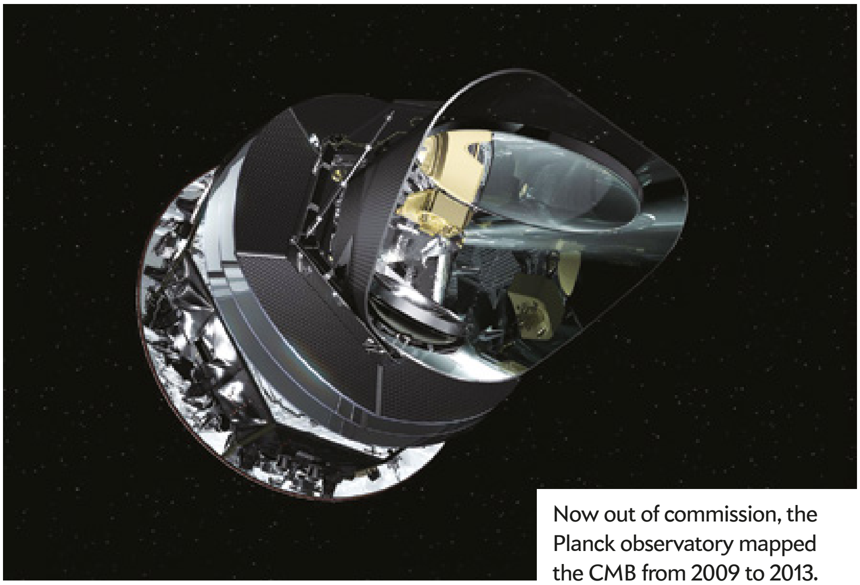
MITCH WAXMAN

COMMENT AT ScientificAmerican.com/dec2015

PHYSICS

The Big Bang's Particle Glow

Astronomers have indirectly spotted neutrinos born just one second after the birth of the universe



COURTESY OF EUROPEAN SPACE AGENCY (*artist's conception of Planck*)

Now out of commission, the Planck observatory mapped the CMB from 2009 to 2013.

The universe's oldest light hasn't made a pit stop for 13.82 billion years—beginning its journey just 380,000 years after the big bang. That light, the so-called cosmic microwave background (CMB), serves as a familiar hunting ground for astronomers who seek to understand the universe in its infancy. Unfortunately, it also obscures what lies beyond it: the first hundreds of thousands of years of the universe. Now astronomers think they have peeked beyond even the CMB by capturing evidence of neutrinos traveling since the cosmos was just a second old.

Neutrinos, fundamental particles with no electric charge and very little mass, escaped from the big bang nearly immediately. Their elusive nature allows them to slip through almost all physical barriers, rarely interacting with normal matter. On the rare occasions that they bump into photons, however, they alter the particles' temperatures ever so slightly. It was this temperature shift that astronomers from the University of California, Davis, recently noticed in maps of the CMB produced by the European Space Agency's Planck satellite. They describe this "cosmic neutrino background" in a recent paper published in the journal *Physical Review Letters.*

Models of the big bang predicted the cosmic neutrino background decades ago, but this indirect observation is the most robust yet. The discovery "gives us a new window on the universe," says Lawrence M. Krauss, codirector of the Cosmology Initiative at Arizona State University, who was not involved with the study. The detection also constrains properties of neutrinos, which are by far the strangest beasts in the particle zoo. For example, it proves that neutrinos cannot interact with themselves, like many other particles do. If they could, they would leave different signatures within the CMB than those observed.

Further detections of these primordial neutrinos may explain why there are 10 billion particles of matter in the universe for every one antimatter particle. The asymmetry was produced in the early universe, and experts think neutrinos had something to do with it, if only because they are so mysterious. "Because we know less about neutrinos, you can be more creative with the kinds of physics you introduce," the study's co-author Lloyd Knox says. Although these particles are incredibly difficult to detect directly, Knox anticipates that hints from cosmological observations will help solve many neutrino puzzles—and therefore provide a more revealing peek of the universe as it once was. —*Shannon Hall*

EDUCATION

She Faired Well

Teen walks away a winner from the Google Science Fair for a speedy Ebola test

Students at Google's annual science fair tackled Alzheimer's, pollution, and more.

It took Olivia Hallisey, now 17, just one year to develop a possible solution to an intractable issue facing public health workers: the lack of a rapid, portable, early diagnostic test for the Ebola virus. The effort did not go unnoticed: she won the grand prize at September's Google Science Fair. (*Scientific American* co-sponsors the awards.)

Hallisey, currently a high school junior (*right*), lives in Greenwich, Conn.—far removed from the West African communities hit hardest by the most recent Ebola outbreak. After reading reports of how quickly the disease was spreading through Guinea, Sierra Leone and Liberia, Hallisey felt moved to help, and with encouragement from her science research teacher, she looked into existing tests for Ebola.

She found that most tests require electricity and refrigeration, which are both in short supply in rural villages, and take hours or days to yield results. Diagnoses often came after patients had transmitted the virus to others. "The best way to limit Ebola's spread is if you can isolate someone before they're contagious," Hallisey says.

With that in mind, Hallisey came across a silk fiber derivative that could keep test components stable without refrigeration. She then conferred with the material's developers, biomedical engineers at Tufts University, and figured out how to use the material to create a paper-based test that is portable, operates at room temperature and returns results within 30 minutes. Next, she hopes to get the test into the hands of doctors who can evaluate her device in the field. —*Anna Kuchment*

COURTESY OF ANDREW FEDERMAN

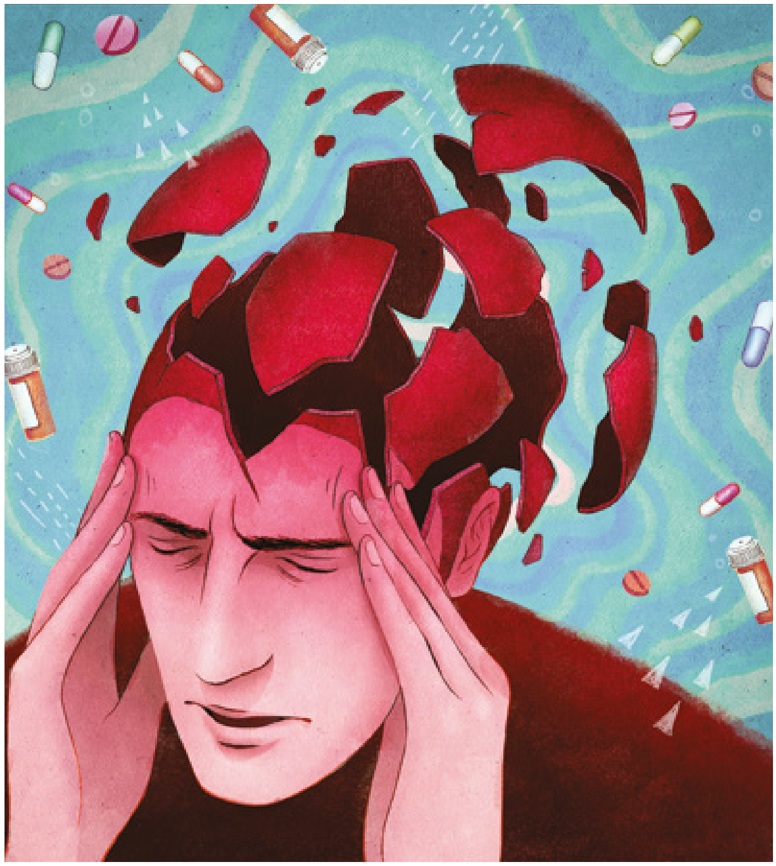
COMMENT AT ScientificAmerican.com/dec2015

David Noonan is a science and medical writer. He wrote about treatments for vertigo in the August issue.

A Pain in the Brain

The cause of migraine headaches has eluded scientists for centuries. Now a theory blaming one nerve has led to drugs that prevent attacks

By David Noonan



The 63-year-old chief executive couldn't do his job. He had been crippled by migraine headaches throughout his adult life and was in the middle of a new string of attacks. "I have but a little moment in the morning in which I can either read, write or think," he wrote to a friend. After that, he had to shut himself up in a dark room until night. So President Thomas Jefferson, in the early spring of 1807, during his second term in office, was incapacitated every afternoon by the most common neurological disability in the world.

The co-author of the Declaration of Independence never vanquished what he called his "periodical head-ach," although his attacks appear to have lessened after 1808. Two centuries later 36 million American migraine sufferers grapple with the pain the president felt. Like Jefferson, who often treated himself with a concoction brewed from tree bark that contained quinine, they try different therapies, ranging from heart drugs to yoga to herbal remedies. Their quest goes on because modern medicine, repeatedly baffled in attempts to find the cause of migraine, has struggled to provide reliable relief.

Now a new chapter in the long and often curious history of migraine is being written. Neurologists believe they have identified a hypersensitive nerve system that triggers the pain and are in the final stages of testing medicines that soothe its overly active cells. These are the first ever drugs specifically designed to prevent the crippling headaches before they start, and they could be approved by the U.S. Food and Drug Administration next year. If they deliver on the promise they have shown in studies conducted so far, which have involved around 1,300 patients, millions of headaches may never happen.

"It completely changes the paradigm of how we treat migraine," says David Dodick, a neurologist at the Mayo Clinic's campus in Arizona and president of the International Headache Society. Whereas there are migraine-specific drugs that do a good job stopping attacks after they start, the holy grail for both patients and doctors has been prevention.

Migraine attacks, which affect almost 730 million people worldwide, typically last from four to 72 hours. Most sufferers have sporadic migraines and are laid low during 14 or fewer days a month. Those with a chronic form—almost 8 percent of the migraine population—suffer 15 or more monthly "headache days." Attacks are often preceded by fatigue, mood changes, nausea and other symptoms. About 30 percent of migraine patients experience visual disturbances, called auras, before headaches hit. The total economic burden of migraine in the U.S., including direct medical costs and indirect costs such as lost workdays, is estimated at $17 billion annually.

In the 5,000 years since migraine symptoms were first described in Babylonian documents, treatments have reflected both our evolving grasp and our almost comical ignorance of the condition. Bloodletting, trepanation and cauterization of the shaved scalp with a red-hot iron bar were common treatments during the Greco-Roman period. The nadir of misguided remedies was probably reached in the 10th century A.D., when the otherwise discerning ophthalmologist Ali ibn Isa recommended binding a dead mole to the head. In the 19th century medical electricity had become all the rage, and migraine patients were routinely jolted with a variety of inventions, including the hydro-

Illustration by Julia Yellow

electric bath, which was basically an electrified tub of water.

By the early 20th century clinicians turned their attention to the role of the blood vessels, inspired in part by observations of strong pulsing of the temporal arteries in migraine patients, as well as patients' descriptions of throbbing pain and the relief they got from compression of the carotid arteries. For decades to come, migraine pain would be blamed primarily on the dilation of blood vessels (vasodilation) in the brain.

That idea was reinforced in the late 1930s with the publication of a paper on the use of ergotamine tartrate, an alkaloid that was known to constrict blood vessels. Despite an array of side effects, among them vomiting and drug dependence, it did stop attacks in a number of patients.

But if vasodilation was part of the puzzle, it was not the only thing going on in the brains of migraine sufferers, as the next wave of treatments suggested. In the 1970s cardiac patients who also had migraines started telling their doctors that the beta blockers they were taking to slow rapid heartbeats also reduced the frequency of their attacks. Migraine sufferers taking medicines for epilepsy and depression, and others receiving cosmetic Botox injections, also reported relief. So headache specialists began prescribing these "borrowed" drugs for migraines. Five of the medications eventually were approved by the FDA for the condition. Unfortunately, it is still not known exactly how the adopted drugs (which are effective in only about 45 percent of cases and come with an array of side effects) help migraines. Dodick says they may act at various levels of the brain and brain stem to reduce excitability of the cortex and pain-transmission pathways.

Overactive nerve cells respond to typically benign lights, sounds and smells by releasing chemicals that transmit pain signals and cause migraine.

The first migraine-specific drugs, the triptans, were introduced in the 1990s. Richard Lipton, director of the Montefiore Headache Center in New York City, says triptans were developed in response to the older idea that the dilation of blood vessels is the primary cause of migraine; triptans were supposed to inhibit it. Ironically, subsequent drug studies show that they actually disrupt the transmission of pain signals in the brain and that constricting blood vessels is not essential. "But they work anyway," Lipton says. A survey of 133 detailed triptan studies found that they relieved headache within two hours in 42 to 76 percent of patients. People take them to stop attacks after they start, and they have become a reliable frontline treatment for millions.

What triptans cannot do—and what Peter Goadsby, director of the Headache Center at the University of California, San Francisco, has dreamed about doing for more than 30 years—is prevent migraine attacks from happening in the first place. In the 1980s, in pursuit of this goal, Goadsby focused on the trigeminal nerve system, long known to be the brain's primary pain pathway. It was there, he suspected, that migraine did its dirty work. Studies in animals indicated that in branches of the nerve that exit from the back of the brain and wrap around various parts of the face and head, overactive cells would respond to typically benign lights, sounds and smells by releasing chemicals that transmit pain signals and cause migraine. The heightened sensitivity of these cells may be inherited; 80 percent of migraine sufferers have a family history of the disorder.

Goadsby co-authored his first paper on the subject in 1988, and other researchers, including Dodick, joined the effort. Their goal was to find a way to block the pain signals. One of the chemicals found in high levels in the blood of people experiencing migraine is calcitonin gene-related peptide (CGRP), a neurotransmitter that is released from one nerve cell and activates the next one in a nerve tract during an attack. Zeroing in on CGRP and interfering with it was hard. It was difficult to find a molecule that worked on that neurotransmitter and left other essential chemicals alone.

As biotech engineers' ability to control and design proteins improved, several pharmaceutical companies developed migraine-fighting monoclonal antibodies. These designer proteins bind tightly to CGRP molecules or their receptors on trigeminal nerve cells, preventing cell activation. The new drugs are "like precision-guided missiles," Dodick says. "They go straight to their targets."

It is that specificity, and the fact that scientists actually know how the drugs work, that has Dodick, Goadsby and others excited. In two placebo-controlled trials with a total of 380 people who had severe migraines up to 14 days per month, a single dose of a CGRP drug decreased headache days by more than 60 percent (63 percent in one study and 66 percent in the other). In addition, in the first study, 16 percent of the patients remained totally migraine-free 12 weeks into the 24-week trial. Larger clinical trials to confirm those findings are currently under way. So far the CGRP drugs work better at prevention than any of the borrowed heart or epilepsy drugs and have far fewer side effects. They are given to patients in a single monthly injection.

Migraine specialists are also exploring other treatments, including forehead and eyelid surgery to decompress branches of the trigeminal nerve, as well as transcranial magnetic stimulation (TMS), a noninvasive way of altering nerve cell activity.

Lipton says he has had some good results with TMS. He has also referred patients for surgical interventions but says the experience "has been disappointing," and he is not recommending it. For his part, Goadsby views surgeries and high-tech efforts as a kind of desperation: "They strike me as a cry for help. If we better understood migraine, we'd know better what to do."

Even though the cause now appears rooted in the trigeminal nerve system, the origin of its overactive cells is still a mystery, Goadsby says. "What's the nature of what you inherit when you inherit migraine?" he asks. "Why you, and why not me?" If researchers untangle the genetics of migraine, Jefferson's "periodical head-ach" may loosen its painful modern grip. SA

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

The Tech Jungle

How big tech companies lure you into their digital ecosystems

By David Pogue

The question is no longer, "What phone should I get?"

That *was* an important question immediately after the arrival of the iPhone and its competitors. But now it's time to admit that today's smartphones (and tablets) are nearly identical. Apple and Google (maker of Android phone software) have copied each other's ideas so completely that the resultant phones are incredibly close in looks, price, speed and features.

These days the Apples, Googles and Microsofts of the world are competing on a different battlefield: they're racing to build the best, most enticing *ecosystem*. Each is creating a huge archipelago of interconnected products and services. It's about velvet handcuffs: making it easy for you to embrace its offerings and as hard as possible to switch to a rival's.

A typical ecosystem includes hardware (phone, tablet, laptop, smartwatch, TV box); online stores (music, movies, TV, e-books); synchronization of your data across gadgets (calendar, bookmarks, notes, photographs); cloud storage (a free online "hard drive" for files); and payment systems (wave your watch or phone instead of swiping a credit card).

For consumers, the choice is now what *suite* of products they like best.

If you're one of these companies, though, you've got a difficult decision to make: Should you open up your services to people who use your competitors' products? Say, let an iPhone user load an Outlook calendar or let a Microsoft Band smartwatch wearer sync data to an Android tablet.

On one hand, making your software available to those outside your ecosystem could introduce the rest of the world to the superiority of your products—and possibly bring in new consumers.

On the other hand, you would lose the exclusivity of those services as a lure. Why would anyone switch if she or he can already get the best of a rival's offerings?

So what approach are the giants taking? It's a mixed bag.

Apple is the most closed. In general, it writes apps only for iPhones and iPads. You can't make a FaceTime call to an Android or Windows Phone, for example, or run the Apple Maps app on those devices (not that you'd want to). And you can't use the Apple Watch with anything but an iPhone. You *can,* however, use Apple's iCloud (online file storing and sync services) on a Windows device—but not on one using Google's Android.

Google goes to great lengths to make its wares available to other platforms. If you have an iPhone, you can use Google's apps (Gmail, Chrome, Google Maps), services (Docs, Sheets, Slides) and even digital store (Books, Music, Newsstand). The services and store are also available to Mac, Windows and Linux users. You can even link an Android Wear smartwatch with an iPhone.

Then there's Microsoft. Microsoft Office is available for just about anything with a screen, as are many of its mobile apps.

Why such inconsistency?

It helps to understand the individual corporate motives. Although these three companies offer so many similar (okay, almost identical) gadgets and services, each is actually running on an entirely different business model. Apple is primarily in the business of selling hardware; Microsoft, software; Google, ads. Each has different considerations in calculating what to open up.

And Apple and Google continue to branch out; both now offer, if you can believe it, software for your car dashboard and home-automation system designed to work with their respective smartphones. Surely Microsoft won't be far behind. Samsung boasts its own cluster of competitive products and linked services. Even Amazon—once a *bookstore,* for goodness's sake—now makes phones, tablets and TV boxes.

You, the consumer, should be delighted by this direction. Perhaps dismayed by all the duplication of effort but happy there's competition, which always begets innovation (and often lower prices). And you should be pleased that overall the trend seems to be for these companies to make more of their services accessible, no matter which phone or computer you own.

Eventually the ecosystems may well become nearly identical, too. Maybe at that point, the question will once again become, "What phone should I get?" SA

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WHAT EACH TECH ECOSYSTEM OFFERS:
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Illustration by Jori Bolton

2015 WORLD CHANGING IDEAS

INNOVATION

10 big advances that will improve life, transform computing and maybe even save the planet

In 1878 Thomas Edison took to the pages of this magazine to clear up a few misconceptions about a new invention of his: the phonograph. Seventy years later one of our correspondents wrote about a replacement for the vacuum tube, a device that could deliver "tinier hearing aids, really small portable radios [and] more compact electronic devices for aircraft." It was called the transistor. To celebrate our 170th birthday, we have collected dozens of historic entries like these from *Scientific American*'s past: the list starts on page 40. And as we do every December, we have gathered 10 of the year's biggest advances for our annual celebration of "World Changing Ideas." Maybe some of them will make the greatest-hits collection 170 years from now.

—The Editors

Illustrations by Tavis Coburn

Eye-Controlled Machines

Software that translates eye movement into commands to control devices could be a boon for motion-impaired people

Earlier this year when Erik Sorto, a quadriplegic man, used his thoughts to direct a robot arm to bring a beer to his lips, the media went wild. It was an impressive feat. The catch is that the technology behind it—an electrode-laden chip implanted in Sorto's brain—is expensive and invasive and often requires months of training. Worse, few paralyzed people have the psychological and physical profile the technology requires.

There could be a better way. Rather than creating a direct link between the brain's electrical activity and machines, Aldo Faisal, an associate professor of neurotechnology at Imperial College London, wants to use eye movements to control wheelchairs, computers and video games. With off-the-shelf video-game cameras, Faisal and his colleagues built goggles that record the user's eye movements and feed those data to a computer. Software then translates the data into machine commands. Almost anyone can use the technology, including amputees, quadriplegics and those suffering from Parkinson's disease, multiple sclerosis or muscular dystrophy. The system costs less than $50 to build. At a science exhibition, the vast majority of thousands of volunteers grasped the technology well enough after 15 seconds to play the game Pong, no instructions needed.

Scientists have long known that the eyes can reveal people's objectives—where they want to go, what they want to do, who they want to interact with. Drawing on 70 years of research into the neuroscience of eye movements, Faisal and his colleagues wrote algorithms that turn a glance into a command for a wheelchair, a wink into a mouse click or the dart of a pupil into the swing of a game paddle. To predict intention, the algorithms depend on training from real-world data, acquired by recording volunteers' eyes as they drove a wheelchair with a joystick or operated a robotic arm. Gradually the software learned to tell the difference between, for example, the way people look at a cup when they are evaluating its contents and when they want to pick it up and take a drink.

Before Faisal can commercialize any medical devices based on the invention, he must secure funding for clinical trials. In the meantime, a €4-million grant from the European Union will support his group as it develops robotic exoskeletons that paralyzed people could control using the eye-tracking software it developed. "I want to see what I can do to help people move again," Faisal says. "That's my focus." *—Rachel Nuwer*

Microwave Rocketry

Beamed power could create a low-cost paradigm for access to space

Humans have been riding rockets into space for more than 50 years, and for all that time, the cost of reaching orbit has remained astronomical—$5,000 to $50,000 per kilogram, depending on which rocket is used. The problem is that *none* of our rockets is very efficient. About 90 percent of a rocket's weight is fuel and propellant, leaving little room for payload. If it could lose some of that weight, a rocket could lift more cargo, reducing the cost of putting a given kilogram of stuff into orbit.

In 1924 Russian scientist Konstantin Tsiolkovsky proposed a way to make this happen, suggesting that beams of microwaves from ground-based transmitters could power a rocket's ascent. Tsiolkovsky proposed using parabolic mirrors to aim "a parallel beam of electromagnetic rays of short wavelength" at the belly of a rocket, heating propellant to produce thrust without the need for large amounts of onboard fuel. This, he wrote, was the most attractive method available "to acquire cosmic velocity." The idea languished until recently, when technology finally caught up with Tsiolkovsky's vision. Microwave lasers—masers—were invented in the 1950s, but it was not until the advent of better, more affordable generators called gyrotrons that masers could reach the megawatt-scale power levels required for space launches. Recent advances in batteries and other energy-storage systems have also made it possible to power sufficiently large gyrotrons without straining the electrical grid.

Today researchers around the world are investigating the concept, including Kevin Parkin, who led a pioneering study in 2012 while at the California Institute of Technology. Based in part on Parkin's work, one private company, Escape Dynamics, is now conducting tests to develop a microwave-powered, reusable system that could launch satellites—and eventually humans. NASA is taking notice: in July the agency added beamed rocketry to its road map for future technology development. *—Lee Billings*

The problem is that *none* of the rockets we use today is very efficient.

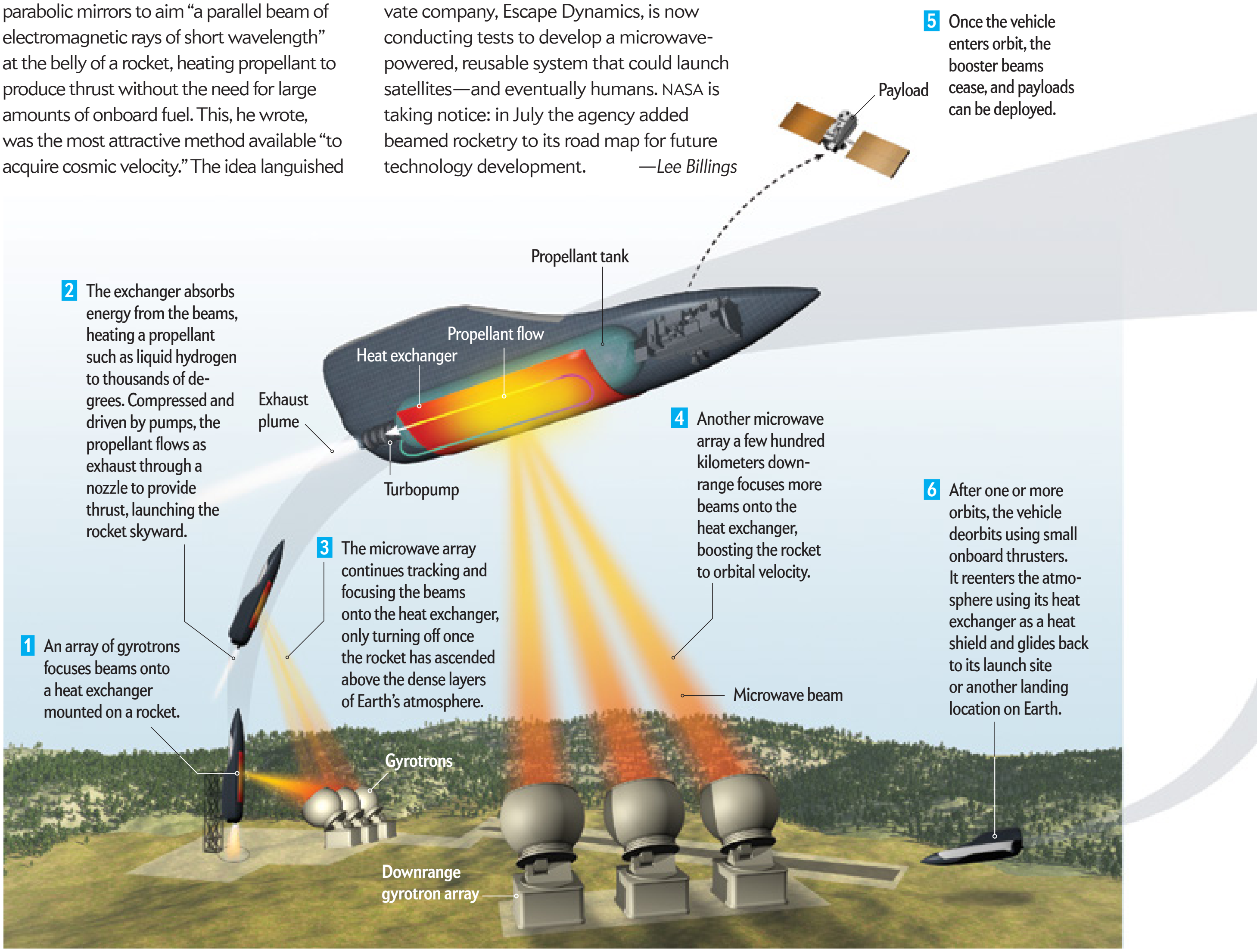


Illustration by Don Foley

Soft, Injectable Electronic Probes for the Brain

Conductive polymer mesh could be a boon to brain research

To solve the mysteries of the brain, scientists need to delicately, precisely monitor neurons in living subjects. Brain probes, however, have generally been brute-force instruments. A team at Harvard University led by chemist Charles Lieber hopes that silky soft polymer mesh implants will change this situation. So far the researchers have tested the mesh, which is embedded with electronic sensors, in living mice. Once it has been proved safe, it could be used in people to study how cognition arises from the action of individual neurons and to treat diseases such as Parkinson's. *—Seth Fletcher*

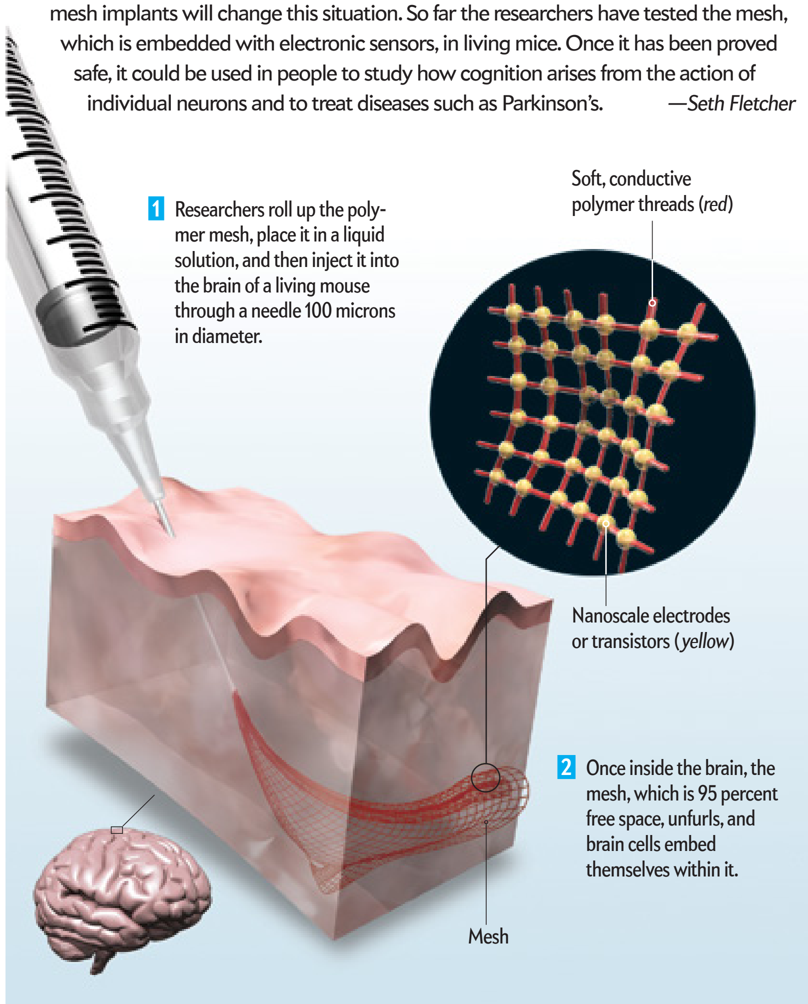
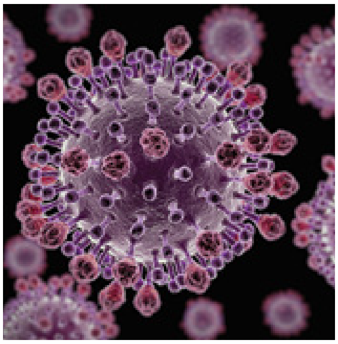


Illustration by Don Foley



H1N1 INFLUENZA is one of many viruses snared by a single new test.

SCIENCE SOURCE (virus)

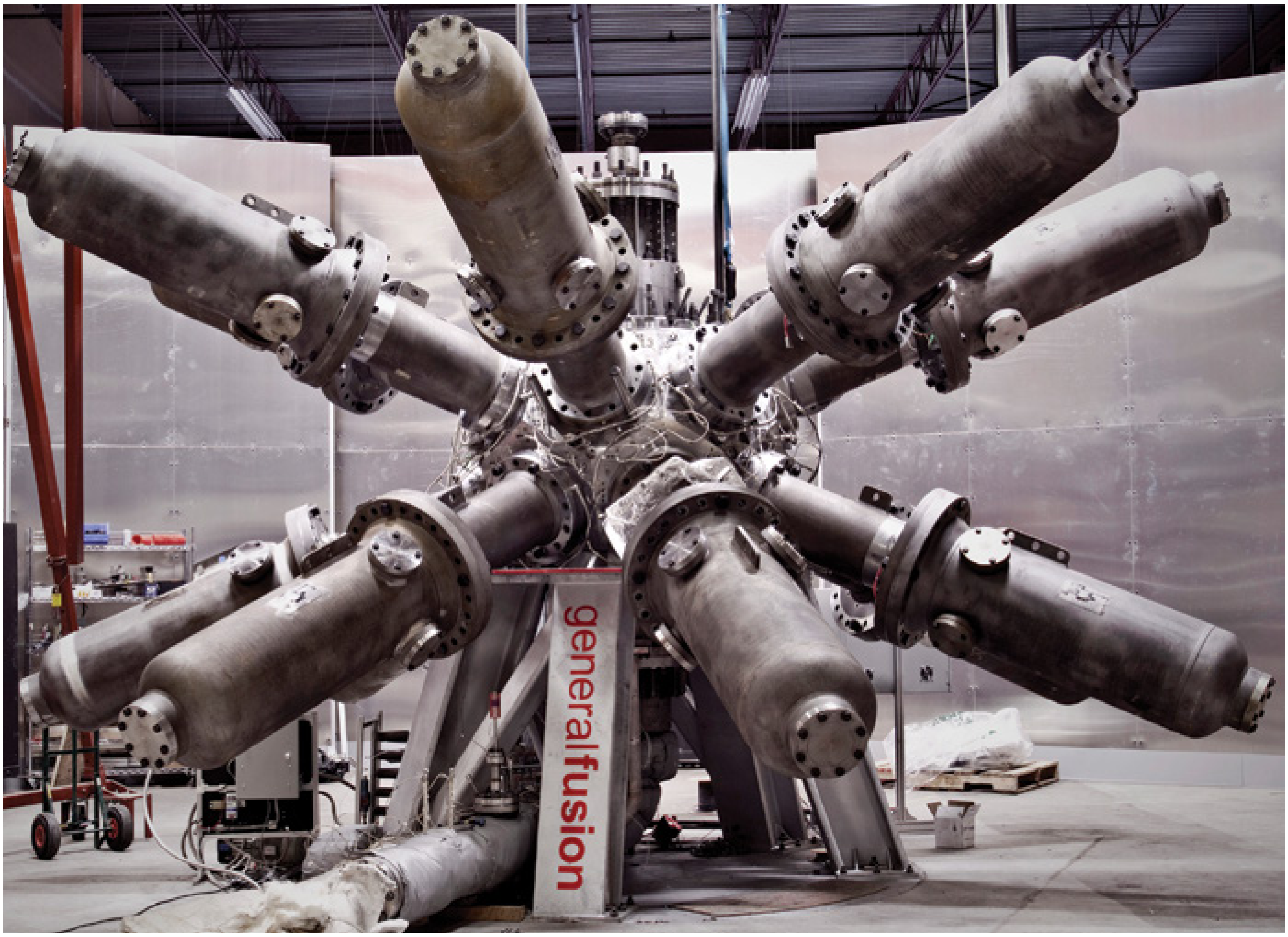
Trawling for Viruses

A new method identifies every virus in a given sample with near-perfect accuracy

When doctors want to identify the virus behind an infection, they usually turn to the polymerase chain reaction (PCR), a method for "amplifying" scattered bits of DNA into a sample large enough to study. To use PCR, however, a physician must know what kind of virus to look for, and that involves guesswork.

This past September a team of Columbia University researchers described a new method that could eliminate that guesswork. The technique, which has the unfortunate name of "virome capture sequencing platform for vertebrate viruses," or VirCapSeq-VERT, can find every virus in a given drop of saliva, tissue or spinal fluid with near-perfect accuracy. The method makes it possible to simultaneously analyze 21 samples in less than 48 hours at an estimated cost of just $200 per sample. It can also detect novel or mutated viruses, so long as they are at least 40 percent identical to known ones. "When someone goes into an emergency room and winds up having all kinds of tests run, it costs thousands of dollars," says W. Ian Lipkin, John Snow Professor of Epidemiology at Columbia University's Mailman School of Public Health. "This method is very inexpensive and allows us to personalize medicine by telling you exactly what you have."

To develop the technique, Lipkin and his colleagues first created a database of more than 1,000 vertebrate viruses. Then they synthesized genetic probes to match every strain of every virus—two million of them, each a strand of DNA 25 to 50 nanometers long. When a probe encounters a matching virus, it binds to it. To extract those viruses, laboratory workers add magnetic beads measuring one to three microns in diameter to the mix; a chemical linker binds the beads to the genetic probes and the viruses they have captured. Researchers then insert a tube containing the mixture into a magnet stand, which pulls the probes to the tube's walls. After researchers isolate and wash the probe-bead-virus combos, they genetically sequence the viruses, eliminating the risk of false positives. Lipkin and his colleagues are now looking to team up with a commercial provider that can distribute the technology to hospitals and clinics around the world. They are also planning on adding probes for all known infectious bacteria and fungi. *—R.N.*



PROTOTYPE compression system for General Fusion's reactor is seen here. The full-scale plant will use 200 pistons to compress plasma in a central sphere.

COURTESY OF GENERAL FUSION

Little Fusion

After decades of slow progress and massive investment, some fusion power researchers are changing tactics

You can accuse fusion power advocates of being overly optimistic but never of thinking small. Fusion occurs when two elements combine, or "fuse," together to form a new, third element, converting matter to energy. It is the process that powers the sun, and the fusion world's marquee projects are accordingly grand. Consider the International Thermonuclear Experimental Reactor (ITER), which a consortium of seven nations is building in France. This $21-billion tokomak reactor will use superconducting magnets to create plasma hot and dense enough to achieve fusion. When finished, ITER will weigh 23,000 metric tons, three times the weight of the Eiffel Tower. The National Ignition Facility (NIF), its main competitor, is equally complex: it fires 192 lasers at a fuel pellet until it is subjected to temperatures of 50 million degrees Celsius and pressures of 150 billion atmospheres.

Despite all this, a working fusion power plant based on ITER or NIF remains decades away. A new crop of researchers are pursuing a different strategy: going small. This year the U.S. Advanced Research Projects Agency–Energy invested nearly $30 million in nine smaller projects aimed at affordable fusion through a program called Accelerating Low-Cost Plasma Heating and Assembly (ALPHA). One representative project, run by Tustin, Calif.–based company Magneto-Inertial Fusion Technologies, is designed to "pinch" a plasma with an electric current until it compresses itself enough induce fusion. The approach has pedigree: scientists at Los Alamos National Laboratory used the pinch technique in 1958 to create the first sustained fusion reaction in a laboratory.

Companies unaffiliated with the ALPHA project are also working on alternative fusion schemes. British Columbia–based General Fusion has built a device that uses shock waves propagating through liquid metal to induce fusion. Tri Alpha Energy is building a colliding beam fusion reactor, a device just 23 meters long that fires charged particles at one another. And defense giant Lockheed Martin has claimed to be working on a magnetic fusion reactor the size of a shipping container that will be commercially available within a decade.

Fusion's track record suggests that these projects should be viewed skeptically. Yet if any of these approaches succeeds in delivering clean, abundant power with no radioactive waste, it could solve ills ranging from energy poverty to climate change with a single innovation. —*David Biello*

Kill Switches for GMOs

A genetic kill switch could prevent industrial espionage and environmental contamination

Untold numbers of genetically modified *Escherichia coli* bacteria live in vats around the world, churning out useful things such as medical insulin, plastic polymers and food additives. When the reprogrammed bugs have served their role, they are packed away as industrial waste or repurposed for fertilizer.

This arrangement currently poses little environmental risk because genetically modified *E. coli* is weak compared with its wild cousins; it would not survive for long outside the lab. But engineered bugs not yet invented might go where they are not wanted and create risks. What if, say, an accident released more resilient engineered bugs that took over a well-balanced ecosystem? Or if tweaked bacteria shared modifications such as antibiotic resistance with their counterparts in nature through horizontal gene transfer? Or if a rival firm stole a patented bacterium for the trade secrets encoded in its DNA? Scientists are developing fail-safes for such contingencies.

Genetically engineered bugs not yet invented might go where they are not wanted. Scientists are developing fail-safes for such contingencies.

In 2009 Brian Caliando, a bioengineer then at the University of California, San Francisco, began working on a way to ensure that a genetically modified organism's engineered DNA could be destroyed before a bug could escape or be stolen. He had recently read about CRISPR, a newly discovered defense tactic bacteria use to cut up and destroy DNA from invading viruses, and realized that he could use it like a built-in kill switch for genetically modified bacteria.

Caliando, under Christopher Voigt, first at U.C.S.F. and then at the Massachusetts Institute of Technology, developed DNAi, a CRISPR-based system that compels bacteria to chop up their own modified DNA. Using CRISPR, Caliando programmed plasmids—tiny circles of autonomously replicating DNA—to code for the RNA bases and enzymes that form the kill switch. He then inserted those plasmids into genetically modified *E. coli,* where they boot up and infect the bacteria with their deadly program. Adding a sugar called arabinose to the vat throws the kill switch, and the DNAi device begins slicing up the bacteria's genetically modified DNA.

Caliando's work, published in *Nature Communications* this year, is a proof of concept. The same principles could be adapted to fit a variety of organisms and conditions. For example, he says, DNAi could prevent genetically modified organisms from cross-pollinating nearby fields. —*Jennifer Abbasi*

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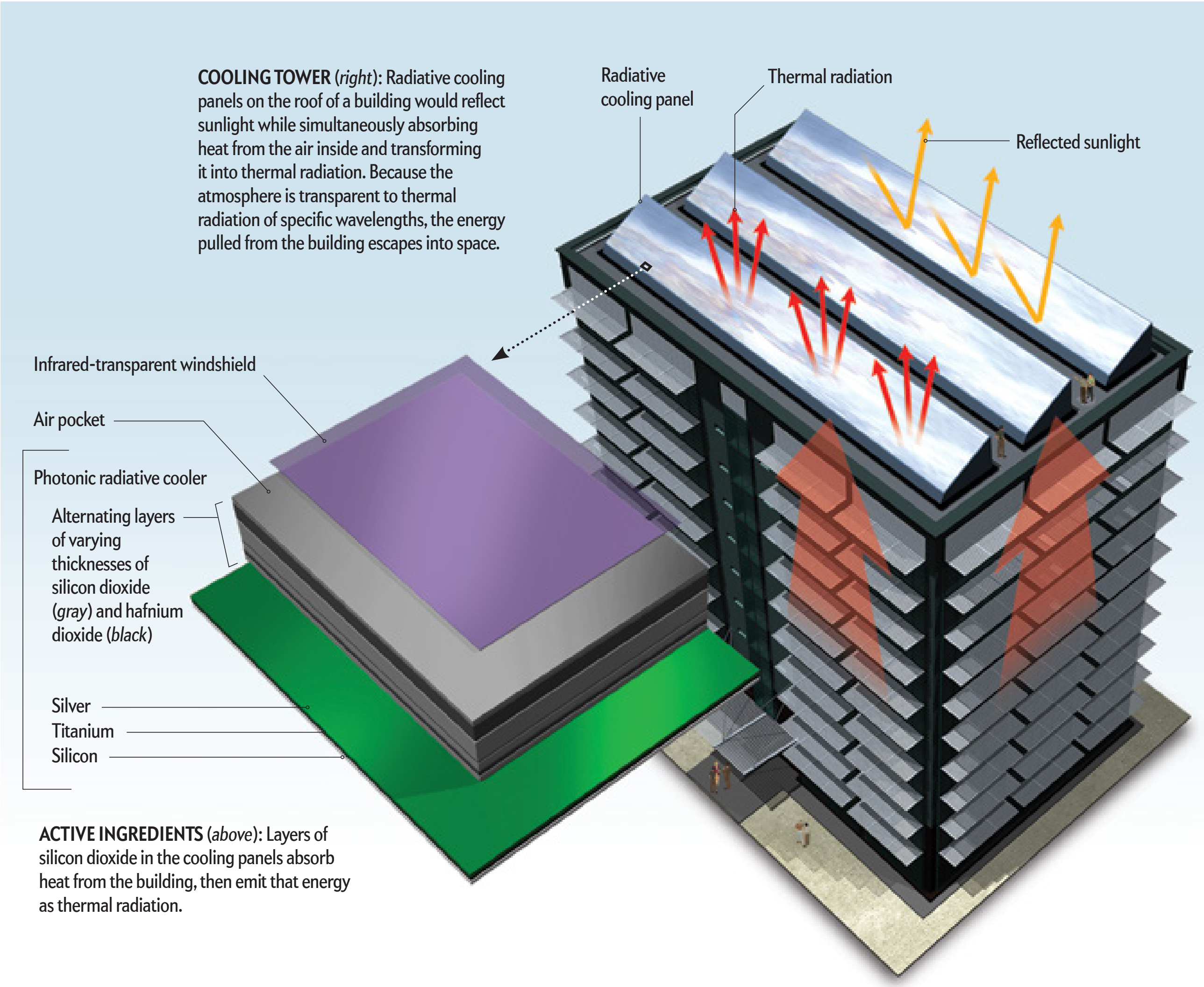


The Heat Vacuum

A multipurpose mirror sucks up heat and beams it into outer space

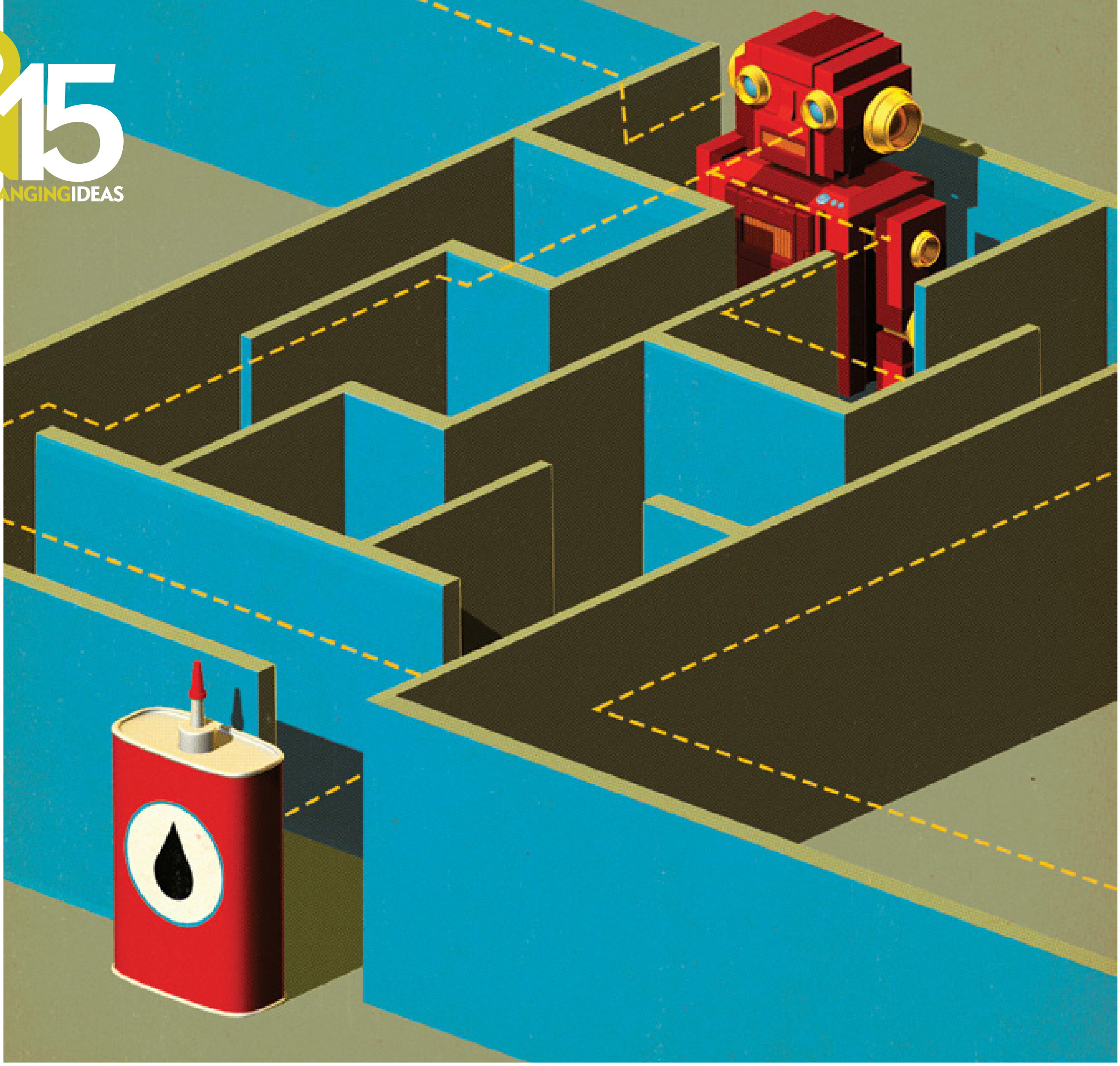
Air-conditioning accounts for nearly 15 percent of building energy use in the U.S. today. The number of days with record heat could soar in the coming decades. These two facts present a difficult problem: In a warming world, how can we cool our homes and workplaces while reducing energy use?

Researchers at Stanford University say part of the solution is a material that sucks heat from sun-drenched buildings and radiates it into outer space. The basic concept, known as radiative cooling, originated in the 1980s, when engineers found that certain types of painted-metal roofing pulled heat from buildings and radiated it in wavelengths that pass through the earth's atmosphere unimpeded. Radiative cooling never worked during the day, however, because no one had made a material that both radiates thermal energy and reflects sunlight. Reflection is critical: if a material absorbs sunlight, heat from the sun negates any cooling that thermal radiation might achieve.

To solve the problem, the Stanford team created what amounts to a very effective mirror. In trials on the roof of its lab, the material, made of layers of hafnium dioxide and silicon dioxide on a base of silver, titanium and silicon, reflected 97 percent of sunlight. The silicon dioxide atoms behave like tiny antennas, absorbing heat from the air on one side of the panel and emitting thermal radiation on the other. The material radiates primarily at wavelengths between eight and 13 nanometers. The earth's atmosphere is transparent to these wavelengths, so rather than warming the air around the building, the heat escapes to space. Even in direct sunlight, the group's 20-centimeter-diameter wafer is about five degrees Celsius cooler than the air.

Shanhui Fan, an electrical engineer at Stanford and senior author of a 2014 *Nature* paper describing the work, imagines panels of the material covering the roofs of buildings. With its roof continually expelling heat, a building's air-conditioning can relax and consume less energy. There could be other applications. Remove the mirror component and pair the material with solar cells, for example, and it could cool the cells while allowing light to reach them, making them more efficient. "It's very interesting to think about how one could tap into this enormous thermodynamic resource that the universe as a heat sink represents," Fan says. "We're really only at the very beginning of recognizing this underexplored renewable energy resource." —*R.N.*

Illustration by Don Foley



Machines That Teach Themselves

Deep-learning technology is helping A.I. fulfill its promise

Google, Facebook and other corporate giants are taking major strides in building technology that can learn on its own. Their efforts rely heavily on something known as deep learning.

Rooted in the decades-old idea that computers would be smarter if they operated more like the human brain, deep-learning networks consist of layer on layer of connected computer processing units called artificial neurons, each of which performs a different operation on the input at hand—say, an image to be classified. The difference between conventional neural networks and deep-learning ones is that the latter have many more layers. The deeper the network—the more layers—the higher the level of abstraction at which it can operate.

Deep learning gained momentum in the mid-2000s through the work of three key figures—Geoffrey Hinton of the University of Toronto, Yoshua Bengio of the University of Montreal and Yann LeCun of New York University—but it only recently began making commercial inroads. An example is the Google Photos app, which came out in May. The software can upload all the images from my iPhone, correctly identify my wife, son and grandson, and then dump their photographs in separate digital bins marked by thumbnail images. It can do this because it has learned to recognize faces through exposure to millions of images analyzed by the system. As it runs an image through each successive layer of its network, the software identifies elements within the image at an increasing level of abstraction—until it ultimately can detect the whole face within the picture.

Once it has trained on enough faces, it can spot the noses and mouths of individual people in images it has never seen before.

Deep learning can do much more than organize pictures. It may, in fact, mark a step toward artificial intelligence that exhibits intelligent behaviors virtually indistinguishable from those of its human masters. In February a team of A.I. experts from the London-based firm DeepMind (which Google bought in 2014 for $617 million) reported that it had used deep learning to build a computer that could teach itself to play dozens of Atari video games. After a lot of practice, the software beat expert human players at half of those games. A small step, but the machine age has to start somewhere. *—Gary Stix*

Slow-Motion Cameras for Chemical Reactions

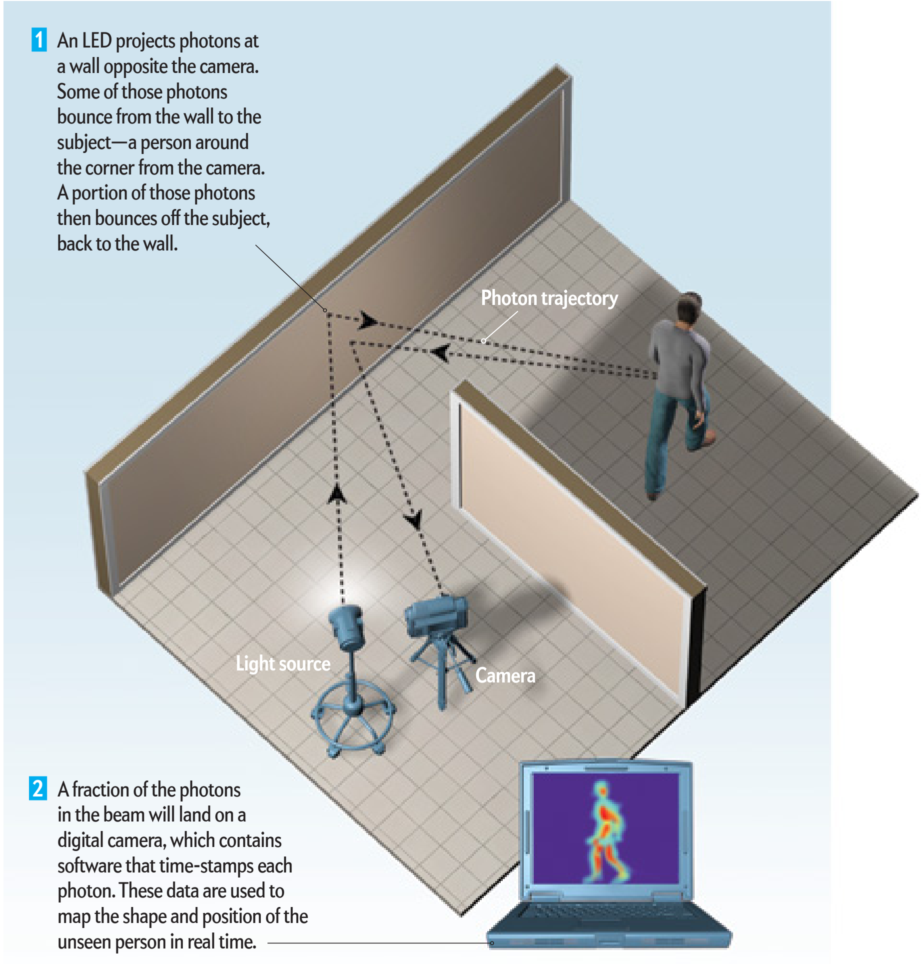
Infrared spectroscopy and computer simulations reveal the hidden world of solvent-solute interactions

The hydrogen bonds that hold together the molecular base pairs of our DNA form in intracellular fluid. Much of our planet's environmental chemistry occurs in oceans and other bodies of water. Most drugs are synthesized in solvents. Yet chemists generally study the bond-by-bond mechanics of chemical reactions only in the gas phase, where molecules are relatively sparse and easy to track. In a liquid there are more molecules and more collisions among them, so reactions are fast, messy and complicated. The process you want to observe will look like an undifferentiated blur—unless, that is, you can take snapshots of the reaction in a few trillionths of a second.

Andrew Orr-Ewing, a chemist at the University of Bristol in England, uses lasers to study chemical reactions. He knew that reactions in liquid catalyzed by heat create vibrations that can be observed in the infrared spectrum. In experiments conducted between 2012 and 2014, Orr-Ewing and then Bristol doctoral student Greg Dunning shot an ultrafast ultraviolet pulse at xenon difluoride molecules in a solvent called acetonitrile. The laser pulse acted like a scalpel, carving off highly reactive fluorine atoms, which in turn stole deuterium atoms from the solvent molecules, forming deuterium fluoride. The speed with which the telltale infrared vibrations appeared and then vanished after the first laser pulse—observed using a standard technique called infrared spectroscopy—revealed how quickly bonds formed between atoms and how quickly the reaction reached equilibrium.

The experiments were a proof of concept for observing the split-picosecond details of reactions in liquids. Most chemists, however, use computer simulations to observe and refine chemical reactions instead of expensive lasers and detectors. For them, Orr-Ewing's Bristol colleagues David Glowacki and Jeremy Harvey wrote simulation software that predicted the results of Orr-Ewing's spectroscopy experiments with an extraordinary level of accuracy. "We can use these simulations to peer more deeply into what's going on," Orr-Ewing says, "because they tell us more precise information than we can get from the experiments."

Together the experiments and simulations provide the best insights so far into how a chemical reaction actually happens in a liquid. Developers are already starting to incorporate the team's methods into computer simulations for academic and industrial use, which could benefit scientists doing disease research, drug development and ecological studies. *—J.A.*

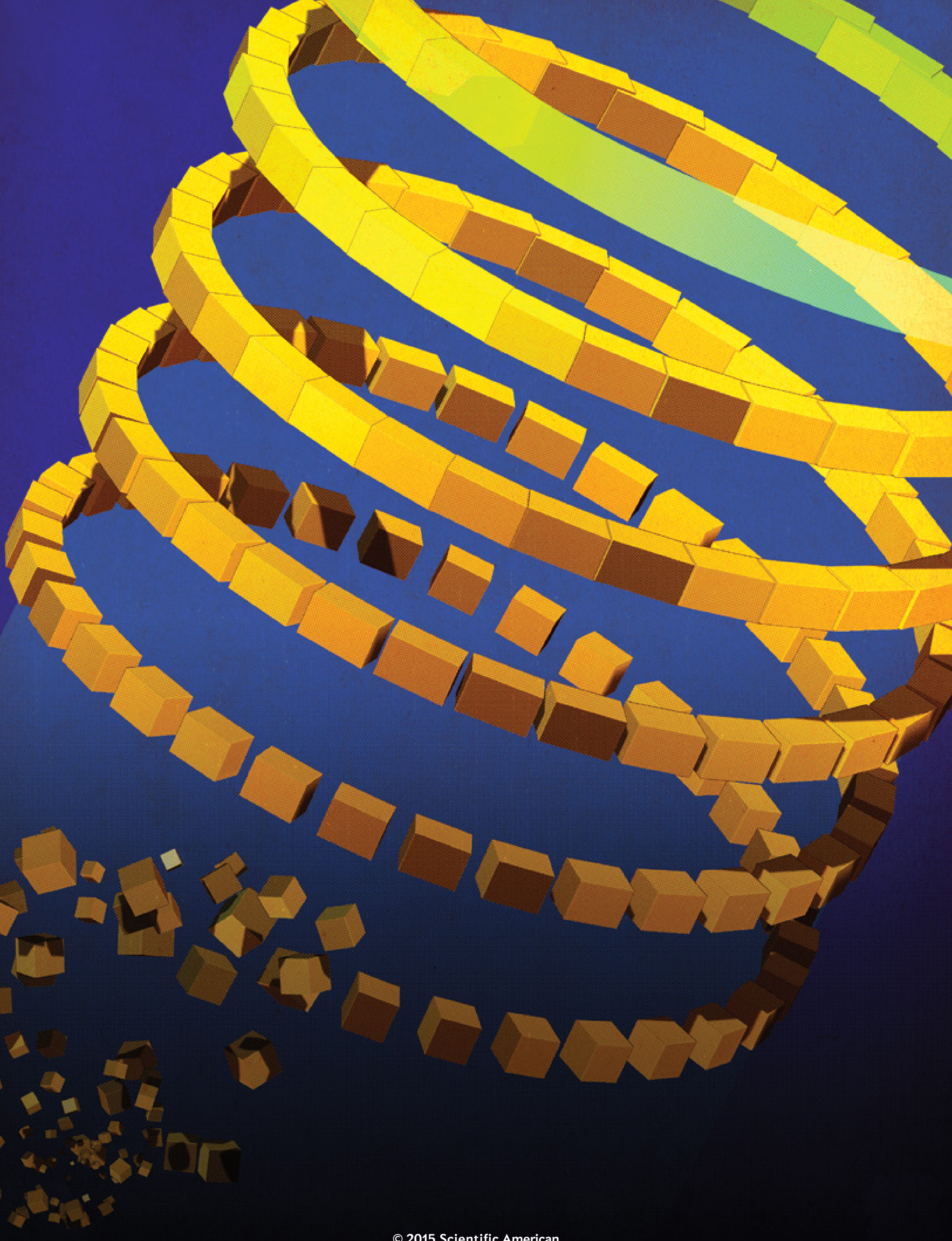


Seeing around Corners

Bouncing photons let cameras see beyond the line of sight

If cameras could see around corners, they could warn drivers of danger waiting around the bend, help firefighters search burning buildings and enable surgeons to see hard-to-reach areas inside the body. A few years ago researchers at the Massachusetts Institute of Technology's Media Lab figured out how to build such a camera, but it was an expensive early prototype. The device used a laser pulse to bounce light from a wall or door onto a stationary object in the next room. A $500,000 camera then recorded the light that bounced back, and software recorded the arrival time of individual photons, calculated distances and reconstructed the unseen object. Since then, the M.I.T. team has improved the technology significantly. Now it can record moving objects beyond the line of sight, and instead of a laser and a $500,000 camera, an LED and a $100 Microsoft Kinect sensor will do. *—Larry Greenemeier*

Illustration by Don Foley



INVENTING THE WORLD 1845

INNOVATION

Scientific American came out 170 years ago celebrating the individual tinkerer and wound up bearing witness to major technological upheaveals in the nation and the world

By Daniel J. Kevles

Rufus Porter lived through a remarkable technological transformation. When he was born, in 1792, Americans traveled overland by foot and horse, communicated by hand-carried letters and resorted to being bled when ill. Fifteen years later Robert Fulton's paddle-wheel steamboat began transporting people up the Hudson from New York City to Albany. By the time Porter published the first issue of *Scientific American* magazine on Thursday, August 28, 1845, steam engines were driving the nation's burgeoning factories, mines and mills, and steam-powered railroads were transporting goods and people across

Illustration by Tavis Coburn

land at breathtaking speeds. "Superbly splendid long cars," Porter wrote, could carry from 60 to 80 passengers in safety, comfort and convenience "while flying at the rate of 30 or 40 miles per hour."

Porter, the son of a well-to-do New England family, had galloped through careers as a landscape artist and inventor; he edited *Scientific American* for only two years. That was enough, however, to fashion it into an organ of technical prophecy. For 170 years *Scientific American* has chronicled the astonishing advances in science and technology and frequently offered commentary on how these advances might transform the ways Americans live and work.

Porter was farsighted in founding a magazine that celebrated science and technology. In the 1870s the nation began running out of new arable land for settlement beyond its western fronti er. Science and technology offered new frontiers to conquer. At the time, game-changing technologies came mainly from individual inventors such as Fulton or Samuel F. B. Morse, the progenitor of the telegraph. Yet the process of invention was itself going through an important transformation. During the half a century that began in the late 1870s, industrial research facilities such as the Bell Telephone Laboratories rose in prominence, exploiting the rich potential of physics and chemistry and overshadowing the industrial development by even the era's founding inventors, such as Henry Ford. They increasingly provided the big breakthroughs that were changing American life—principally in electrical, chemical and automotive technologies.

The Second World War ushered in a new transformation. Beginning in the 1940s, the federal government began to fuel much of the nation's scientific and technological development through grants and contracts in support of research and training, vastly enlarging opportunities for technical careers and accelerating the pace of innovation. Public and private investment together produced antibiotics and vaccines, transistorized electronics, as well as digital computers, and promised cheap nuclear power.

The rise of the personal-computer and biotechnology industries in the 1970s expressed a reinvigoration of private small-scale innovation. Entrepreneurs were encouraged by the promotion of free-market capitalism, governmental policies that fostered economic deregulation, tax write-offs for research, the patenting of living organisms and vital software, and the transfer from universities to small business of useful knowledge gained with federal research support. Innovators spawned high-tech start-ups in Silicon Valley and elsewhere, which played an outsized role in reshaping the technology landscape. They brought new technologies, such as the now ubiquitous microprocessor, to the marketplace with startling speed. Handsomely funded federal agencies, such as the National Institutes of Health, pushed advances in molecular biology and genomics, stimulating dramatic changes in the diagnosis and treatment of disease.

To appreciate the sweep and magnitude of the changes, I have imagined what each period would seem like through the eyes of a few curious observers. We start with Aurora, a teenager in the 1870s and a grandmother in the 1930s, reflecting on the vast changes in American life with her young grandson Michael. We will also follow Michael, from his boyhood during World War II to his grandfatherly years in 1970s, and his grandson Joel, our contemporary.

Daniel J. Kevles writes about science and technology in American society, past and present. His books include *The Physicists* (1978), *In the Name of Eugenics* (1985) and, as a co-author, *Inventing America: A History of the United States* (2006).

IN BRIEF

When the first issue of *Scientific American* magazine was published in 1845, steam engines were driving the nation's burgeoning factories, mines and mills, and steam-powered locomotives were transporting goods and people overland on railroads at astonishing speeds.

Industrial research laboratories rose to exploit possibilities in physics and chemistry in the late 1800s and government facilities after World War II. In the 1970s entrepreneurs got into the action with microprocessors.

Although technology has had its critics, Americans for the most part have not dissented from the advances that have transformed society many times over.

170 YEARS OF SCIENTIFIC AMERICAN

Since 1845, *Scientific American* has chronicled ideas and inventions that have changed the world. On the following pages, we present highlights from our archives on evolution, the cosmos, the brain and other topics, including a few written for us by our 155 Nobel Prize–winning authors.

N Indicates a Nobel award winner who wrote for *Scientific American*

EARTH & ENVIRONMENT

1968 PANGAEA

Citing convincing data from the young field of plate tectonics, Patrick Hurley maintains that the present continents were indeed once assembled into two great landmasses, called Gondwanaland in the south and Laurasia in the north.

2001 KATRINA FORESHADOW

Editor Mark Fischetti presents climate models and maps that show that a large hurricane crossing the Gulf of Mexico would drown New Orleans under many feet of water. Four years later, unfortunately, Hurricane Katrina does just that.

1946 DDT

Sixteen years before Rachel Carson's famous book, *Silent Spring,* prompts investigations that lead to a ban on the pesticide DDT, D. H. Killiffer writes an article entitled "Is DDT Poisonous?"

1953 Earthquakes

The Amateur Scientist column, which ran from 1952 to 2001, told readers each month how to investigate scientific phenomena on their own while using the latest technology or methods. The June 1953 edition shows how to run an electronic seismometer.

N

1990 Worldview

Al Gore, a senator from Tennessee, proposes that the U.S. launch a Strategic Environmental Initiative to protect the world's forests, close the ozone hole, prevent mass extinctions and keep huge quantities of carbon dioxide out of the atmosphere.

Planetary Boundaries

2010 To protect the earth from ruin, the world must stay within nine environmental limits, each given a specific measure. They include levels of ocean acidification (2.75 omega units), ozone depletion (276 Dobson units), freshwater use (4,000 cubic kilometers a year), and so on, according to Jonathan Foley and an international team.

1959 Carbon Dioxide

Long before scientists begin to publicly raise concern about global warming, Gilbert Plass writes "Carbon Dioxide and Climate," which considers the question: "How do man's activities influence the climate of the future?"

2009 SUSTAINABLE ENERGY

Mark Jacobson and Mark Delucchi calculate that wind, water and solar technologies can provide 100 percent of the world's energy by 2030. Needed are 3.8 million wind turbines, 1.7 billion rooftop solar modules, 900 hydroelectric plants, a better power distribution system, and more.

1984 NUCLEAR WINTER

Richard Turco and his co-authors, including Carl Sagan, make a case that immense clouds of smoke and dust raised by a medium-scale nuclear war could shroud the earth in a long period of darkness and cold, killing crops worldwide.

2006 Warming Wedges

Robert Socolow and Stephen Pacala draw a pie chart with seven wedges—steps that each reduce global carbon emissions by 25 billion tons. Overall, 15 technologies can be used to achieve the goals.

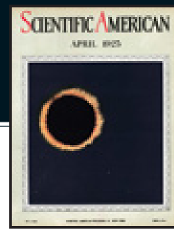
Scientists blow the whistle on human activities that threaten our food supply, our atmosphere and our future—and offer solutions

170 YEARS OF SCIENTIFIC AMERICAN

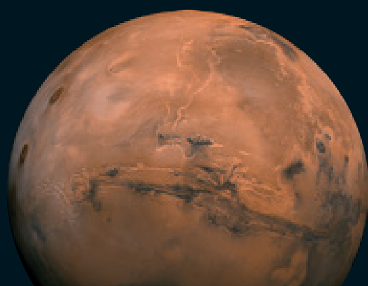
THE COSMOS

Slowly, we discover how the universe formed, how it works and how we came to be here

1956 RADIO GALAXIES
Ⓝ Martin Ryle explains that radio telescopes are discovering galaxies far beyond those seen by optical telescopes and that many are colliding violently.



1925 Corona
Scientific American publishes its first color photographic cover in April 1925—an image of the sun's corona.



1920 CALLING MARS

H. W. Nieman and C. Wells Nieman propose a vocabulary of dots, dashes and pictures to communicate between beings living on different planets of the solar system.

1956 Humans as Stardust
Ⓝ In "The Origin of the Elements," William Fowler tackles a new theory that the heavier atoms on Earth were built up from hydrogen in stars.

1970 FASTER THAN LIGHT
Gerald Feinberg explains why proposed particles called tachyons would comply with the theory of relativity even though they would move faster than the speed of light.

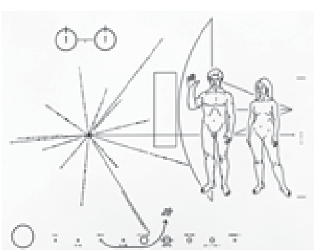
1984 Inflation
A new theory puts cosmologists on their heels: the universe is embedded in a much larger region of space that is eternally inflating.

Ⓝ
2004 Dark Energy
Adam Riess co-authors an article suggesting that pinpointing when the expanding universe switched from slowdown to speedup could reveal the nature of dark energy and the ultimate fate of the universe.

1950 Einstein Unsuited
Ⓝ Having transformed physics and philosophy, the most famous scientist of all time still struggled to expand his general theory of relativity. When submitting his 1950 article about that to *Scientific American,* he writes, "The article is somewhat long and not quite easy to grasp. I should, therefore, not be astonished if you find it unsuited for publication."

2003 The Multiverse
Max Tegmark says observations of space prove that we live among an infinite number of parallel universes.

1975 E.T.
Carl Sagan and Frank Drake explain in "The Search for Extraterrestrial Intelligence" how messages could be sent and received. They have little doubt that civilizations more advanced than Earth's exist elsewhere in the universe.



1976 Black Holes
Physicist Stephen Hawking has defied the odds by living and working for many years while paralyzed by ALS. In "The Quantum Mechanics of Black Holes," he also defies the accepted wisdom about black holes, observing that particles of matter could actually escape them by "tunneling" out.

LIGHT, SOUND AND MOBILITY

When Aurora visited the nation's Centennial Exhibition in Philadelphia in 1876, she took a horse-drawn coach from the train station to the exhibition. Horsepower was how people traveled locally and wherever else the railroads and steamboats did not go. Aurora raised her skirts and held her nose whenever she walked the manure-speckled streets. Her mother did the cleaning and washing by hand and kept the family food fresh in boxes cooled by ice. When her brother broke his leg, the doctor could only guess at the location of the fracture. She and her friends kept in touch mainly by postal mail, although some acquaintances sent missives via their servants. Aurora found pleasure, if she had the time, mainly in live entertainments—lectures, concerts, theater, vaudeville—and her brother especially liked the increasingly popular sport of baseball.

But Aurora knew, in part because she read *Scientific American,* that enormous changes were germinating. The year of the centennial, Alexander Graham Bell demonstrated the ability of his new telephone to convey conversations over wires. Some experts derided the invention as a toy, but the magazine's editors noted just a few years later: "Who … can have the courage … to forecast the social and commercial changes which the annihilation of time and trouble, and the doing away of forgetful or erring servants, will bring in their train? Soon it will be the rule and not the exception for business houses, indeed for the dwellings of all well-to-do people as well, to be interlocked by means of the telephone exchange."

One day the next year Thomas Edison walked into the magazine's offices on Park Row in New York City, set down a small contraption on a table, and, saying little, turned the crank. To the editors' astonishment, the machine said, "How do you do? How do you like the phonograph?" Edison predicted, correctly, that the phonograph would record and play the spoken texts of entire novels such as *Nicholas Nickelby* and the voices of prima donnas, prime ministers and presidents.

At the time, Edison was devoting his energies to the development of the incandescent electric light, which he first demonstrated to 3,000 people on New Year's Eve in 1879 at his pioneering industrial research lab in Menlo Park, N.J. The demonstration included a crucial element—a practical means of generating and distributing electric power. "After the electric light goes into general use, none but the extravagant will burn tallow candles," Edison was widely reported to have said. Electric lighting soon began replacing gas in streets, offices and homes. *Scientific American* detailed the advantages: it was brighter, didn't flicker, and didn't take the oxygen out of the air or load it with soot.

Through the succeeding decades the magazine's editors prognosticated on the dividends to come from the discovery of x-rays for their potential uses in medicine and the detection of contraband; the advent of the horseless carriage, which would rid cities of "the dust and mud" (the editors were too decorous to mention manure) "and noise" of horses clattering on cobblestone pavements; and the prospects of heavier-than-air flight. They failed, however, to appreciate the invention of the three-element vacuum tube in 1907, which, by generating and amplifying variable signals such as those characteristic of voice and music, would in little more than a decade turn out to be crucial in the development of electronics, including wireless communications.

Chemistry and electricity transformed the horseless carriage into the ubiquitous "automobile," a name that signified autonomy of movement.

By the 1930s Aurora could recognize how much electricity and chemistry had changed everyday life. Her son worked in an office lit by electricity, came home to an electrically lit house and went out to dinner in a downtown of bright lights. She and her daughter stored food in an electric refrigerator and vacuumed the floors. She dialed family and friends, who lived on the other coast, directly on the telephone, without having to go through an operator. She and her husband listened to political conventions, concerts and prizefights on the radio and watched movies in air-conditioned theaters.

Chemistry and electricity had transformed the horseless carriage into the ubiquitous "automobile," a name that signified autonomy of movement. The open touring car that sold for \$1,500 in 1915 had turned into the sleek family sedan, with a \$680 sticker price that included safety glass, durable paints, cushioning rubber tires and electric lights. With electric starters, Aurora no longer had to turn the crank to start the engine. Gasoline was cheap, not least because between 1910 and 1930 oil company chemists had figured out how to quadruple the volume of gasoline they could extract from a barrel of crude.

The new technologies brought out a corps of critics. The metropolis of automobiles, streetcars, loud radios and foul smells had created a cesspool of pollutions, hazardous to life, limb and sanity. With the onset of the Great Depression, some attributed the collapse to technological unemployment. During the 1930s the auto industry was engulfed in bitter, sometimes deadly labor strife that was largely of its own making.

But the industrial bet on the new frontier had paid off, generating new industries, new jobs, and a cornucopia of consumer conveniences in transportation, communications and daily life. The leaders of the auto industry could rightly say that, counting ancillary businesses such as repair shops, gas stations, and steel, paint, glass, rubber and fabric producers, their overall operations accounted for one in five or six of the country's jobs. Even in the depths of the Depression, Americans remained optimistic that science and technology would forge a better future.

Aurora herself might have enjoyed the report in *Scientific*

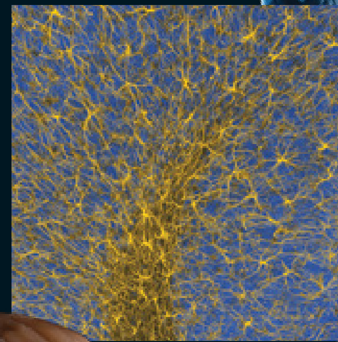
PAGES 42 AND 43:: COURTESY OF NASA/NOAA/GSFC/SUOMI NPP/VIIRS/NORMAN KURING (*Earth*); CORBIS (*DDT*); *SCIENTIFIC AMERICAN*, APRIL 1990 (*cover*); ROGER VIOLLET *Getty Images* (*nuclear blast*);
OPPOSITE PAGE: GORONWY TUDOR JONES, UNIVERSITY OF BIRMINGHAM *Science Source* (*particle tracks*); NASA AND JPL-CALTECH (*Mars and black hole*); NASA *Science Source* (*Pioneer 10 and 11 plaque*); *SCIENTIFIC AMERICAN*, APRIL 1925 (*cover*)

170 YEARS OF SCIENTIFIC AMERICAN

MIND & BRAIN

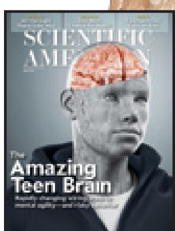
Increasingly powerful tools have revealed how thinking, memory, emotions and behavior arise, defining who we are

2004 GLIA
In "The Other Half of the Brain," R. Douglas Fields claims that long-overlooked glial cells may be nearly as critical to thinking as neurons are—a view now widely accepted.



1898 EARLY YEARS
The nascent science of psychology receives this review: "The history of psychology here prior to 1880 could be set forth as briefly as the alleged chapter on snakes in a natural history of Iceland—'There are no snakes in Iceland.'"

2015 TEEN BRAIN
Jay Giedd makes a case that the teen brain is not an old child brain or a half-baked adult brain but its own unique entity, prone to risky behavior but also capable of leaps of cognition.



1967
SPLIT BRAINS
Michael Gazzaniga reveals that the human brain's two hemispheres can think independently and have their own consciousness.

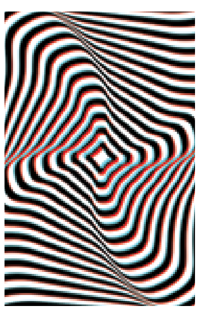
1993 AUTISM
Uta Frith describes her pioneering work on autism in an article for *Scientific American* that is still frequently cited as a clear explanation for this enigmatic disorder.

1992 LEARNING
N Eric Kandel co-authors an article on discoveries that show that learning occurs by strengthening connections among neurons.

2012 FREE WILL
In a *Scientific American Mind* story, Christof Koch questions whether humans actually have free will.

1964 Hallucinogens
In the psychedelic era of Timothy Leary, *Scientific American* publishes a hard-hitting debate on whether the dangers of psychoactive drugs such as mescaline and LSD outweigh possible benefits in treating mental illness.

2010 Two psychiatrists explore whether drugs such as LSD and mescaline "can in fact help people overcome their addictions."



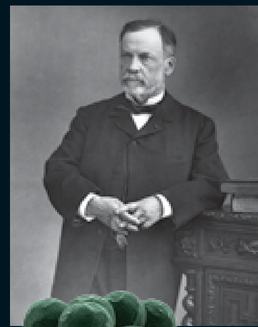
1956
FEAR AND SEX
James Olds makes a case that the brain has local seats of emotions such as fear and has centers of pleasure that can be stimulated by eating or by sex.

2004
SA MIND
As the science of mind and brain matures, the premier issue of *Scientific American Mind* explores altruism, memory and antidepressant drugs.

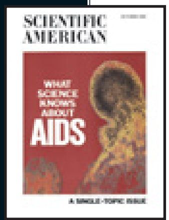
HEALTH, MEDICINE & BIOLOGY

By drilling down into the tiny building blocks of human and animal biology, science has prompted sweeping changes in how we fight illness and disease

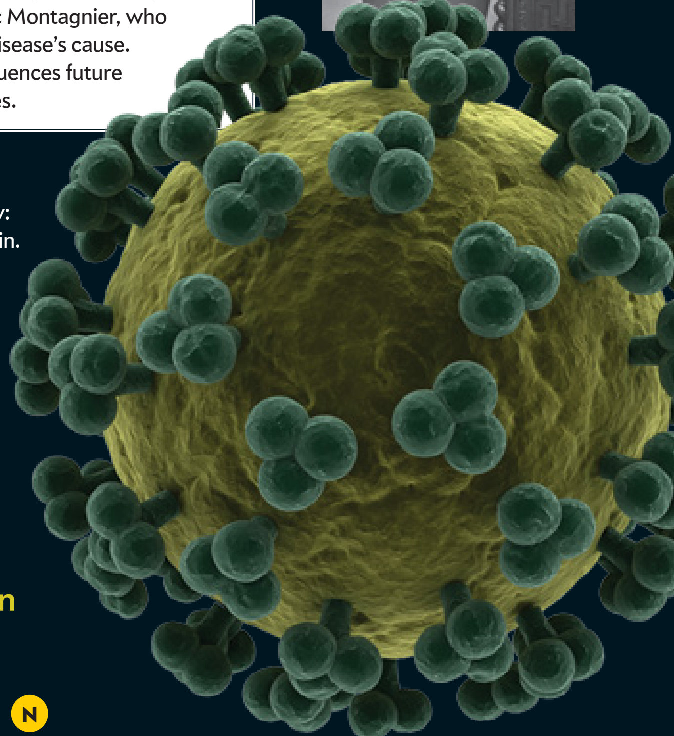
1881 VACCINATION
The magazine publishes a lecture by Louis Pasteur, "Vaccination of Animals," which explains how immunizing animals could protect humans from contagious diseases.



1980 CLONING
In "Monoclonal Antibodies," Cesar Milstein explains how cloning could allow cells to live forever.



1988 AIDS
Scientific American devotes an entire issue to the AIDS epidemic, led by an article by Robert Gallo and Luc Montagnier, who isolated HIV as the disease's cause. The issue greatly influences future research into vaccines.



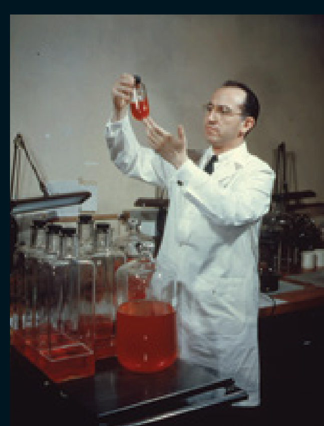
1961 PROTEIN FOLDING
John Kendrew reports on a major discovery: how amino acid chains fold to form a protein.

1962 SMOKING AND CANCER
An 1848 article indicates that smoking tobacco causes "emaciation." In 1923 the magazine says that although smoke contains poisons, it is not injurious to the mouth or throat. But in 1962 E. Cuyler Hammond writes "there is no longer any doubt" that smoking tobacco is linked to lung cancer.

1984 PRIONS
In his first of three articles for *Scientific American*, Stanley Prusiner notes that "proteinaceous infectious particles" can spread maladies such as mad cow disease without DNA or RNA. He also notes this infection pathway was "once dismissed as an impossibility."

1976 Cancer Growth
Judah Folkman shows how tumors recruit blood vessels that help them grow. Two decades later he authors another article on how cancer can be treated by attacking its blood supply.

1955 POLIO
While waiting for field-test results of his polio vaccine, Jonas Salk argues that a killed-virus vaccine could be as effective as a live-virus vaccine—and safer.



1990 GENE THERAPY
Kary Mullis writes that he conceived the polymerase chain reaction—the process for making unlimited copies of segments of DNA—while driving along a moonlit mountain road in California, with his female chemist friend asleep in the car.

1954 DNA
Francis Crick diagrams the double-helix, base-pair structure of DNA only a few months after he, James Watson and Rosalind Franklin discover it.

2004 OUR GENETIC CODE
John Mattick makes the case that the genetic effects of RNA, more than DNA, are responsible for human evolution.

American in early 1940 that the DuPont Corporation had developed a cluster of synthetic superpolymers that it dubbed "nylon" and that could be made into woven dresses, bathing suits, underwear and stockings—all advertised as feeling smooth as silk. When Michael accompanied his grandmother to the 1939 World's Fair in New York City, he was more excited about the new high-technology miracles such as television that the exhibits promised were just around the consumer corner.

MEDICINE AND ELECTRONICS

YOUNG MICHAEL, growing up in the late 1930s, took for granted that families listened to radios and phonographs. Both appliances were big, and not always reliable, because they depended on multiple vacuum tubes, which were prone to failure. His parents knew all too well that their doctor's bag included few medicines for the treatment of infectious diseases and nothing to combat dreaded polio. They had worried during the Depression about unintentionally incurring the expense of raising another child because the birth control they used—condoms or a diaphragm—was not altogether reliable. The principal treatment for cancer was surgery; the radiation from such sources as radium or x-ray machines posed their own risks of injury. Michael's older sister worked in an office as a "computer"—processing numerical data using hand-operated adding machines. Most computers were women.

Not everyone was happy with the high-tech changes. Rachel Carson's searching and eloquent *Silent Spring* helped to stimulate a new environmental movement.

During the decade following victory in World War II in 1945, Michael learned from *Scientific American* that the wartime mobilization of science and engineering had yielded major innovations applicable to civilian life. Among the most significant was microwave radar, a system that emitted and detected echoes of ultrahigh-frequency radio pulses, tracking aircraft in the sky and revealing targets on the ground. In peacetime, the magazine rightly predicted, microwave networks could simultaneously carry "hundreds of thousands" of private phone calls and deliver "high-definition and color television" programs all over the country.

Wartime research on chemical weapons had serendipitously led to chemotherapy for certain cancers; it had a significant impact on survival rates of childhood leukemia and lymphomas. But the dramatic medical dividend of the war was penicillin, the by-product of mold. This first of many antibiotics offered an effective treatment for syphilis and other infectious diseases. By 1952 the development of other antibiotics such as streptomycin and tetracycline constituted, the magazine rightly said, a "revolution in medicine."

Research on polio had long been hindered by the inability of scientists to grow this virus except in the spinal tissue of monkeys, a scarce commodity. Yet in 1952 the magazine wrote glowingly about the achievement of scientists at Harvard University who had found a way to multiply the virus in ordinary tissue culture, a breakthrough that gave "a tremendous impetus to the study of the disease" and the development of a vaccine against it. In 1955 bells rang out across the country on the announcement that Jonas Salk's polio vaccine had been successfully tested in a nationwide trial.

The war had also given birth to the electronic digital computer. The first models contained thousands of vacuum tubes, occupied entire rooms and consumed enormous amounts of power. Reliance on these tubes was a major obstacle to increasing the complexity of what the machines could accomplish. In 1948, however, as Michael read in *Scientific American,* engineers invented a device, called a transistor, that performed the same work as tubes but was smaller and less power hungry.

By the 1970s Michael was flying around the world in jets, another spin-off of defense research, confident that radar would track his plane through its entire journey and that electronic instruments would guide it to a safe landing in bad weather.

Michael and his wife could purchase inexpensive goods for his home, including microwave ovens, plastic furniture, and clothing made of polyester that was easy to clean and resistant to shrinkage and wrinkling, not to mention moths. He did not have to worry that his grandson, Joel, might contract polio because vaccinations were widespread in the U.S. Cancer was still a dread but could often be staved off by an expanding menu of chemotherapies. His wife thought it wonderful that their daughters, one married, the other not, could use birth-control pills to divorce sexual pleasure from the risk of pregnancy.

Grandfather Michael liked to point out to Joel and his friends how much autonomy they enjoyed in listening to whatever they wanted on their transistorized portable radios and compact stereophonic record and tape players. Michael himself wore a transistorized hearing aid, unobtrusively miniature in size and powered by a long-lasting battery. He took great pleasure in joining Joel to watch live distant news and sporting events such as Wimbledon because, as *Scientific American* had predicted in 1961, communication satellites operating thousands of miles above the earth now relayed "not only telegraph and telephone messages but also television pictures ... to the farthest corner of the globe."

Yet not everyone was happy with the high-tech changes. In the 1960s Rachel Carson's searching and eloquent *Silent Spring* helped to stimulate a new environmental movement whose targets were DDT and toxics. Critics attacked computers for relegating human beings to mere entries of code to be managed by academic and industrial bureaucracies. Anger about the Vietnam War, with its use of herbicides as weapons and mass bombings from altitudes of 30,000 feet, was often directed against the scientific and technological enterprise that had produced such armaments.

PAGES 46 AND 47: ADAM VOORHES *Gallery Stock* (*brain*); THOMAS DEERINCK, NCMIR *Getty Images* (*glia*); © ISTOCK.COM (*abstract pattern*); *SCIENTIFIC AMERICAN*, JUNE 2015 (*cover*); *SCIENTIFIC AMERICAN MIND*, DECEMBER 2004 (*cover*); GETTY IMAGES (*DNA strand and Salk*); *SCIENTIFIC AMERICAN*, OCTOBER 1988 (*cover*); SCIENCE SOURCE (*Pasteur and HIV*); OPPOSITE PAGE: RYOICHI UTSUMI *Getty Images* (*phonograph*); GETTY IMAGES (*laptop*); *SCIENTIFIC AMERICAN*, SEPTEMBER 1977 (*cover*)

170 YEARS OF SCIENTIFIC AMERICAN

COMMUNICATIONS & COMPUTING

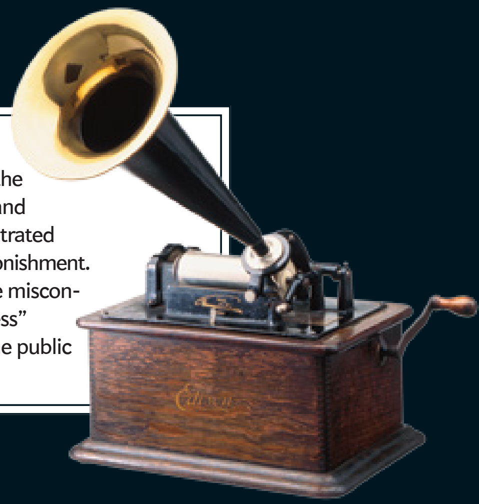
Pioneers from Bell to Berners-Lee completely change how people communicate and calculate

1845 Morse Code

On August 28 the premier issue of *Scientific American* reports that Samuel Morse's telegraph, "this wonder of the age," has successfully linked Washington and Baltimore with nearly instantaneous electrical communication.

1878 The Phonograph

Thomas Edison had walked in to the *Scientific American* offices in 1877 and for the first time in public demonstrated his phonograph, to the editors' astonishment. In his 1878 article, he clears up the misconceptions "disseminated by the press" about the technology because "the public is liable to become confused."



1985 Nuclear War

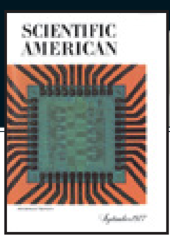
Ashton Carter, a physicist and today the U.S. secretary of defense, explains why "command and control" systems facilitated by satellites and computers may be just as important as policy in deterring nuclear weapons attacks.

1981 Supercomputers

Ronald Levine shows how radical new "supercomputers," such as the Cray-1, can solve complex scientific problems like fluid dynamics.

1977 PRESCIENCE ABOUT PORTABLES

Alan Kay, working at the famous Xerox PARC computer research center, predicts that in a decade or so, many people will possess a notebook-size computer that has the capacity of a large computer of 1977. Kay went on to key jobs at Atari, Apple, Disney and HP.



1977 Who's Who

In September 1977 *Scientific American* publishes an issue on the exploding impact of microelectronics. Articles are written by many Silicon Valley pioneers, including David Hodges (Bell Labs, U.C. Berkeley), James Meindl (Stanford), Ivan Sutherland (Caltech, Sun Microsystems) and Carver Mead (Caltech), who coined the term "Moore's law."

1887 Bell's Telephone

After describing how the ear and brain process speech, Alexander Graham Bell then explains how a selenium rheostat mimics these processes in his telephone.

1949 AUTOMATIC BRAINS

In a sweeping account of emerging mathematical machines—today's computers—Harry Davis notes, "Already the building and operating of automatic brains is becoming a big business. The electronic brains cost from $50,000 to $1,000,000 each, and there are eager waiting lists of customers."

2000 Computer-Generated Actors

Alvy Ray Smith, co-founder of Pixar Animation, assesses whether animators can digitally create realistic humans to star in computer-generated films.

2010 The Web at 20

Twenty years after inventing the World Wide Web, Tim Berners-Lee sets an agenda for protecting its fundamental principles, under attack from corporations and governments. They must prevail, he says, to make sure that anyone can access the Web and create applications for it and to protect an individual's privacy while using it.

170

YEARS OF SCIENTIFIC AMERICAN

PHYSICS & MATH

Accurately describing how the world works reveals magnificent and dangerous ways to exploit it

1985
Fractals
A. K. Dewdney delights in the brilliant geometric images called fractals, developed by IBM researcher Benoit Mandelbrot.

1910
RADIATION
N Marie Curie explains the nature of radiation in "Radioactivity" before winning the Nobel Prize in Chemistry in 1911.

1963 INFERIOR EXPERIMENTS
N Nobel Prize winner P.A.M. Dirac explains that physics theories, seemingly stalled, must evolve; otherwise, scientists will have to rely on experiments, an inferior option.

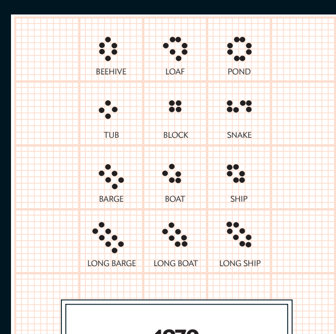
N

1950
The Bomb
After leaving the Los Alamos defense laboratory, physicist Hans Bethe writes "The Hydrogen Bomb II," which is quickly censored by the U.S. government; the Atomic Energy Commission destroys 3,000 copies of the magazine.

2003 Neutrinos and Nobels
N In 2015 two *Scientific American* authors, Takaaki Kajita and Arthur McDonald, win the Nobel Prize in Physics for pinning down traits of the elusive neutrino particle. Related articles, written by them and co-authors, are "Detecting Massive Neutrinos" (Kajita, 1999) and "Solving the Solar Neutrino Problem" (McDonald, 2003).

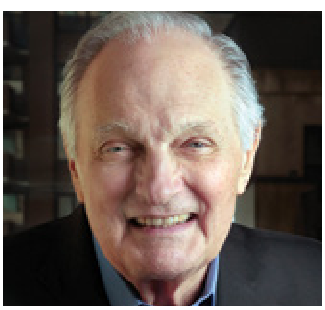
1975 No Backward for Time
In "The Arrow of Time," David Layzer asks why time never goes backward and explains why the answer lies in the conditions that prevailed during the early universe.

1979 Quantum Existence
According to Bernard d'Espagnat, quantum mechanics indicates that objects cannot exist unless they can be grasped by human consciousness.



1970
Fun with Math
Martin Gardner's popular Mathematical Games column ran for 29 years; a game in October 1970 simulates the rise and fall of living organisms.

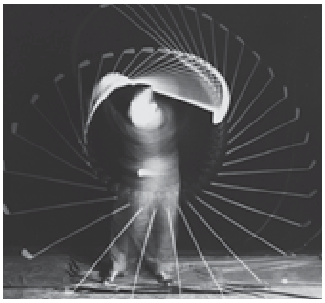
1999
Actor Explains Cats
Alan Alda, star of television hit show *M.A.S.H.*, grapples with the physics paradox known as Schrödinger's cat. He is one of many science-interested celebrities who have appeared in our pages, including filmmaker and explorer James Cameron.



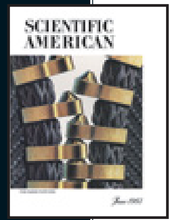
1910
Quantum Theory
N Max Planck writes that the long-prevailing "mechanical theory" of nature cannot adequately explain light and other phenomena, leading him to create quantum theory, which revolutionized physics and our understanding of matter.

Illustrations by Don Foley

1939
Strobe Photography
Scientific American introduces a young engineering professor from M.I.T. who creates "stop-action" photography using a strobe light. Harold "Doc" Edgerton would become famous as the man who stopped time in his photographs of bullets, milk drops and golfers.



1996
NANO CONTROVERSY
In "Waiting for Breakthroughs," editor Gary Stix takes a skeptical look at the promise of molecular machines that will "produce anything from a rocket ship to minute disease-fighting submarines that roam the bloodstream," setting off a backlash from the nanotechnology community.



1983 THE ZIPPER
Occasionally *Scientific American* publishes a complete surprise, such as "The Slide Fastener," with 10 large, beautiful illustrations showing in incredible detail the many different designs for … the zipper.

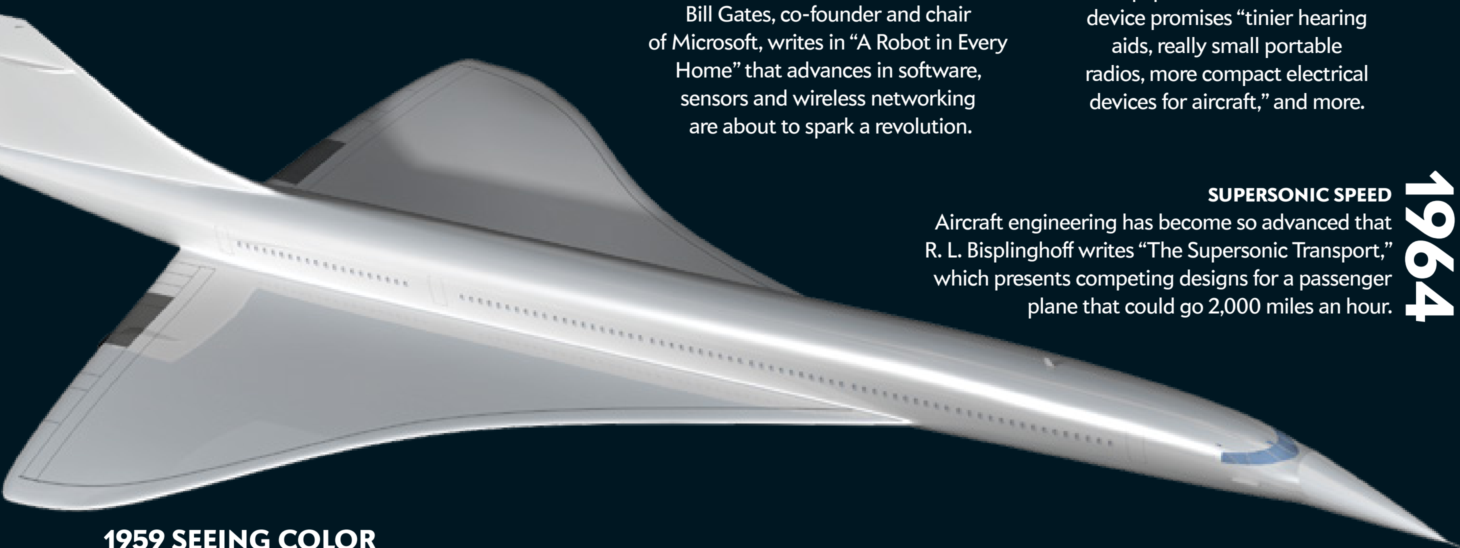
1904
INCANDESCENT LAMP
Thomas Edison writes "a brief personal narrative" of how he created the incandescent lamp, which was republished from *Electrical World and Engineer.*

1989 COMPETITIVENESS
Political economist Robert Reich, before becoming the U.S. secretary of labor under President Bill Clinton, writes that instead of relying on enormous, centralized projects to spur competitiveness, the federal government should link its research and development programs to those in corporations.

1936 ATLANTIC FLYOVER
"New York to London in 36 hours, with passengers, mail, and express!" So exclaims the first line of the article, "And Now, the Atlantic," about the debut of commercial air service across the pond.

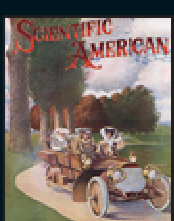
1948
TRANSISTOR RADIO
Frank Rockett introduces the "transistor," made from solid materials, which he notes could make the vacuum tube used in most electronic equipment obsolete. The device promises "tinier hearing aids, really small portable radios, more compact electrical devices for aircraft," and more.

2007
ROBOT REVOLUTION
Bill Gates, co-founder and chair of Microsoft, writes in "A Robot in Every Home" that advances in software, sensors and wireless networking are about to spark a revolution.



1964
SUPERSONIC SPEED
Aircraft engineering has become so advanced that R. L. Bisplinghoff writes "The Supersonic Transport," which presents competing designs for a passenger plane that could go 2,000 miles an hour.

1959 SEEING COLOR
Edwin Land invented the instant camera, marketed from 1947 on by Polaroid (which he co-founded). But Land was also a scientist. In a 1959 article he proposes new insights into how the human eye perceives color, and 18 years later he completes the explanation in an article entitled "The Retinex Theory of Color Vision."



1906 HORSELESS CARRIAGES
Munn & Co. is now publishing an annual "Automobile Number" of *Scientific American,* filled with details and practical advice about the increasingly popular motor car.

TECHNOLOGY & INDUSTRY
Science and innovation relentlessly alter daily life, allowing people to see at night, travel across oceans and (maybe) rely on robots big and small

170 YEARS OF SCIENTIFIC AMERICAN EVOLUTION

The theory of evolution, along with spectacular fossil and archaeological finds, fuels heated debate about the origins of humans and other organisms

2000
HUMANS APLENTY
Ian Tattersall contradicts conventional wisdom with robust evidence that for at least four million years many humanlike species shared the planet.

2002
Creationist Nonsense
Editor in chief John Rennie debunks the arguments against evolution in "15 Answers to Creationist Nonsense."

1950 Nature and Nurture
Very early in the new science of genetics, Theodosius Dobzhansky writes "The Genetic Basis of Evolution," which says that the variety of plants and animals results from a subtle interplay between genes and the environment.

1958 Behavior
N Konrad Lorenz maintains that behavioral traits—from how dogs scratch to how birds defend their nest—are as much an evolutionary characteristic as body structure and appearance.

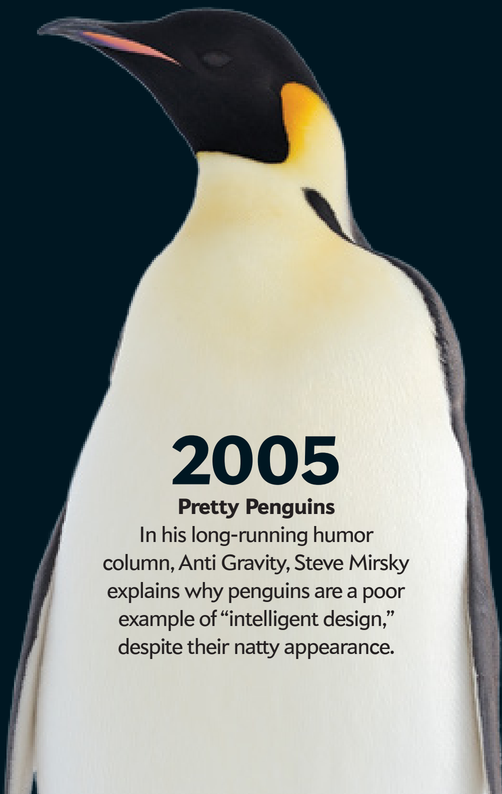
2005
Hobbits
Editor Kate Wong chronicles a spectacular find in Indonesia of a mini human species that lived as recently as 13,000 years ago and the rising argument over its authenticity.

1994 Punctuated Equilibrium
Heralded biologist Stephen Jay Gould makes a case that evolution is not a steady process but jumps ahead in fits and starts, in a progression he labels "punctuated equilibrium."

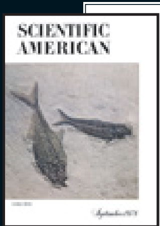
1959 Scopes Monkey Trial Redux
In the infamous 1925 trial of substitute science teacher John Thomas Scopes, the State of Tennessee found him guilty of teaching evolution in a public school, against state law. In his 1959 article, Fay-Cooper Cole, an expert witness at the trial, looks back and concludes that the spectacle actually improved public acceptance of the theory.

1982 Leakey Dynasty
Anthropologist Mary Leakey shares her interpretation of a bonanza of animal tracks—including those from human predecessors—that she found in 3.5-million-year-old volcanic ash in Tanzania. Her famous anthropologist husband, Louis, had written for *Scientific American* in 1954, and her son Richard and daughter-in-law Meave, rising stars in the field, write or co-author four articles over the years.

1877 Infant Development
Charles Darwin explains his observations of infants. He shows that they develop mental faculties at different rates and notes that it is "difficult to decide at how early an age" they feel anger, in an essay *Scientific American* republishes from the journal *Mind.*



2005
Pretty Penguins
In his long-running humor column, Anti Gravity, Steve Mirsky explains why penguins are a poor example of "intelligent design," despite their natty appearance.



1978 Group Selection
An entire special issue on evolution presents several radical theories, including that *Homo sapiens* arose only 100,000 years ago, that natural selection may favor group survival rather than individual survival, and that the genetic variation within species is much greater than previously thought.

All the same, Americans as a whole did not dissent. People who marched against environmental pollution still relished jet travel, transistorized stereos, color TVs and birth-control pills. Once the war ended, much of the anger subsided. Pollution remained a threat, although reformers found the means to mitigate it using cleanup technologies and science-based regulation.

A BIOMEDICAL AND SILICON SOCIETY

IN THE 1970S Joel had a teenager's impatience with life's inconveniences. Using a computer meant slogging to his school's computer center, submitting a program and picking up the printed output the next day. He had to call a travel agent to book a trip. His television watching was limited to three national networks and a few local stations. To withdraw money from the bank, he had to cash a check, and to make a call outside his home he had to find a payphone. When his mother was diagnosed with an abdominal cancer, she had to undergo exploratory surgery to determine the location and extent of the malignancy. He was pleased to learn in *Scientific American* that new technologies promised to dissolve the reasons for his impatience. The microchip would make it possible to downsize computers. "Desk-sized computers will become nearly as common as typewriters," one of the magazine's contributors predicted. So would access to the World Wide Web, the magazine said in 1991 in an issue devoted entirely to the Internet and its potential uses.

Recombinant DNA enabled the manipulation of life at its genetic essence. Scientists could cut out a gene from one organism and insert it into another.

Scientific American, along with other media, also reported on the advent of recombinant DNA, the molecular biological method that enabled the manipulation of life at its genetic essence. Using the technique, scientists could cut out a gene from one organism and insert it into another. Recombinant DNA could in principle be exploited for many purposes: the diagnosis of hereditary diseases and the application of gene therapies to cure them; the genetic engineering of farm crops such as corn to make them resistant to specific maladies; and the modification of microorganisms to produce advantageous proteins for pharmaceutical purposes.

Recombinant DNA aroused fears that the ability to manipulate life at its genetic essence would lead to a new eugenics, that genetically modified organisms jeopardized environmental balances or that genetic engineering for any purpose constituted an act of human hubris, an invasion of prerogatives reserved only for God. By the end of the 1970s the controversies, though not all the objections, had largely abated, quelled in part by federal regulation of recombinant initiatives in both lab and field, and by the benefits of these new genetic powers, such as the production of human insulin for the treatment of diabetes—the first of an extensive line of pharmaceutical products developed over the decades.

In recent years Joel found the conditions of life not only more satisfying but also more conducive to maintaining the health of himself and his family. In the 1970s *Scientific American* had showcased ultrasound, a technology of medical imaging that, unlike invasive procedures or x-rays, revealed features of the body's interior, including a fetus, "painlessly and with a minimum of risk and expense." It soon reported as well on a cluster of additional game-changing imaging technologies—CT, MRI and PET scans. If Joel or a member of his family fell victim to a chronic disease, physicians could obtain images of his bodily processes such as blood flow and brain activity or of tumors and painful displacements such as in the spine.

Joel lives, as we all do, in a world of microprocessors. They enable his cell phone, tablet and computer; they regulate his car, oven, refrigerator, house alarm, digital camera and the ATM that gives him cash 24/7. He owes a debt of thanks to microprocessors whenever he uses the Internet, which he often does, to find directions on a map or check his Facebook account.

As in the past, new technologies have stimulated new apprehensions, notably about personal and medical privacy in the information age, the vulnerability of a computerized society to attack at its cybernetic core, the impact of technologies and genetically engineered drugs on the costs of medical services, and the human price of learning that you may be fated to contract a genetic disease for which there is no known therapy or cure. Still, Americans relish the Internet's at-will access to commerce and information and the prospect that genetics, imaging and computing will lead to a more individualized, tailored medicine. They also hope that the world's societies can at once feed their voracious demand for energy and retard the pace of global warming through the cheaper technologies of wind and solar power.

If history is a reliable guide, Americans will welcome whatever science and technology may bring, much as they have since Rufus Porter extolled the railroad in the first pages of *Scientific American*. The record of the past 170 years offers ample reasons to believe that, despite any downsides, science and technology will continue to transform American life in preponderantly beneficial ways, many of them as yet unimagined. SA

MORE TO EXPLORE

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Communication Satellites. John R. Pierce; October 1961.

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SCIENTIFIC AMERICAN ONLINE For more about our 170-year history, go to ScientificAmerican.com/report/celebrating-170-years-of-scientific-american1

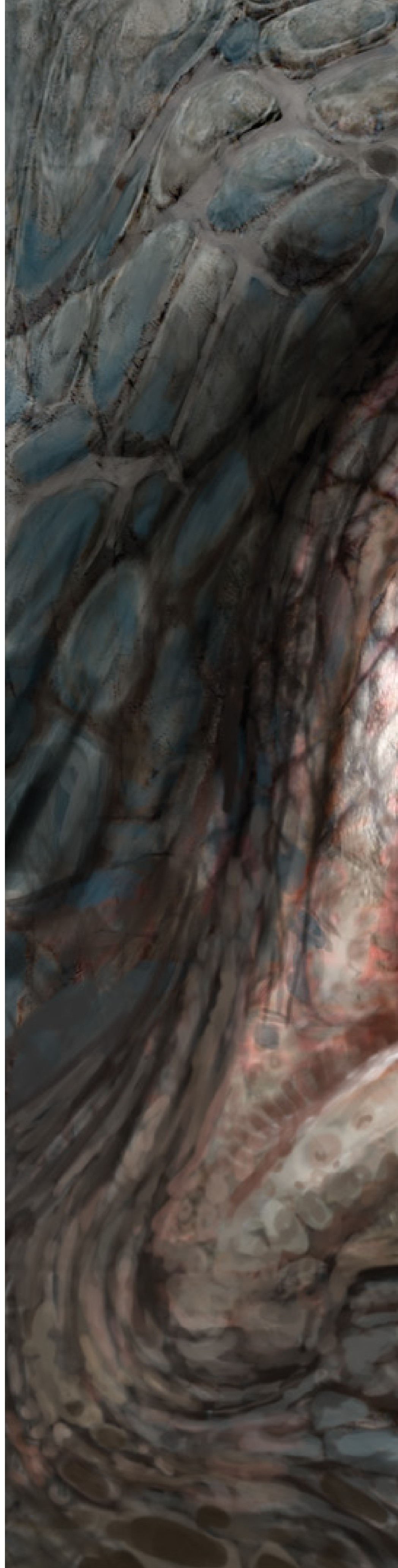
PAGES 50 AND 51: SCOTT CAMAZINE *Getty Images* (*fractal*); CAROLYN COLE *Contour by Getty Images* (*Alan Alda*); HAROLD EDGERTON *Corbis* (*golf swing*); *SCIENTIFIC AMERICAN*, JUNE 1983 (*cover*); SIMON BELCHER *Getty Images* (*lightbulb*); *SCIENTIFIC AMERICAN*, JANUARY 13, 1906 (*cover*); OPPOSITE PAGE: JAVIER TRUEBA *Science Source* (*skull*); JOHN READER *Science Source* (*Leakey*); GETTY IMAGES (*Scopes trial*); MARTIN RUEGNER *Getty Images* (*penguin*); *SCIENTIFIC AMERICAN*, SEPTEMBER 1978 (*cover*)

PALEONTOLOGY

what killed the dinosaurs

The asteroid strike was bad. The timing was worse

By Stephen Brusatte



IN BRIEF

The extinction of the dinosaurs is one of science's biggest mysteries.

A popular theory proposed a few decades ago holds that an asteroid impact brought about the group's demise.

But skeptics have wondered whether other factors might have contributed to its downfall.

A new analysis indicates that the giant space rock struck at a time when dinosaur communities were already vulnerable.

Illustration by Jon Foster

Stephen Brusatte is a paleontologist at the University of Edinburgh in Scotland. His research focuses on the evolution and anatomy of dinosaurs. His last article for *Scientific American* examined the ascent of the tyrannosaurs.

THE CHURCH ON SPILT BLOOD IN ST. PETERSBURG, RUSSIA, IS LIKE SOMETHING out of a fairy tale. Perched on the edge of a frigid canal, it has a forest of onion domes that stretches toward the sky and pastel-colored mosaics that cover every square inch of the interior. This is not the type of place where paleontologists typically hang out, but I was in town to study a new dinosaur, and I insisted on taking a detour. The visit was personal. The church was built on the spot where Czar Alexander II was assassinated by revolutionaries in 1881, setting in motion a sequence of events that led, eventually, to me. The czar's death ushered in a frenzy of anti-Jewish pogroms. Jews on the edge of the Russian empire grew frightened, and a family in Lithuania panicked and sent their young son to safety in America. That man was my great-grandfather. If not for that chain of dominoes that began more than 100 years ago in St. Petersburg, I would not be here today.

All families have stories like this one—weird twists of fate in the distant past, without which the present would be very different. Evolution works this way, too. The history of life is one big contingent tale, liable to be rerouted at any time. Indeed, that is precisely what happened 66 million years ago, at the end of the Cretaceous period. For the preceding 150 million years dinosaurs had dominated the planet, growing to colossal sizes and thriving in nearly every conceivable environment on land. But then something changed, and *Tyrannosaurus, Triceratops* and their kin vanished.

The extinction of the dinosaurs is one of the greatest mysteries in all of science, and it hooked me on science as a teenager. Over the past decade, as I have collected dinosaur fossils around the world, it has gnawed at the back of my mind: How could such successful creatures just disappear? A popular theory, advanced in the 1980s, holds that an asteroid did them in. But skeptics have wondered whether other forces might have contributed to their demise. As researchers discover new dinosaurs and learn more about this group's evolution, we are getting closer to a conclusive answer.

I recently organized a large international gathering of paleontologists who met to hash out exactly what we know about why the dinosaurs went extinct. We used the most up-to-date inventory of dinosaur diversity to examine evolutionary trends over time, reviewed the latest information on the timing of the extinction and took a long look at the many environmental changes occurring around the time the dinosaurs disappeared. To our surprise, our team of nearly a dozen dinosaur experts—often an argumentative bunch—came to a clear consensus: as popular wisdom has it, the extinction was abrupt, and an asteroid was primarily to blame. But that story is incomplete: the asteroid happened to hit during what was already a horrible time for dinosaurs, when their ecosystems were vulnerable because of previous environmental change. It is a new and unexpected twist on an old tale and one that has surprising relevance to the modern world and our own evolutionary story.

AN ENDURING MYSTERY

LIKE MOST TEENAGERS, I did some rash things in high school. Perhaps nothing was more brazen than picking up the phone one day in the spring of 1999 and cold-calling Walter Alvarez, a geologist at the University of California, Berkeley. I was a 15-year-old kid obsessed with dinosaurs; he was the eminent National Academy of Sciences member who nearly 20 years earlier had proposed the idea that a massive asteroid impact killed off the dinosaurs. His hypothesis began with a curious observation. The geologic record preserves a thin band of clay that marks the boundary between the dinosaur-dominated sediments of the Cretaceous period, which spans the time between 145 million and 66 million years ago, and the dinosaur-barren sediments of the Paleogene period, between 66 million and 23 million years ago. Alvarez found that the clay band was saturated with iridium, an element that is rare on Earth but common in extraterrestrial bodies such as comets and asteroids. He first noticed this anomaly in a rocky gorge near the medieval commune of Gubbio in Italy's Umbria region. As chance had it, my family was gearing up for a trip to Italy to celebrate my parents' 20th wedding anniversary. I nagged my parents to take a break from the basilicas and art museums and visit Gubbio for a day to see the geologic feature that spawned Alvarez's famous killer-asteroid scenario. But I needed directions, so I decided to go straight to the source.

That Alvarez not only answered my call but also gave me detailed directions to the very spot in the gorge where he detected the iridium spike still floors me. I did not expect such a scientific giant to be so kind, so generous with his time. His asteroid theory, published in *Science* in 1980 with his Nobel Prize–winning physicist father, Luis, and two Berkeley colleagues, touched off a decade of frenzied debate. Dinosaurs and mass extinctions were constantly in the news; the impact idea appeared in countless books and television documentaries; and hundreds of scientific papers argued back and forth as to what really killed the dinosaurs, with paleontologists, geologists, chemists, ecologists and astronomers all weighing in on the hottest scientific issue of the day.

By the end of the 1980s it was undeniable that an asteroid or comet crashed into the planet 66 million years ago. The same iridium layer had been found around the world. And other geologic oddities known to stem from extraterrestrial impacts, including blobs of glass called tektites and deformed grains of quartz known as shocked quartz, turned up alongside the iridium. Furthermore, geologists even located a crater dated to the exact moment of the dinosaur extinction—the 180-kilometer-wide Chicxulub Crater in Mexico. Something unexpected and huge, about 10 kilometers across, had arrived from space and triggered a cataclysm of volcanic eruptions, wildfires, tsunamis, acid rain and sunlight-blocking dust, dooming the dinosaurs.

Still, scientists had precious little information on how dinosaurs were changing during the run-up to the impact and exactly how they and their ecosystems responded to this extraordinary environmental disaster. Debate thus continued to rage over whether that asteroid knocked out the dinosaurs suddenly, while they were still in their prime, or whether it delivered a final blow to a moribund group that was gradually wasting away and would have gone extinct anyway. After all, the asteroid did not strike a static planet but one that was experiencing dramatic sea-level fluctuations, temperature shifts and extreme volcanism. Maybe some of these things had factored into the extinction?

FRESH FINDINGS

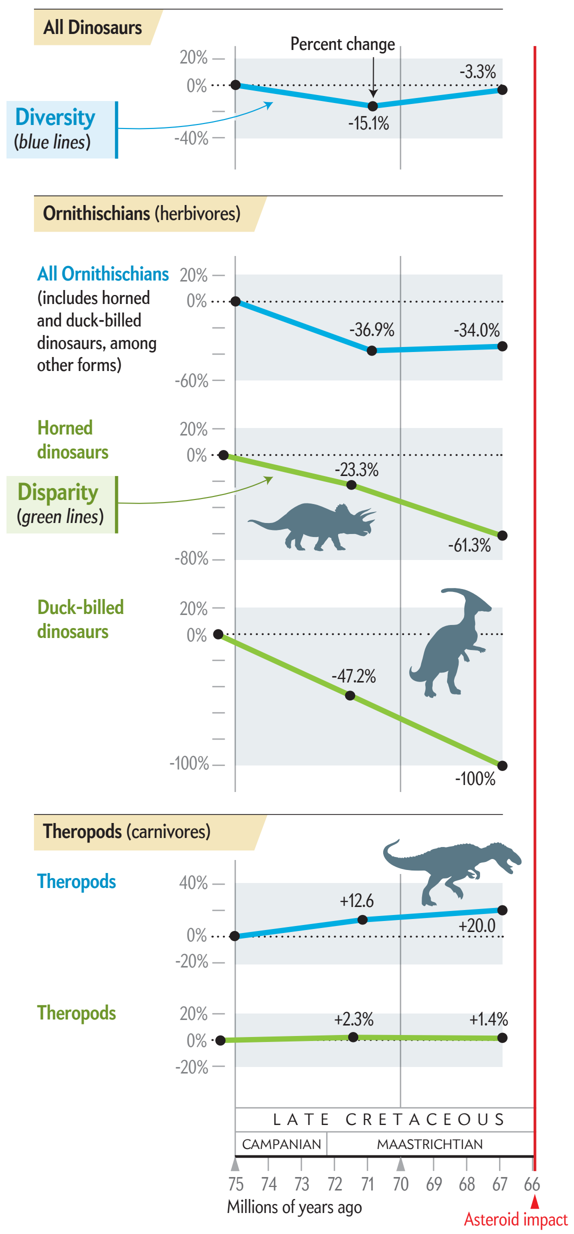
I NEVER MADE IT to Gubbio during that family trip to Italy. Floods closed the main rail line from Rome, and I was devastated. Fate can be cruel (just ask the dinosaurs), but it goes the other way, too. So imagine my surprise when, five years later, I was back in Italy for a college geology field course. We were staying in a small observatory in the Apennine Mountains run by Alessandro Montanari, one of many scientists who made names for themselves in the 1980s studying the end-Cretaceous extinction. On our first-day tour we passed through the library, where a solitary figure was scrutinizing a geologic map under a flickering light. "I want you all to meet my friend and mentor, Walter Alvarez," Montanari said in his singsong Italian accent. "Some of you may have heard of him."

A few days later we were in the gorge in Gubbio, the Medi-

HIDDEN TREND

Herbivores in Trouble

Analyses of North American dinosaurs show that, on the whole, they were flourishing in terms of the overall number of species—a measure known as diversity—when the asteroid struck 66 million years ago (*top*). But a closer look reveals hidden declines. One major group, the theropods, was doing fine (*bottom*). But another major group, the ornithischians, was dwindling in diversity as well as in disparity, a measure of the extent to which the species that are present vary in anatomy and size (*middle*). Two subgroups of ornithischians—the horned and duck-billed dinosaurs—were particularly hard-hit. Their downturn almost certainly had consequences for other dinosaurs.



SOURCE: "THE EXTINCTION OF THE DINOSAURS," BY STEPHEN L. BRUSATTE ET AL., IN *BIOLOGICAL REVIEWS*, VOL. 90, NO. 2; MAY 2015

Graphic by 5W Infographics

terranean sun beaming down and fast cars whizzing by. Alvarez stood in front of a class of college students, pointing to the exact place where the asteroid theory was conceived. My classmates were ragging on me because after I introduced myself to Alvarez and he remembered our discussion five years earlier, I could not stop smiling. That day is seared into my memory as one of the most important moments of my early career. I knew then that the riddle of the dinosaur extinction had a hold on me.

Somewhat paradoxically, as a graduate student my research focused mostly on the rise of the dinosaurs to dominance and the origin and early evolution of birds (which stemmed from dinosaurs and are thus the only dinosaur group that did not go extinct). But I finally had the chance to contribute to the dinosaur extinction debate in 2012, when I was finishing up graduate school. My colleague Richard Butler of the University of Birmingham in England, who uses statistics to study evolutionary trends, came up with a nifty idea: How about we pool our expertise on different dinosaur groups and different analytical techniques to take a fresh look at how dinosaurs were changing during the 10 million to 15 million years before their extinction?

We decided to examine dinosaur diversity trends using a metric called morphological disparity. Disparity is essentially an anatomical measure of biodiversity—it quantifies the variability in body size, shape and anatomy in a group over time or across ecosystems. Imagine two ecosystems, one with 15 species of small rodent and the other with a bat, a gazelle and an elephant. The first ecosystem may have more species, but the second has a suite of species with much greater diversity of size, shape and behavior. Disparity can often give a fuller picture of the vitality and biodiversity of groups than simple species counts can, and we wanted to see if there were any obvious trends in dinosaurs. Increasing or stable disparity during the latest Cretaceous period would indicate that dinosaurs were doing quite well when the asteroid so rudely interrupted their glory days, whereas declining disparity would suggest they were in trouble regardless of the big rock that fell from the sky.

We found some intriguing results. Most dinosaurs had relatively steady disparity during the 10 million to 15 million years before the impact, including the meat-eating theropods (such as *Tyrannosaurus* and *Velociraptor*), the long-necked sauropods, and the small to midsize plant eaters (the dome-headed pachycephalosaurs, for example). But two subgroups were in the midst of a disparity decline when the asteroid came: the horned dinosaurs (*Triceratops* and kin) and the duck-billed dinosaurs. Both groups were large-bodied plant eaters that consumed enormous amounts of vegetation. If you were around 66 million years ago, you would have readily noticed that these dinosaurs were the most abundant. They were the cows of the Cretaceous, the keystone herbivores in the food web.

Around the same time we published our results, other researchers were examining the dinosaur extinction from other angles. Teams led by Paul Upchurch of University College London and Paul Barrett of London's Natural History Museum undertook a census of dinosaur species diversity over time and found that dinosaurs as a whole were still very diverse at the time the asteroid hit but that the group that included the horned and duck-billed dinosaurs was undergoing a decline in species numbers. Their findings quite clearly jibed with our disparity calculations.

How would a decline of species richness and disparity in big plant-eating dinosaurs have influenced the rest of the group? Insights have come from an innovative computer modeling study led by Jonathan Mitchell, then a Ph.D. student at the University of Chicago. Mitchell and his team built food webs for several Cretaceous dinosaur ecosystems and simulated what would happen if a few species were knocked out. The result was striking: the food webs that existed when the asteroid struck, which had fewer large herbivores because of the diversity decline, collapsed more easily than the more diverse food webs from a few million years before the impact.

BROADER IMPACT

Weakened Food Web

Computer modeling of the food webs of Late Cretaceous North American dinosaurs from the Careless Creek Quarry in Montana and the younger Lull 2 Quarry in Wyoming suggests that the losses of horned dinosaurs and duckbills would have dramatically affected other dinosaur species. These large-bodied plant eaters were keystone species, serving as prey for carnivorous dinosaurs. Their disappearance destabilized the food webs, leaving dinosaurs all the more vulnerable to the devastating effects of the asteroid impact.

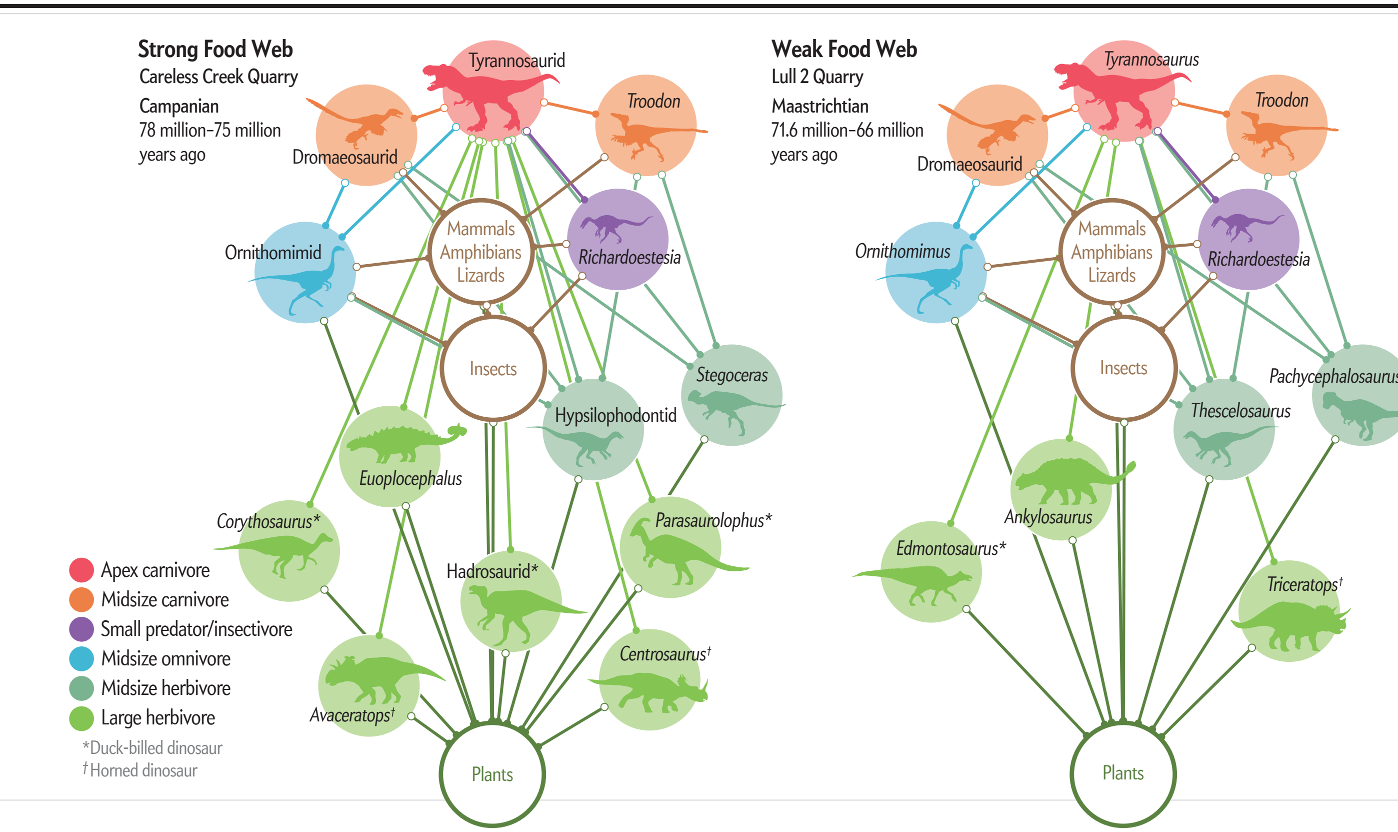
BAD TIMING

WITH SO MUCH new data on the dinosaur extinction appearing in the journals, Butler and I had something of a dangerous idea: perhaps we could recruit a crack team of dinosaur experts willing to sit down, discuss everything we currently knew about the dinosaur extinction and try to come to a consensus on why we thought dinosaurs died out. It was mostly for a bit of fun at first. Paleontologists had been arguing for decades on this topic. Who were we to think we could resolve it? More likely our subversive little plot would end in deadlock or, worse, in a shouting match. In fact, quite the opposite happened. Our group, which included 11 scientists from the U.S., Canada and the U.K., actually came to an agreement. We published our study this past May in *Biological Reviews*.

Here is what we found when we reviewed all the evidence: Dinosaurs seem to have been doing fairly well in the latest part of the Cretaceous. There are no signs that their overall diversity (in terms of both species numbers and disparity) declined gradually over millions of years. The major groups of dinosaurs all persisted into the very latest Cretaceous, and at least in North America, where the fossil record of latest Cretaceous dinosaurs is most complete, we know that *Tyrannosaurus, Triceratops* and clan were all there to witness the asteroid impact. This finding rules out the once popular hypothesis that dinosaurs wasted away gradually, probably because of long-term fluctuations in sea level and temperature that altered the amount of land and types of food accessible to them. Instead the dinosaur extinction was abrupt in geologic terms. It stands to reason, then, that the asteroid impact—a sudden and unexpected event—was the culprit.

But, as we had suspected based on our earlier studies, the asteroid was not the whole story. The big plant-eating dinosaurs did undergo a bit of a decline right at the end of the Cretaceous. The exact reason for this downturn is uncertain, but it may have had to do with a shorter-term sea-level drop that

SCIENTIFIC AMERICAN ONLINE Watch a video about dinosaur extinction at ScientificAmerican.com/dec2015/dinosaurs



greatly changed the land area available for dinosaurs during their final few million years—at least in North America, which preserves by far the best fossil record of this period. As the most abundant herbivores, the horned and duck-billed dinosaurs would be the first dinosaurs to feel the effects of changes in home range and vegetation. Their decline apparently had consequences: it made ecosystems more vulnerable to collapse by destabilizing the foundation of the food web, increasing the likelihood that the extinction of just a few species would cascade through the ecosystem.

All told, it appears that the asteroid impact occurred at a horrible time for dinosaurs. If it had happened a few million years earlier, before the dip in large herbivore diversity, dinosaur ecosystems would have been more robust and better able to endure the impact. If it had struck a few million years later, maybe herbivore diversity would have recovered, as it had countless other times over the preceding 150 million years of dinosaur evolution. It is never a good time for a 10-kilometer-wide asteroid to drop out of the sky, but for dinosaurs, 66 million years ago may have been the worst possible time. With only a modest shift in the chronology, the dinosaurs might still be here today.

What happened 66 million years ago, when that hunk of rock and ice from beyond slammed into Mexico at the most inopportune time for dinosaurs, reverberates today. Mass extinctions are tragic, but they also clear out space for new plants and animals to evolve and become dominant. The death of the dinosaurs brought opportunity for mammals, which had lived in the shadows for more than 100 million years but now had the chance to evolve unencumbered. Mammals blossomed almost immediately after the dinosaurs went extinct, evolving large size and myriad new diets and behaviors, and they spread around the world. This flowering eventually led to the emergence of primates, which led to us. Remove any link in that historical chain reaction, and that probably means no humans.

But there is a greater lesson in the dinosaur extinction. It is not just a mind-twisting tale of evolutionary contingency—another one of those events in the distant past that lets us play the what-if game. Simply put, what happened at the end of the Cretaceous tells us that even the most dominant groups of organisms can go extinct and quite suddenly at that. Dinosaurs had ruled for more 150 million years when their time of reckoning came—a split-second collision between Earth and space. And their extinction was made easier, perhaps even enabled, by losses in biodiversity that preceded the asteroid impact. Modern humans have been around for, at most, a few hundred thousand years, and we are changing the environment at such a fast rate that a so-called sixth extinction is occurring, with global biodiversity in rapid decline. Who knows how vulnerable we are making ourselves in the process? SA

SOURCE: STEPHEN BRUSATTE

MORE TO EXPLORE

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scientificamerican.com/magazine/sa

Graphic by Daisy Chung

TELESCOPE WARS

Old grudges between three teams of astronomers have threatened the survival of ground-based astronomy's boldest, biggest projects

By Katie Worth

For 15 years three competing groups of astronomers have chased a single dream: to build the grandest telescope on earth. The stargazing behemoths they aim to build would be three times larger than the world's current largest optical telescopes, powerful enough to take pictures of planets circling other stars and to peer across the breadth of the universe, gazing back in time nearly to the big bang.

This dream observatory comes in three versions: the Giant Magellan Telescope (GMT), developed by a consortium including the Carnegie Institution for Science; the Thirty Meter Telescope (TMT), developed by the California Institute of Technology, the University of California system and others; and the European Extremely Large Telescope (E-ELT), developed by the European Southern Observatory (ESO). Building all three would cost nearly $4 billion, but so far the world has balked, leaving each project short on cash and hustling for more. There could have been at least one giant telescope gazing at the heavens today; instead partially built hardware awaits delivery to barren construction sites.

All three telescopes are likely to limp across the finish line of their race and begin operations sometime in the 2020s, albeit behind schedule and over budget.

Illustration by Alex Nabaum

Katie Worth is a reporter at *Frontline,* a television production of WGBH in Boston. She spends a lot of time thinking about politics, science and their myriad intersections.

How did this happen? How did three separate projects with common goals come to be fighting one another for funding? And what has prevented them from joining forces to minimize the chance of their collective failure?

These questions have been asked repeatedly, including by a bewildered national panel considering two of the telescopes for federal funding. Dozens of scientists interviewed for this story pondered what might have been if instead of three ventures, there had been one or two. Nearly all agreed that humankind would be much closer to building the next, greatest generation of observatories if competing groups of astronomers had not spurned repeated chances to collaborate. That competition started in the first decades of the 20th century and has been sustained across the years by personality conflicts, miscommunications, competing technologies and an expanding universe of bitterness.

THE BIG DEAL

THE STORY BEGINS IN 1917, when an ambitious astronomer and observatory director named George Ellery Hale unveiled something entirely new to science, a 100-inch optical telescope.

In the world of telescope construction, size matters: the larger a telescope's mirror, the farther it sees. The new telescope, perched on Mount Wilson in what was then still a dark-skied Los Angeles County, dwarfed all others on earth. Its revolutionary size rapidly produced revolutionary results. Edwin Hubble used it to discover that our galaxy is but one among many and then to gather evidence that the universe is expanding.

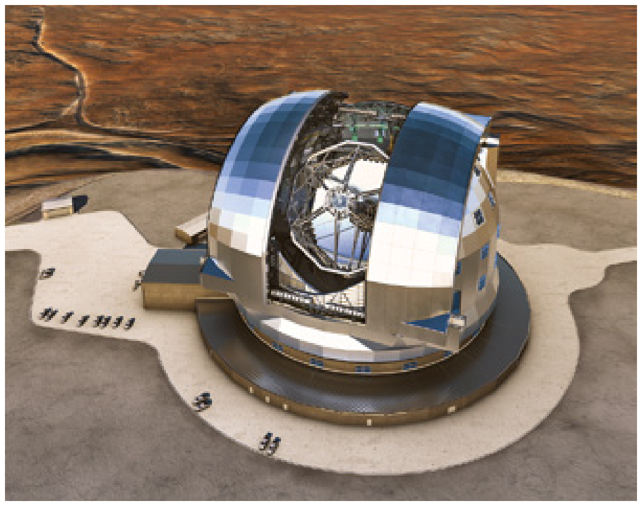
But Hale was not satisfied. He wanted a 200-inch telescope.

The 100-inch one was built and run by what was then called the Carnegie Institution of Washington, a charity created by steel baron Andrew Carnegie. Carnegie was not prepared to spend millions more on a new telescope, so Hale slyly pitched the project to an organization funded by Carnegie's rival, oil magnate John D. Rockefeller. In 1928 Rockefeller personally approved Hale's 200-inch telescope, eventually providing it with a \$6-million grant—at the time, the largest sum ever donated to a scientific project.

There was a catch: the astronomers at the Carnegie Institution were the only ones in the world with the expertise to build the new telescope, but Rockefeller would not fund his old rival's charity. "It was just not going to happen," says historian Ronald Florence, who wrote *The Perfect Machine,* a book about the 200-inch telescope. "So that sets up the pool shot for problems."

Hale came up with a solution: Rockefeller would give the telescope money as a gift to Caltech, which had just been established only two miles (three kilometers) from Carnegie's observatory headquarters in Pasadena, Calif. Caltech was still so embryonic that it did not employ a single astronomer, let alone an astrophysics department. Nevertheless, the Rockefeller Foundation funded Caltech's construction of Hale's new telescope and the Palomar Observatory in San Diego County, which housed it. Hale believed Carnegie's leaders would find working on such a magnificent stargazing tool irresistible and would lend their expertise to design and construct the new telescope.

Hale was mistaken. According to Florence, the deal enraged the Carnegie Institution's president, John Merriam, who saw it as an unforgivable deceit. He worked to scuttle the project, refusing to allow Carnegie scientists to help and pressuring the Rockefeller Foundation to walk away. Desperate, Hale called on the diplomat Elihu Root, an old friend of both Rockefeller and Carnegie. Root swayed Merriam, who at last signed on to the project.



COURTESY OF L. CALCADA *European Southern Observatory*

But the discord was only beginning: Merriam was still angry and tried for years to wrest control from Caltech, Florence says, until the institutional distrust became mutual and profound.

After Merriam retired, the warring charities at last formed an uneasy truce. The Rockefeller Foundation approached its astronomical adversaries with a deal: Caltech would own the telescope when it opened its 16-foot eye in 1949, but Carnegie would operate it.

IN BRIEF

Three extremely large telescopes are currently under construction and slated to begin operations in the 2020s.

Each telescope will boast a primary mirror around 30 meters in diameter. Such gigantic mirrors will allow astronomers to study the cosmos with unprecedented, revolutionary clarity.

Despite such great scientific potential, the projects all have funding troubles, leading critics to wonder why astronomers are simultaneously building three giant telescopes rather than just one or two. The answer lies in an old rivalry that traces back to the first large telescopes of the early 20th century.

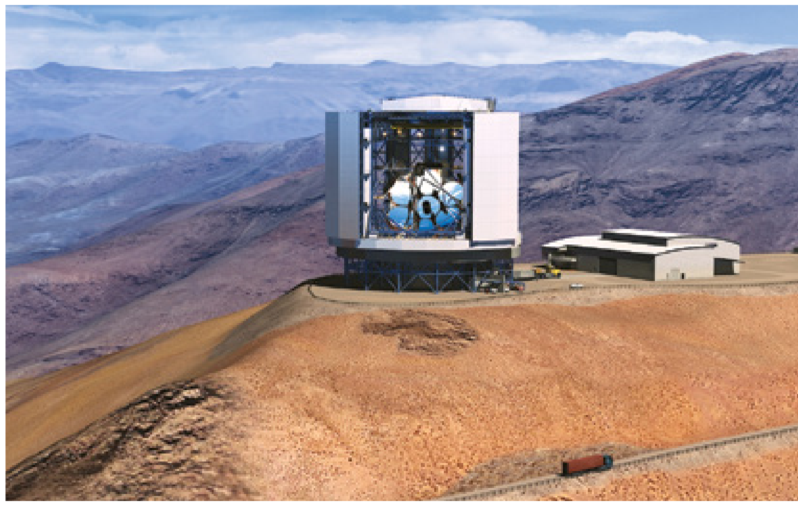
The fragile relationship between the institutions inevitably spilled into science, especially after the identification of "quasi-stellar objects"—quasars—in the early 1960s by Dutch-American astronomer Maarten Schmidt. Although they at first seemed to be dim stars in the sky, further studies showed quasars to be shining with almost unthinkable brilliance from the far distant universe. The mysterious objects quickly became astronomy's sexiest subject, and Caltech and Carnegie researchers vied for time on the world's largest telescope to study them, sometimes resorting to "junior high–level pettiness," Florence says.

In 1979, after half a century of tensions, Caltech finally sought to end its strained shared custody of Palomar. The split did not go well and proved intensely personal. The late Allan Sandage, Carnegie's legendary astronomer, who had achieved his life's work at Palomar, refused to set foot in the observatory again. "It was the kind of divorce where you had to choose the husband or the wife," Florence says. "There was no staying friends with both."

To most astronomers, jumping from a 10-meter telescope to a 100-meter one was absurdly ambitious. But a 30-meter telescope seemed viable, to the consternation of Gus Oemler, then the observatories director at Carnegie. He remembers waking up to Caltech's announcement and feeling sick. "We were struggling to finish the Magellan telescopes, which were finally going to give us some kind of parity with Caltech after many years, and suddenly they were starting the next phase."

After much debate, Carnegie pitched Caltech on a collaboration. Both sides were hesitant, but the boards of each institution thought it was time to traverse the freeway and the old grudge that separated them. "We recognized it would be kind of crazy to have two giant telescopes centered on two institutions within two miles of each other," says Carnegie astronomer Alan Dressler.

So on June 21, 2000, two scientists from Caltech—the late astronomer Wal Sargent and the late Tom Tombrello, then the physics chair—and two from Carnegie—Oemler and Dressler—met to discuss a partnership.



GLASS GARGANTUANS: The Thirty Meter Telescope (*above left*) and the Giant Magellan Telescope (*above right*) will be about the same size; the larger European Extremely Large Telescope (*opposite page*) will boast a nearly 40-meter mirror.

COURTESY OF THIRTY METER TELESCOPE (*left*); COURTESY OF GIANT MAGELLAN TELESCOPE ORGANIZATION (*right*)

CONFLICTING DESIGNS

OVER THE NEXT TWO DECADES the institutions trod separate paths. In the 1990s Caltech partnered with the University of California to unveil the twin 10-meter Keck telescopes on Mauna Kea in Hawaii, using what was then a novel segmented mirror design in which many small mirrors created one larger, light-gathering aperture. Their risk paid off: the design worked beautifully, and their astronomers enjoyed years of scientific preeminence before anyone else built something competitive. Meanwhile Carnegie stuck with the older, single-mirror technology but ventured into the Southern Hemisphere, constructing the twin 6.5-meter Magellan telescopes in the Atacama Desert in northern Chile.

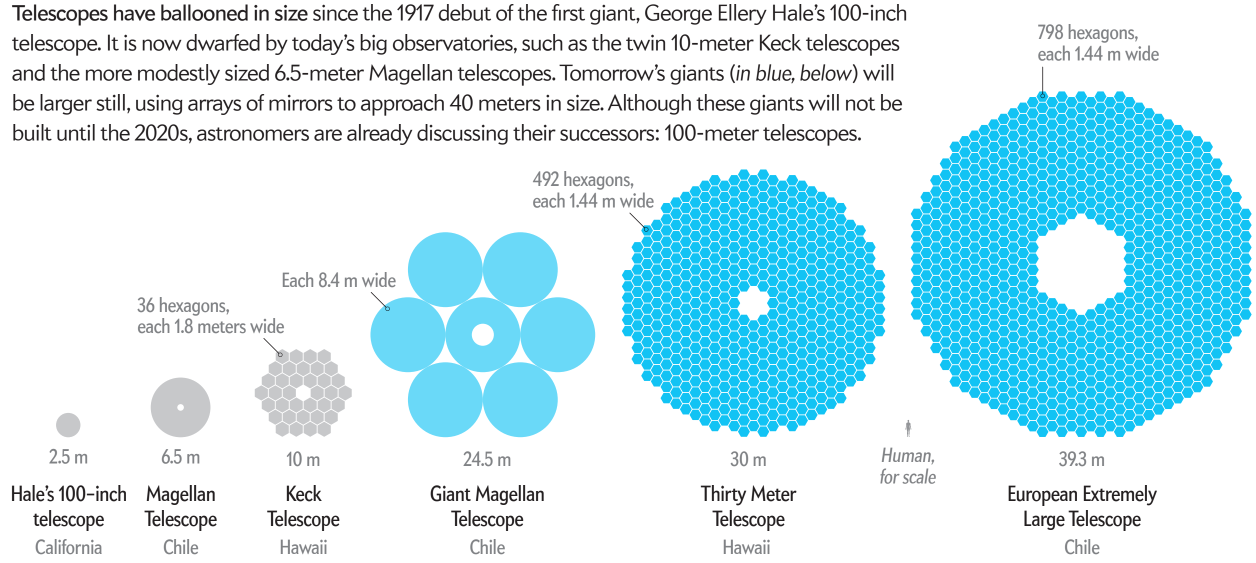
Carnegie was just completing these telescopes in 1999 when Caltech and the University of California announced their intention to build a 30-meter telescope. The ESO, an intergovernmental organization of astronomers throughout Europe, was already toying with something even more ambitious—a 100-meter (and appropriately named) OverWhelmingly Large Telescope.

By all accounts, that discussion went terribly. The meeting was tense, disjointed and plagued by misunderstanding. Both Wendy Freedman, who would later become director of the Carnegie Observatories, and Richard Ellis, now a senior scientist at the ESO, who was then on the verge of replacing Sargent as Caltech's Palomar Observatory director, spoke to all four men immediately after the meeting and heard a different story from each: Dressler felt that the Caltech men were not taking Carnegie's proposal seriously, whereas Tombrello mistakenly believed that Carnegie did not have serious money to contribute. Oemler said Sargent sat in icy silence through most of the meeting. Sargent later said he was worried about upsetting Caltech's then delicate relationship with the University of California. But Sargent had not explained that concern during the meeting, Ellis says, so "of course, the Carnegie people were offended."

The next day Tombrello sent an e-mail "to summarize our rambling discussion." Caltech was not interested in working with Carnegie on the telescope for the time being, Tombrello wrote, al-

Big, Bigger, Biggest

Telescopes have ballooned in size since the 1917 debut of the first giant, George Ellery Hale's 100-inch telescope. It is now dwarfed by today's big observatories, such as the twin 10-meter Keck telescopes and the more modestly sized 6.5-meter Magellan telescopes. Tomorrow's giants (*in blue, below*) will be larger still, using arrays of mirrors to approach 40 meters in size. Although these giants will not be built until the 2020s, astronomers are already discussing their successors: 100-meter telescopes.



though he would not exclude the possibility if the work got expensive. The Carnegie astronomers felt condescended to and insulted. The nascent collaboration died, and the long tradition of acrimony between the institutions grew longer.

That meeting is now a part of giant telescope lore. Ellis is one of many astronomers who wonder what might have happened had the meeting gone differently.

"When you look back on that moment—what a tragedy," he says. "With a few phone calls and a bit of diplomacy, we could have brought Carnegie in. And had we brought them in, we'd probably have a telescope by now."

Garth Illingworth, an astronomer at the University of California, Santa Cruz, says there remained "just enough residual resentment and unhappiness" from the old rivalry to derail a constructive conversation. "You just think, jeez, why wasn't there a little adult supervision in the room to help these folks to get over this?" he adds.

DIVIDED THEY FALL

AFTER THIS FAILED DÉTENTE, the rivalry only expanded. Caltech and the U.C. system developed the TMT, to be constructed next to the Keck telescopes in Hawaii. Meanwhile Carnegie designed the GMT, a 24.5-meter telescope, to cap its Las Campanas Observatory in Chile. Around the same time, the Europeans scaled down their dreams from overwhelmingly large to merely extremely large and planned the construction of the 39-meter E-ELT in Chile.

The three projects scoured the globe for financing, sometimes searching in the same places. Pony up money, the typical pitch went, and your astronomers will be guaranteed telescope time. Canadian astronomers, for instance, were courted by both the Carnegie group and the Caltech-U.C. teams and chose the latter. Harvard University was also wooed by both but committed to Carnegie. At least once, the two American teams awkwardly ran into each other in an airport as they traveled to meetings with the same potential partners. And the Europeans were not above the fray: they initially secured support from Brazil, whose president agreed to join the ESO and underwrite a major chunk of the E-ELT. But fractured Brazilian politics stalled the agreement. Carnegie has taken advantage of the E-ELT's woes: in July 2014 the University of São Paulo joined the GMT project, and according to Dressler, GMT leadership hoped the Brazilian government would soon follow, although that has not turned out to be the case.

The most sought-after partner of all has been the U.S. government, which could open its strongbox of federal funding to finance a giant telescope and provide access for all American astronomers. In 2000 the Astronomy and Astrophysics Decadal Survey, a once-a-decade national panel that guides U.S. federal funding, had declared a next-generation giant telescope the country's highest priority in ground-based optical astronomy.

With this endorsement, the National Science Foundation began discussing a partnership with the Caltech-U.C. TMT project in 2003. But within months GMT astronomers wrote a letter saying the deal would unfairly favor the TMT. The letter was effective: the NSF balked, unwilling to take sides in the increasingly divisive politics of top-tier optical astronomy.

In reality, there was not much federal money to provide anyway, according to NSF senior adviser Wayne Van Citters. But the feud did not help, he says: "We needed the community to come together and decide which one they wanted to do. We couldn't possibly do both."

The community, for its part, tried repeatedly to do just that, but the efforts proved fruitless. European astronomers discussed collaborations with both their rivals but ultimately only agreed to share technology insights. And in 2007, at the insistence of their boards, TMT and GMT leaders held several coldly cordial meetings to discuss ways they might work together. Nothing came of it.

The situation confounded panel members of the 2010 decadal survey, who questioned why the U.S. astronomy community was

Graphic by Daisy Chung

being asked to support two separate American-led large optical telescopes. In the end, they backed neither, kicking the projects to the bottom of the priority list and effectively quashing federal funding for another 10 years.

Rivalry is hardly rare in science: brilliant minds are often accompanied by big egos with a penchant for clashing. Sometimes feuds can yield innovation; other times they can turn the high-minded pursuit of discovery into a series of petty personal conflicts. Some disciplines have successfully convinced potential rivals to join forces: High-energy physicists work in massive international ensembles on particle accelerators. Radio astronomers have collaborated on their field's largest next-generation tool, the $1.4-billion Atacama Large Millimeter/submillimeter Array.

In contrast, optical astronomy in the U.S. has been riven with competition. Italian-American astronomer and Nobel laureate Riccardo Giacconi described it in a July 2001 speech to the National Academy of Sciences as a sociological problem.

To historian W. Patrick McCray of the University of California, Santa Barbara, who wrote *Giant Telescopes,* a book about the American optical astronomy community, what is striking about the enmity between Caltech and Carnegie is its longevity: they have been bickering over large telescopes since 1928. "You just think, Have you people learned nothing?" McCray says.

But rivalry alone does not explain the state of affairs. There were rational reasons to work on separate telescopes, notes astronomer Ray Carlberg of the University of Toronto, which is part of an association involved with the TMT project. Initially astronomers believed there would be money for all three, and giant telescopes in both the Northern and Southern hemispheres would ensure full coverage of the entire sky. "The world had just built quite a few eight- and 10-meter telescopes, and it didn't seem unreasonable to have a bunch of these big ones," Carlberg says. By the time it was clear that Caltech could use Carnegie's help, Carnegie was too deeply invested in its own project to abandon it.

TOO MANY TELESCOPES

ON THE BIG ISLAND OF HAWAII, a corner of Mauna Kea's immense summit has been flattened to make way for the TMT. The telescope's 30-meter mirror, the diameter of the U.S. Capitol Dome, will be composed of a honeycomb of 492 hexagonal, 1.44-meter segments, all housed in an 18-story structure on the dormant volcano. The project has been granted land-use permits, although it still faces vocal opposition and legal challenges from some native Hawaiians and environmentalists. To help pay for the $1.5-billion endeavor, Caltech and the U.C. system have secured international partnerships with India, China, Japan and Canada. They are still searching for an additional $270 million; the project's current best guess for its telescope's debut is sometime in the early 2020s.

Eleven blocks from the TMT's Pasadena headquarters, Carnegie and its partners are coaxing the 24.5-meter GMT into life. It will consist of seven 8.4-meter mirrors, with six mirrors arranged like flower petals around one in the center—an approach very different from, and incompatible with, the smaller, more numerous hexagonal mirrors of the TMT. Four mirrors have already been cast at a laboratory at the University of Arizona. The more modest size and design come with a more modest cost: just under $1 billion. Carnegie has enlisted the support of universities from South Korea, Australia and Brazil, as well as several domestic universities. They have raised roughly half the money needed to build the telescope at its construction site within the Las Campanas Observatory. If all goes as planned, the GMT will begin collecting light by 2022.

A 12-hour drive up the Pan-American Highway from Las Campanas is Cerro Armazones, the desert mountain where the E-ELT will one day perch. The site was initially scoped out by TMT astronomers, who spent years monitoring the atmosphere above Cerro Armazones for transparency and turbulence before concluding they preferred to build in the Northern Hemisphere instead; the Europeans took advantage of that groundwork and claimed Armazones for their own project. Today a newly paved road leads to the mountain's bald scalp, which has been shaved with dynamite and heavy machinery into a soccer-field-sized flattop. Visible to the east of the mountain, the firmament meets the 6,723-meter Andean volcano Llullaillaco, where the Inca once sacrificed children to the gods. It and the rest of the arid panorama fade at nightfall, making way for a playground of stars overhead.

With a mirror 39 meters wide, the E-ELT will be the grandest next-generation telescope of all. Like the TMT, the E-ELT will have a segmented design, but instead of 492 hexagonal mirrors, it will boast 798. In December 2014 the ESO voted to move forward with first-phase construction. A second phase has not yet been funded. The E-ELT's leadership plans for the telescope to begin stargazing in 2024, for a total construction cost of €1.1 billion.

Once constructed, the three telescopes will have synergistic strengths, says the E-ELT's Roberto Gilmozzi. The E-ELT will specialize in zooming in to provide high-resolution images of small regions of the sky; the GMT will excel at wide-field astronomy. And the TMT will be located in a different hemisphere, observing a different sky.

Gilmozzi, like most other astronomers interviewed for this story, thinks that had there been two telescopes instead of three, both might be nearing completion by now, at a cost hundreds of millions of dollars less. "If you don't consider the problem of finding the money, it's wonderful to have more than one," he says. "Scientifically speaking, I could use 100 telescopes if I could afford to build them."

Unfortunately, building telescopes is just the first step. Neither the GMT nor the TMT currently has enough money to sustain operations once it is constructed. Both hope the federal government will eventually step in to assist, but Van Citters says it is not clear how much money the government will be able to contribute. The telescopes are each expected to cost tens of millions of dollars a year to operate. "That's enough to give people nightmares," McCray says.

Even so, the problem of too many telescopes has a silver lining: the world could one day have three giant eyes gazing at the cosmos. This would be a big win for science, McCray says. "If this situation is a tragedy, it's a tragedy with a small 'T.'" SA

MORE TO EXPLORE

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FROM OUR ARCHIVES

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Origami Observatory. Robert Irion; October 2010.
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MARK KINSINGER (*left*) and his younger sister, Ruth (*right, not their real names*), were born with the same genetic disorder. Mark, not diagnosed until age four, suffered irreversible brain damage. Since then, a pilot screening program and early intervention have fully prevented disability in other children with the condition, including Ruth.

MEDICINE

GENOMICS FOR THE PEOPLE

A children's clinic raised and supported by Amish and Mennonites proves that high-tech genetics research can be harnessed right now to prevent disease

By Kevin A. Strauss

Levi and Emma Kinsinger operate a small greenhouse in southern Pennsylvania. On November 6, 2002, they traveled 450 miles round-trip by taxi, at a rate of a dollar per mile, to bring their eldest son—Mark—to the Clinic for Special Children in Strasburg, Pa. At age four, Mark was frail and socially detached. He lay on the floor in constant, restless motion. His eyes roamed but did not fix, and he was unmoved by sound. From time to time, a guttural noise escaped his throat as he shook violently. The Kinsingers' question, one I've heard countless times in my work as a pediatrician, gave voice to their quiet desperation:

"What can we do to help our child?"

Photographs by Grant Delin

Kevin A. Strauss, who earned his M.D. from Harvard Medical School, is medical director of the Clinic for Special Children in Strasburg, Pa.

Our clinic is a medical home for children like Mark. (For privacy, I have changed the names of all patients and their families.) Its sturdy timber frame, erected by Amish and Mennonite hands, encloses a modern pediatric office equipped with an arsenal of high-tech gene-sequencing tools. We serve the North American "Plain" communities descended from European Anabaptists who fled to the New World in the 1600s to 1800s seeking religious asylum. Today's Plain people live in small, isolated Christian settlements throughout North America and eschew modern ways. Electricity and telephones are commonly forbidden in the home, codes of dress and conduct emphasize group cohesion, private and government insurance are rejected, and members distrust technologies that erode social interdependence.

The Plain people choose to live differently in the modern world, but every parent knows what it means to fear for a sick child: "Will my daughter ever walk?" "Can you stop the seizures?" "Is it autism?" Such are the questions that move us to translate the complex language of modern biochemistry and genetics into meaningful answers for children and families. To date, our laboratory has identified more than 170 different disease-causing gene mutations disproportionately represented among the Plain people. Nearly half endanger the developing brain and, left untreated, cause death or disability in children. Rapid, affordable, on-site molecular testing opens a precious window; it allows us to expose future health threats, craft more precise therapies and preempt disease before it strikes.

Our collaborative relationship with the Plain people also provides a glimpse into how genomics research will transform understanding of more common diseases. With the cooperation of a few dedicated Amish families, we recently discovered a specific genetic variation that appears to be linked to bipolar (manic-depressive) disorder, which affects between 2 and 4 percent of people worldwide and remains woefully underdiagnosed and undertreated. Linking a genetic variation to bipolar disorder moves genomics one step closer to the medical mainstream; it challenges the medical research community to close the gap between what we know about the causes of human suffering and what we can do for the people who need our help.

PROGRESS, ONE CHILD AT A TIME

WHAT THE KINSINGERS NEEDED was clarity. Within a few days we detected a constellation of chemical abnormalities in Mark's blood that implicated deficiency of an enzyme—5,10-methylenetetrahydrofolate reductase (MTHFR)—as the cause of his disabilities. Our lab director, Erik Puffenberger, worked quickly to discover an error in both of Mark's MTHFR-coding genes. This knowledge allowed us to diagnose three more affected children from the Kinsingers' home settlement.

I searched the medical literature and found the first description of MTHFR deficiency, published 30 years earlier by S. Harvey Mudd and his colleagues. Mudd was a legend in the small world of research devoted to intermediary metabolism, the collective processes that convert food into the energy and building blocks of cells. He elucidated what came to be known as the transsulfuration pathway—a complex network of chemical reactions that recycles an essential amino acid, methionine, while simultaneously supplying methyl groups (CH_3) to molecules throughout the body. Methionine is indispensable for the growth of the brain and other tissues, and methyl tags profoundly affect how these tissues function. MTHFR is a vital link in the chemical supply chain; lacking this enzyme, Mark had suffered the devastating neurological consequences of cerebral methionine and CH_3 deprivation.

I called Mudd, then age 75 and emeritus researcher at the National Institute of Mental Health. He generously guided me through the complexities of transsulfuration and suggested a treatment: an over-the-counter compound called betaine, which supplies the brain with methionine and CH_3 via an alternative metabolic pathway and can be administered as a dietary powder for just 60 cents a day. In the months that followed, I frequently made the four-hour trip to the Kinsingers' settlement with clinic nurse Christine Hendrickson. We traveled from farm to farm, carefully assessing the effects of betaine on our young patients. Armed with a cooler of dry ice, a portable centrifuge and a power inverter in my car's cigarette lighter, we spun and froze blood samples in the field. We shipped them to Mudd, who called on his network of colleagues to analyze methionine, betaine and a host of other chemicals in the transsulfuration pathway. This partnership allowed us to correlate the dose of betaine to its specific therapeutic actions and thereby establish a treatment protocol that we published together in 2007.

Weeks after starting betaine, Mark took his first steps and awoke to light and sound. Other patients also made quick and decisive progress, but we learned a poignant lesson about the arrow of biological time. Mark and other children who started betaine later in life were left with permanent disabilities traced to stagnant brain growth during infancy. The dense matrix of neural connections that form within this narrow window becomes an enduring substrate for our mental life. Once that window closes, the damage is done. Mark's case brought the tragedy of an entire community into sharp relief. During the three decades after Mudd's

IN BRIEF

The Clinic for Special Children in Strasburg, Pa., in collaboration with the Amish and Mennonite families it serves, has closed the gap between growing scientific knowledge of human genetics and its translation into effective medical care.

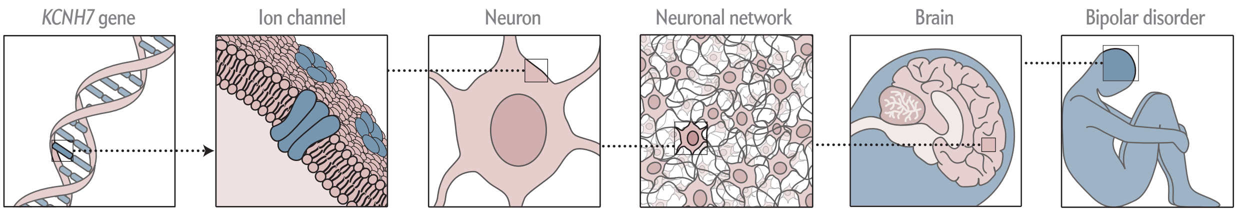
Genetic information—gathered with high-tech, low-cost approaches—enables the nonprofit clinic to efficiently diagnose and treat dozens of potentially crippling or fatal genetic conditions.

The clinic's practice is a model for improving medical care in underserved communities throughout the world.

A recent study spearheaded by the clinic links a gene mutation to bipolar disorder and shows how research in isolated communities might enrich understanding and treatment of common human afflictions.

How Genetic Mutations Lead to Disease

Gene mutations can disrupt biology at multiple levels (molecules, cells, tissues and organs) to cause disease. Certain mutations are particularly prevalent in Amish and Mennonite populations. For each patient the clinic sees, it applies advanced technologies to identify the individual's genetic variants, understand their causal links to disease, and devise ways to alleviate or prevent the mutations' harmful effects. In related work, the clinic and its collaborators recently identified a gene mutation linked to bipolar disorder among the Amish, and they are now constructing a picture of how it might impair emotional regulation (*below*). This knowledge could lead to a deeper understanding of bipolar disorder in the general population and to new strategies for prevention and treatment.



Gene
A gene consists of a sequence of DNA "letters" that spell out the amino acids needed to make a protein. Proteins are the main workhorses of cells. A mutation in a gene can alter the functioning of the encoded protein. The bipolar study pinpointed a mutation in a gene called *KCNH7.*

Protein
To function properly, proteins must have the right structure, location and abundance in each cell. *KCNH7* encodes a protein that spans the cell membrane, forming a channel that regulates the flow of potassium ions. The mutant is altered at just a single amino acid, but this subtle change affects potassium movement across the membrane.

Cell
All cells contain the same genes, but many genes are expressed (that is, give rise to proteins) only in select cell types. The ion channel encoded by *KCNH7* is used by neurons throughout the brain. Potassium currents critically shape each neuron's electrical behavior, and the mutant alters the cells' firing patterns.

Tissue
Tissues can contain a mixture of cell types. Brain tissue, for instance, includes neurons and supporting cells called glia. The mutant *KCNH7* gene would be expected to disrupt the operation, not only of individual nerve cells, but of whole neuronal circuits, such as those regulating emotions and behavior.

Organ
Nerve cells throughout the brain make the ion channel encoded by the *KCNH7* gene, but the channel is most abundant in brain regions underlying emotions and cognition. Consistent with that finding, mutation of the gene has been tied to mania observed in laboratory animals.

Behavior
Bipolar disorder is marked by a spectrum of behaviors that can include depression, mania and psychosis. New insight into how the *KCNH7* mutation affects each level of biology—from misspelled protein to perturbed brain function—could lead to fresh ideas for interrupting the chain of events underlying the disorder.

publication about MTHFR deficiency, children like Mark lived and died in obscurity, shrouded in confusion and sorrow.

While working out the details of therapy, we developed a test to screen young couples for the genetic defect and were alarmed to find that 30 percent of healthy Amish from the Kinsingers' settlement carried one mutant copy of MTHFR. From this figure, we could infer that one in 50 of their babies would be born with the disease. In 2003, recognizing the critical role of preemptive therapy, we reached out to biochemist Edwin Naylor at his pioneering newborn screening lab in Pittsburgh. Together we were able to develop and implement a method for detecting the MTHFR mutation from the dried filter-paper blood spots collected on every newborn as part of mandatory state screening for various hereditary disorders.

Remarkably, the first child diagnosed by this novel filter-paper method was Mark's sister Ruth, born September 2003, just 10 months after the Kinsingers first brought Mark to our clinic. Ruth started betaine therapy during her second week of life and has flourished during 12 years of follow-up. Today she is an accomplished student, affectionate daughter and formidable stickball player.

In 2009 Mudd and his wife had the opportunity to meet the Kinsingers at a Clinic for Special Children 20th anniversary celebration. As the Mudds spoke with Ruth's parents, Ruth quietly climbed into Mudd's lap. He told me later that it was the finest moment of his scientific career.

Mudd died in January 2014 at age 86. Several weeks later his widow received a handmade card that read: "Dear Mrs. Mudd, Greetings of love are being sent your way. How are you today? I'm fine. It is a foggy morning, and looks as if it would be sunny. I am looking forward to going barefoot. Love, Ruth."

GRASSROOTS GENOMIC MEDICINE

THE UNUSUALLY HIGH INCIDENCE of MTHFR deficiency and other genetic disorders among the Plain people is rooted in their unique social and cultural history. Small bands of Anabaptists who survived the trans-Atlantic migration composed a meager gene pool. Like all of us, these individuals unknowingly harbored damaging sequence variants (more commonly called mutations) in their genetic code. In isolated populations, such gene variants can propagate silently through carriers over generations, randomly drifting up or down in prevalence, until a child inherits two copies of the damaging genetic change from parents who share a common ancestry. This recessive pattern of inheritance is an important mechanism of genetic disease in isolated communities across the world. Among modern Anabaptists, the ancestral constellation of gene variants causes much individual and communal suffering, a problem compounded by limited science

Illustration by Amanda Montañez


MENNONITE BOY on the left has maple syrup urine disease [*see box on opposite page*] and lives 23 miles from the clinic. The boy on the right has glutaric aciduria type 1. His family relocated so that he could be cared for at the clinic.

education and poor access to the U.S. health care system.

In the early 1960s the late Victor McKusick, a pioneer of modern medical genetics, first recognized the potential for studying hereditary disease patterns among the Amish and launched a comprehensive field study to this end. Though wary of technology's power to undermine social relationships, Plain people opened their homes to McKusick and his collaborators in the hope that future generations might benefit. This work culminated in the 1978 publication of *Medical Genetic Studies of the Amish,* which catalogued 18 previously recognized and 16 newly diagnosed genetic disorders among the Amish of North America. These early research efforts established many key principles about human genetic disorders but did little to help the population under study. Many Amish grew weary of doctors who were interested in investigating their patterns of disease but unable or unwilling to care for them.

A decade later a young physician by the name of D. Holmes Morton would take a different approach. In 1988, while Morton was a fellow in biochemical genetics at Children's Hospital of Philadelphia, a colleague asked him to analyze a urine sample from a six-year-old Amish boy named Danny (his real name) who had suffered an abrupt and unexplained regression of motor skills at 14 months of age. Local doctors called it cerebral palsy, but Morton, using a technique called gas chromatography/mass spectrometry, detected a substance called 3-hydroxyglutaric acid in the boy's urine. This distinctive chemical footprint implicated a rare genetic disorder called glutaric aciduria type 1 (GA1)—not cerebral palsy—as the cause of Danny's brain injury.

Morton visited Danny at his home in Lancaster County, where he learned of the many families who communicated in letters about their children with so-called Amish cerebral palsy. In 1991 he and his colleagues published a report of 10 definite cases of GA1 among the Amish, doubling the number of published cases worldwide. He listened to harrowing stories from parents who had fallen into a kind of learned helplessness; generation after generation, they watched their children struck down by a mysterious brain disease only then to be vexed by a medical system too remote, too fragmented and too expensive to help them. This wheel of anguish convinced Holmes and his wife, Caroline, of the need for a local clinic—a medical home—where uninsured Plain families could bring their special children for affordable and compassionate care.

Thus began a health care experiment fundamentally different from the profit-driven U.S. health system: a grassroots collaboration between the Mortons and a handful of committed parents who knew firsthand the pains inflicted by genetic disease. An Amish farmer who had two grandchildren with GA1 offered two and a half acres of his field to site the clinic. Other Plain community members provided timber and labor to raise its mortise-and-tenon frame. From then until now, the Plain communities have continued to support the project as a valuable investment in their children. Nearly 75 percent of the current annual operating budget of $2.6 million comes from charitable sources, including more than $850,000 raised by Plain people at benefit auctions that offer quilts, furniture, plants, ponies, barbecued chicken, handmade pretzels, whoopie pies, and more. This support limits out-of-pocket clinical and lab fees to between $50 and $150 per visit, 70 to 90 percent below the cost of comparable services at academic health centers.

The Mortons recognized from the outset that the most effective approach for treating GA1 and other disorders was to start with healthy newborns, detect genetic risks before disease onset and provide informed, local services across the arc of youth. Yet preemptive strategies are easier to conceptualize than to implement. And the details matter: an accurate genetic diagnosis is meaningless if it comes too late, and a clever molecular therapy is useless if it costs too much. The clinic is a place where science is harnessed to practical ends, empowering communities to better care for their own while shielded from medical bankruptcy.

Our ground floor is equipped with an array of advanced gene-sequencing tools. The on-site lab team, led by Puffenberg-

The Economics of Prevention

The Clinic for Special Children's progress in managing a disorder called maple syrup urine disease (MSUD) illustrates the practical economic benefits of integrating biochemical and genetic science with the everyday practice of medicine. MSUD is rare worldwide but common among Mennonite settlements of Pennsylvania, where it affects about one in 380 newborns. It is a dangerous disorder; before the clinic opened its doors in 1989, 39 percent of MSUD victims died during childhood, and most survivors were left with severe mental and physical disabilities.

Children with MSUD lack an enzyme necessary for degrading three dietary amino acids. Consequently, certain chemicals reach concentrations that poison the brain. In excess, these chemicals spill into the urine, giving it the characteristic odor of maple syrup. Affected children appear normal at birth, but within three to five days become inconsolable and then develop forceful, involuntary muscle spasms. Left untreated, accumulating toxins cause brain swelling, coma and death.

Before the clinic's inception, health services for children who had rare and complex genetic disorders were woefully inadequate in rural communities. Those with conditions such as MSUD had medical care that was fragmented, costly and ineffective. During each medical crisis, families were forced to travel 100 miles or more to reach the nearest academic medical center, where they remained for weeks and paid cash rates of $50,000 to $100,000 for emergency services. This reactionary cycle encumbered the Mennonite people with medical debt but did not alleviate the burden of disease.

Since 1989 our clinic has managed 80 Mennonite MSUD patients from the time they were newborns. Half were diagnosed on-site between 12 and 24 hours of life and transitioned safely at home. The remainder were diagnosed by mandatory state newborn screening and discharged safely to home after an average five-day hospital stay. Over 25 years we have made incremental improvements in the monitoring and treatment of MSUD that include inexpensive filter paper–based chemical testing from home, sophisticated intravenous nutritional mixtures used to reduce toxin levels, and new dietary formulas designed to optimize the chemical environment of the brain. These innovations have decreased hospitalizations from 7.0 to 0.1 days per patient per year. A 98 percent decrease in hospital costs applied to all the MSUD patients under our care saves the community at least $4.8 million annually—nearly twice the clinic's operating budget.

Advanced technologies have the reputation of being prohibitively expensive, but the cost depends in large part on how they are deployed. Investing resources in preemptive diagnosis and disease prevention can be instrumental in reducing unnecessary and wasteful medical spending. *—K.A.S.*

er, has worked closely with clinic physicians to discover between five and 15 population-specific damaging gene variants each year since 1998. Focused molecular strategies allow the team to accurately diagnose most genetic disorders within fewer than 24 hours for a cost of $50. Precise genetic knowledge allows us to look into the future, understand when and how disease is likely to unfold, and take actions to keep children safe.

In the instance of GA1, Morton worked closely with Naylor to implement elective statewide newborn screening in 1994. A few years later Stephen I. Goodman of the University of Colorado School of Medicine deciphered the specific genetic change underlying "Amish" GA1, which enabled Puffenberger to perform rapid, inexpensive molecular testing. By identifying affected children before disease onset and intensifying their medical care, we were able to reduce the risk of disability from 94 to 36 percent, but we still agonized each time an affected infant succumbed to brain injury.

Then, in 2006, I collaborated with Richard Finkel, a founder of the nutrition-supplement company Applied Nutrition, to design what we call a "medical formula"—a prescription diet—for infants and children with GA1. We knew that the mutation responsible for GA1 caused glutaric acid and other toxins—produced from the amino acid lysine—to accumulate in the brain and that the presence of a different amino acid, arginine, could limit lysine's entry into the brain. By judiciously manipulating the relative dietary proportions of these two amino acids (with the help of computer modeling), we thought we could reduce cerebral lysine uptake and thereby limit neurotoxin production by the brain.

I tested the new approach on 12 affected infants in a clinical trial conducted between 2006 and 2011. Treated infants had half the toxin excretion, a third of the hospitalizations and complete protection from brain injury. We published our findings in 2011 and to date have treated a total of 25 consecutive newborns with the customized medical formula. The results have been durable; the brain injury rate remains less than 5 percent, and nearly all children born today with GA1 grow up healthy. For many other genetic disorders we treat, similar stepwise innovations in diagnosis and treatment have enabled us to reduce rates of disability, hospitalization and death by between 50 and 95 percent—a powerful testament to the idea that science guided by conscience can do much to prevent human misery.

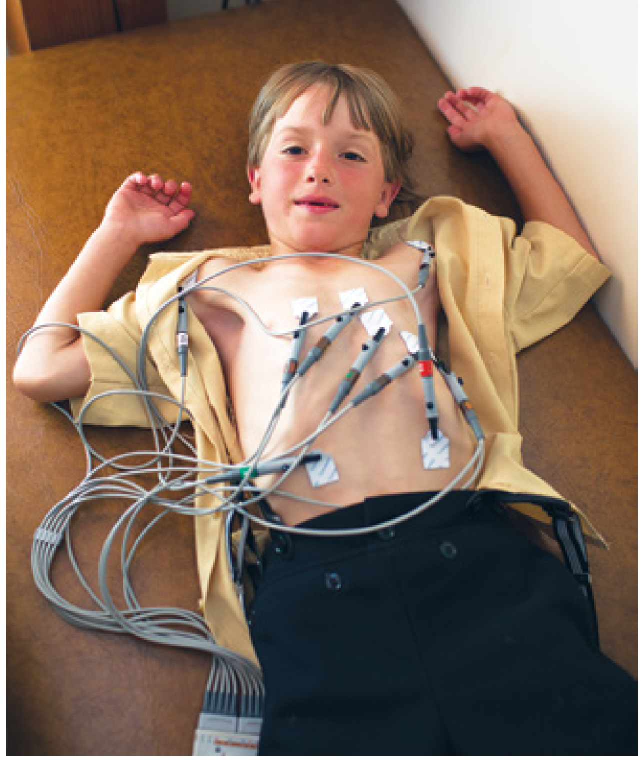
MANY POPULATIONS, ONE BIOLOGY

THE STUDY OF RARE GENETIC DISORDERS has a special role to play in the growth of biological science. Only by carefully observing the medical consequences of a gene mutation can we fully appreciate how the normal gene contributes to human biology. William Harvey foresaw this in 1657, when he suggested that investigation of rare disorders is the best way to reveal nature's "secret mysteries" and thereby advance mainstream medical practice. Three and a half centuries later we understand Harvey's axiom in modern terms. By attending closely to the dynamic interplay between a rare gene variant and mental health, we recently gained key insight into one of the most common human afflictions.

It was a crisp autumn morning when I first met Katie, a woman of about 40 who had agreed to participate in our research study of bipolar disorder among the Pennsylvania Amish. She preferred we meet in the barn where her husband, David, repaired small engines. Machine parts were strewn about carelessly in a manner unexpected for an Amish shop. Most days David did the work of two—Katie's bipolar disease had dominated their shared life for more than a decade, and David often struggled in isolation to raise their five children.

Bipolar disorder first exacted its toll on Katie after the birth

CHILDREN treated at the clinic have many serious health issues, such as heart arrhythmias (*top panels*), brain malformations (*bottom left*), and hereditary attention deficit disorder (*all three, bottom right*).



of her second child. She began to speak fast, sometimes very fast, and often followed random trains of thought into obliquity. At intervals she stayed up nights on end, cleaning and recleaning the house. “These floors are filthy. Filthy. Filthy.” During the dark periods that followed, Katie lay in bed ruminating, hopeless and racked with guilt. Familiar voices—her husband, children, and parents—incessantly whispered to her from behind: “You’re worthless.” But her biggest concern, conveyed repeatedly when we first met, was a mass that filled her abdomen and tormented her relentlessly, a chronic perceptual hallucination that she called her “miserableness.”

Mental disorders—including bipolar disorder—are common worldwide, affecting 12 to 47 percent of different populations. In the U.S., psychiatric disease accounts for 40 percent of medical disability among young adults, and suicides outnumber homicides two to one. Isolated groups such as the Amish provide distinct advantages for investigating the heritability of psychiatric illness and other common medical conditions. One such effort, the Amish Study of Major Affective Disorders, began in 1976 and tracks several large, multigeneration Amish pedigrees with a high prevalence of bipolar disorder. Over three decades the cohort swelled to include more than 400 subjects and remains one of the most intensively studied in the history of medical genetics.

On October 31, 2011, Puffenberger and I attended a Family Meeting hosted by Alan Shuldiner and the University of Maryland’s Amish Research Clinic. Leading psychiatric investigators addressed a gathering of Plain people concerned about mental illness within their families and communities. As the meeting drew to a close, researchers summarized 35 years of Amish bipolar research with a dispiriting message: “There is not a lot new to tell you.” On the way to the parking lot, I was stopped by three Amish sisters whose family had participated in familial bipolar research for more than two decades. Nine of 11 siblings from their generation had spent much of adult life debilitated

SCIENTIFIC AMERICAN ONLINE Read more about the clinic’s work at ScientificAmerican.com/dec2015/clinic

by mania or depression. They wondered if our clinic, which had a reputation for taking on intractable problems, might help them better understand if "some gene was involved."

The timing was right. We had recently begun collaborating with the Broad Institute in Cambridge, Mass., to explore the utility of whole exome sequencing for investigating rare genetic disorders in children. The exome consists of all coding letters, or nucleotides, that are "read" to construct the body's 19,000 proteins.

Although the exome represents only about 1 percent of the human genome, it contains the vast majority of genetic changes that can cause disease, and whole exome sequencing is at present the most efficient and lowest-cost method for disease-gene discovery.

Although our clinic has historically focused on pediatric health, psychiatric disorders pervade every aspect of family and community life, and our collaborators in Cambridge allowed us to reserve seven exome samples for Amish adults with bipolar disorder. Remarkably, all seven people shared an exceedingly rare variation in a gene that encodes the KCNH7 protein. This single-letter substitution, called a missense change, alters the structure of KCNH7 at an amino acid conserved across the evolution of many different animal species; changes in such conserved regions often critically alter the way a protein functions.

Over the next two years, Sander Markx and Michael First of Columbia University's department of psychiatry helped us expand the study to more individuals and implement a method to rigorously categorize their symptoms. Ultimately we were privileged to collaborate with investigators at Weill Cornell Medical College, the University of Pennsylvania, Franklin & Marshall College and the McKusick-Nathans Institute of Genetic Medicine. This team approach also allowed us to track the movement of KCNH7 protein in cells, demonstrate how its mutant form alters electrical firing in neurons and establish a statistical foundation for our discovery. For the first time, we identified a specific genetic change that signals a strong predisposition to bipolar disease among the Amish. We published our findings in 2014; they now allow investigators worldwide to explore the connection between KCNH7 and mental illness in other populations.

KCNH7 is especially abundant in brain regions that affect mood and cognition, where it forms channels that mediate potassium movement across cell membranes. These ephemeral waves of ions, moving in and out of membranes too thin to see, are directly linked to what we think and feel. Our everyday experience belies this fact; it is difficult to imagine electrochemical signals at the root of violence, addiction, psychosis and suicide. But our research suggests that a subtle change in the threshold and timing of ion currents can cast a person into repeated cycles of madness and despair.

To realize at the genetic level that the mind is embodied in this way allows us to understand mental suffering in concrete terms. Discovery of the KCNH7 variant is important because it provides a foothold for rational discussions among scientists and patients and helps to strip away the layers of guilt and shame that surround mental illness. In the near term, knowledge that connects genetic variation to bipolar disease can lead to more timely and effective medical care for people such as Katie. On a longer time scale, it might be possible to design drugs that modulate the KCNH7 ion channel—a form of precision medicine that could open up a whole new class of therapeutics for the treatment of bipolar disorder in all populations.

TIME AND OPPORTUNITY

THE STUDY OF BIPOLAR GENETICS in the Amish is a parable about the future of medicine—about how genetic information might be used to predict *your* future. At the clinic, we now have a simple and inexpensive blood test that can be collected from umbilical cord blood at birth to inform us about a child's risk for bipolar disorder 30 years hence. Because adult-onset psychiatric disorders are often preceded by erratic thought and behavior in youth, early detection of a genetic risk factor could enable more timely and effective mental health care across a lifetime. But should we begin screening Amish newborns for the damaging KCNH7 variant?

Such questions are accruing quickly and pertain to all of us. Peer into your exome, and you will find between 20,000 and 40,000 deviations from the so-called normal human sequence of nucleotide letters. Twenty percent of the variants in your DNA code have the potential to alter protein function, and about 1,000 are exceedingly rare, possibly even unique to you. How many of these changes can predict your future? And if so, what can or should be done about it? The answer depends, in part, on what knowledge we deem actionable for any particular person at a specific time. That is perhaps one key to our clinic's success: cumulative population knowledge—painstakingly acquired over the past 25 years—works like a Rosetta Stone. It allows us to decipher the meaning of genomic data within a specific social context and thereby tailor medical care to the individual: the right treatment for the right person at the right time.

In all populations, this kind of deep knowledge about gene action will allow scientists to visualize cellular machinery in exquisite detail and understand how the various molecular parts interact in health and disease. But it is people—not their component parts—who suffer. Clinicians and molecular biologists who work side by side at an appropriate scale, one patient at a time, can weave genomics into the physician's craft, yielding strategies that are preemptive rather than reactive.

Pediatric practice is a good place to put this idea to the test. At our clinic, knowledge and treatment grow in lockstep as we explore the complex interactions between gene variation and environment that play out over the formative stage of life. Caring for children challenges us to leverage the predictive power of genetic knowledge, focusing on outcomes that matter most. One child at a time, we continue to close the gap between genomic research and the day-to-day practice of medicine, which at our clinic is a practical endeavor, driven by what this child needs, right now. SA

MORE TO EXPLORE

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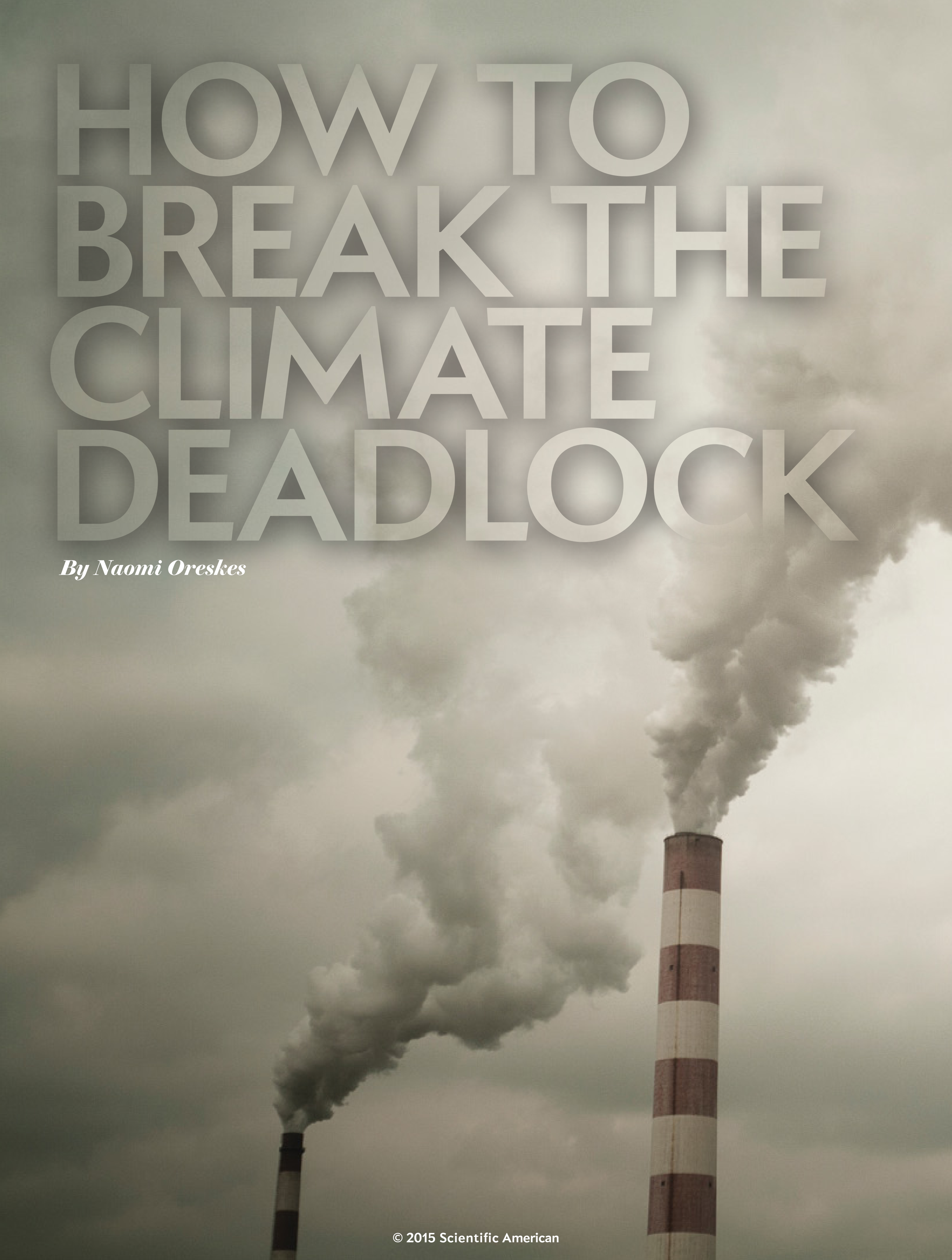
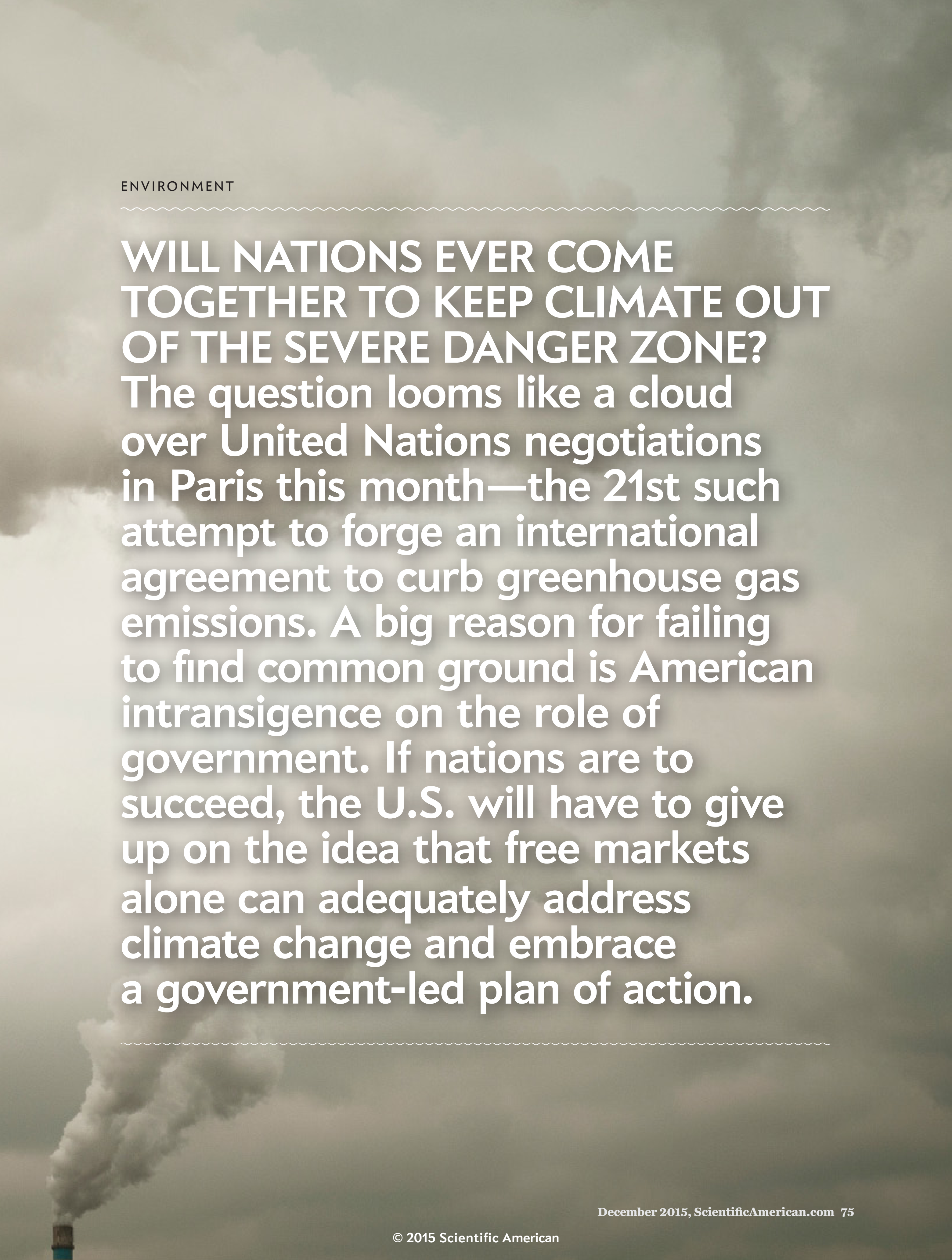
HOW TO BREAK THE CLIMATE DEADLOCK

By Naomi Oreskes





ENVIRONMENT

WILL NATIONS EVER COME TOGETHER TO KEEP CLIMATE OUT OF THE SEVERE DANGER ZONE?

The question looms like a cloud over United Nations negotiations in Paris this month—the 21st such attempt to forge an international agreement to curb greenhouse gas emissions. A big reason for failing to find common ground is American intransigence on the role of government. If nations are to succeed, the U.S. will have to give up on the idea that free markets alone can adequately address climate change and embrace a government-led plan of action.

A U.N. TREATY IS EFFECTIVE only if signatory nations are prepared to follow suit with firm domestic policies, but American politicians have resisted action, afraid of paying a political price. The rejection of climate action is largely based on suspicion of big government, and an international treaty is government at its biggest. Yet making a substantial impact on something so fundamental as the sources of energy that drive our civilization is going to require billions (if not trillions) of dollars of investments and incentives that span diverse industries—the kinds of actions that the private sector has historically not made. If nations are ever going to put the brakes on climate change, the U.S. will have to overcome its aversion to government playing a major role.

Naomi Oreskes is a professor of the history of science and an affiliated professor of Earth and planetary sciences at Harvard University. She is co-author, with Erik M. Conway, of *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco to Global Warming*. She also wrote the introduction to the Melville House Press 2015 edition of the papal *Encyclical on Climate Change and Inequality*.

UNREASONABLE RELIANCE ON FREE MARKETS

IT HAS LONG BEEN a maxim in American life that the government that governs best governs least. It was expressed in the weakness of the original Articles of Confederation, in the structure of the U.S. Constitution (designed to prevent the concentration of power) and at various times throughout U.S. history. In the 20th century it was an important element in reactions against federal labor standards, rural electrification and, especially, the New Deal, the spectacular government intervention that followed the equally spectacular market failure of the Great Depression. The deal empowered the federal government with substantive oversight of business, industry, and financial and labor markets. But the opponents of the New Deal never denied the fact of the Depression.

Opponents of an international treaty on climate change have allowed their hostility to government not only to lead them to deny the facts of climate change but also to spill over into conspiratorial thinking. In a 1992 speech Dixy Lee Ray, a former governor of Washington State and a former head of the U.S. Atomic Energy Commission, insisted that the agenda of the United Nations Framework Convention on Climate Change was to "bring about … world government with central planning by the United Nations." The flame she lit has burned brightly ever since. In his 2012 book Senator James Inhofe of Oklahoma accused climate scientists of being part of a liberal conspiracy to dismantle global capitalism and compared the Environmental Protection Agency to the Gestapo.

Inhofe's views may be extreme, but they reflect a greater conservative mind-set. In our 2010 book, *Merchants of Doubt,* Erik M. Conway and I show how conservative and libertarian think tanks have questioned the scientific evidence of climate change under the rubric of defending freedom, which they equate with laissez-faire capitalism: low rates of taxation, minimal regulation of business, and little or no government intervention in the marketplace. Social scientists have also shown a strong correlation between "free market ideology" and the beliefs that global climate change is not occurring, is not human-caused or will have positive effects—all positions that contradict the findings of the global scientific community.

The main claim of politicians, lobbyists and CEOs who lead the charge to minimize the government's role in addressing climate change is that the world should rely on the marketplace to fix the problem. Greenhouse gas emissions are part of the world's economy, so if they are a problem, markets will respond, for instance, by offering technologies to prevent climate change or allow us to adapt to it.

In truth, however, energy markets do not account for the "external," or social, costs of using fossil fuels. These are not reflected in

IN BRIEF

American rejection of climate action is based on suspicion of big government, often expressed as a threat to freedom.

Free markets will not solve climate change by themselves; they have failed to account for the damage done by carbon emissions to people and the environment.

A carbon tax, or emissions-trading system, could slow climate change, but government is needed to create those systems.

History shows that government is also needed to create and fund major technological innovations of the scale required to solve climate change. For that to happen, Americans will have to stop demonizing government.

PRECEDING PAGES: GETTY IMAGES

the price we pay at the pump, the wellhead or the electricity meter. For example, pollution from coal causes disease, damages buildings and contributes to climate change. When we buy electricity generated from coal, we pay for the electricity, but we do not pay for these other real, measurable costs.

In a properly functioning market, people pay the true cost of the goods and services they use. If I dump my garbage in your backyard, you are right to insist that I pay for that privilege, assuming you are willing to let me do it at all. And if you do not insist, you can be pretty sure that I will keep on dumping my garbage there. In our markets today, people are dumping carbon dioxide into the atmosphere without paying for that privilege. This is a market failure. To correct that failure, carbon emissions must have an associated cost that reflects the toll they take on people and the environment. A price on carbon would encourage individuals, innovators and investors to seek alternatives, such as solar and wind power, that do not cause carbon pollution. When Hoesung Lee became the new head of the Intergovernmental Panel on Climate Change in October, he named carbon pricing as the world's top climate change priority.

Several countries and regions have implemented carbon prices. In British Columbia, a carbon tax has helped cut fuel consumption and carbon emissions without harming economic growth. To prevent taxes from rising overall, the government also lowered personal and corporate income taxes; the province now has the lowest personal income tax rate and one of the lowest corporate tax rates in Canada.

Another way to remedy the market failure of pollution is to create a trading system where people can buy the right to pollute—a right that they can use, save or sell. A company that can reduce its emissions more than the law requires can sell any unused credits, whereas a company that cannot meet the standards can buy credits until it figures out how to solve its pollution problem.

The idea of being able to buy the right to pollute offends many people, but properly implemented, emissions trading can work. In 1990 Congress passed, by a wide margin, a set of amendments to the Clean Air Act that implemented trading in sulfur dioxide emissions to reduce acid rain. The program was highly successful: over the ensuing decade emissions were cut by more than 50 percent. In 1993 California followed this example and implemented the Regional Clean Air Incentives Market to reduce air pollution in southern California. The air in Los Angeles is far cleaner today than it was 30 years ago, but hardly anyone knows that this was achieved to a substantial degree through emissions trading. China has been experimenting with regional emissions trading for several years and has announced that it will soon make the system national.

Whether one supports emissions trading or a carbon tax, the essential idea is to harness the power of market forces. Many business leaders prefer emissions trading over taxation because once the system is in place, it enables a good deal of freedom and flexibility. But the key phrase here is "once in place." An emissions-trading system, or a tax, has to be created, and that does not happen by the "invisible hand" of the marketplace. It happens through government action. Which brings us back to the role of government and the aim of the U.N. Conference of the Parties talks, known as COP21.

We are dumping carbon into the atmosphere without paying for that privilege. This is a market failure. A price on carbon emissions that reflects the toll they take would correct that failure.

TECHNOLOGIES WAIT FOR SCALE

SOME PEOPLE ARGUE that, despite the political failures of the past 20 COPs, the world must keep working to implement a market mechanism. There is no doubt that this is necessary.

But even if Americans could agree to and implement one, it might not be sufficient. Although a price on carbon emissions will encourage consumers to seek better alternatives, those alternatives are not quite ready for prime time.

To create the backbone of a new energy system, we need large-scale renewable power, coupled with dramatic increases in energy efficiency, demand management and storage. Solar and wind power work, but they are not at the scale needed to replace enough fossil-fuel power plants to stop the ongoing rise in atmospheric CO_2 levels. After half a century of work, nuclear power remains costly and controversial. And carbon capture and storage—which collects emissions and puts them underground—is not working.

A price on carbon will push demand in the right direction, but it needs to be reinforced by the pull of public investment in innovation. The most likely way we will get the innovation we need, at the scale we need, in the time frame we need, and at a retail price that people can afford, is if the public sector plays a leading role.

It is possible that the market will bring us a technological breakthrough on climate change. But history suggests that this would be a long shot—even with a hefty price on carbon—because not one of the major technological developments of the 20th century was produced by the private sector working alone. Entrepreneurs such as Thomas Edison and George Westinghouse developed electricity, but it took the federal government to build the delivery systems that brought it to the lion's share of Americans. The same is true of telephone service. The federal government, starting with President Dwight Eisenhower, was needed to build an interstate highway system. Nuclear power was not a response to market demand: the U.S. government wanted to prove that the destructive power unleashed at Hiroshima and Nagasaki could have a constructive use. Senator Al Gore may not have invented the Internet, but the U.S. military did, as a technology under the Defense Advanced Research Projects Agency.

Gore did, however, help draft and pass the legislation that released the Internet as a civilian technology that the private sector could commercialize and sell to millions of customers. The federal government developed digital computers, satellite communications, weather forecasting and the global positioning systems that tell mobile phones where we are. These transformative technologies were all created as public-private partnerships, more often than not with the government as lead partner. And they all took sustained effort over decades, the kind of effort for which the private sector has little stomach. A government pull is needed to develop climate solutions that, like the Internet, can be further advanced and marketed by the private sector. ARPA-E (Energy), an agency modeled after DARPA, is funding research in these areas, but its budget is peanuts. Its 2016 fiscal year request is $325 million. For comparison: in 2015 the world will spend $5.3 *trillion* in fossil fuel subsidies, according to the International Monetary Fund.

Carbon capture and storage requires special attention. The emissions-reduction goals being promised by many countries for COP21 assume that these nations will be capturing carbon and storing it in the ground. The dirty secret is that a proved system does not exist, not to mention a cost-effective one.

Technology exists to capture carbon dioxide (or any fluid) and pump it into geologic reservoirs: the oil industry already pumps CO_2 underground to help push oil out. But using CO_2 to flush a reservoir is very different than securely locking away that carbon for centuries or millennia. If carbon capture could be made feasible and economic, even at a moderate scale, it could greatly enhance emissions reductions. So we should invest in research—in geology, geophysics, hydrology and engineering—a domain in which our federal government has a long and strong track record. Many other countries have substantial expertise in these disciplines as well.

> *Appropriate forms of government authority are essential to the guarantee of liberty. As disruptive climate change unfolds, they will also be essential to the guarantee of life and the pursuit of happiness.*

RECLAIMING THE COMMON GOOD

A HEFTY PRICE on carbon, coupled with major investment in technology, can definitely limit climate change. But both steps require government action. That suggests one other necessary step: we need to stop demonizing government and recognize its crucial role in doing the most important thing that markets do not do, which is

SCIENTIFIC AMERICAN ONLINE For insights into how to make a carbon tax work, go to ScientificAmerican.com/dec2015/oreskes

prioritizing and sustaining the common good.

For the past 30 years the ideology of the unfettered marketplace has so dominated our discourse that most of us can scarcely imagine an alternative way of organizing our affairs. Individuals who try are dismissed as unrealistic, romantic, polemical or (in America) communists. When environmentalist and writer Bill McKibben suggested that a zero-growth economy could provide good lives for people while greatly reducing demand for the earth's dwindling resources, he was mocked. When Pope Francis released his encyclical on climate change and inequality, in which he urged the world to take on the interdependent challenges of caring for the planet and caring for the poor, one prominent public intellectual all but accused him of being a socialist. Another suggested he was "out of touch."

The pope is very much in touch with one essential fact: markets are effective in distributing goods and services efficiently to those who have the money to pay for them, but the needs of the poor go largely unaddressed, and the external costs remain almost entirely unpaid. Our dominant discourse insists that we can solve these problems by continuing the policies and practices that created them. The pope also noted that blind faith in the marketplace leads people to believe that they are free "as long as they have the supposed freedom to consume." So if the government acts to restrict the marketplace, it is (allegedly) restricting our freedom. But as philosopher Isaiah Berlin noted many years ago, freedom for wolves can lead to the death of lambs, and surely the right to exist is more fundamental than the right to consume.

To build a better world, we first have to seek it. This requires a different vision, one that embraces priorities other than profit and places care—for creation and for one another—at its center. We have to accept the reality that markets are not motivated by the priority of care.

RETHINKING THE MAGIC OF THE MARKETPLACE

ECONOMIST NICHOLAS STERN and others have made the same point in more prosaic language. Investment in scientific research, public education and infrastructure is a common good, but our commitments to those activities have been weakened in recent decades. Yet history demonstrates that markets, by themselves, do not remedy market failures. Governments do.

In the aftermath of the cold war, conservatives and liberals agreed that market-based democracies had done a better job than centrally planned ones at providing goods and services, as well as protecting civil liberties and quality of life. But even Adam Smith, the champion of laissez-faire capitalism, noted that markets only function well with appropriate rules and regulations. One might have thought that the global financial crisis of 2008, the worst since the Depression, would have reminded us of the need for a reasonable set of rules. Yet decades of deregulated capitalism have led to environmental damage on a scale that threatens the very prosperity it is meant to generate.

We need a new conversation about the appropriate role of government in fostering innovation, remedying market failure and tackling inequality. We have to abandon magical thinking and quasi-religious faith in the marketplace. We must acknowledge that we need governance to foster the technologies needed to meet our energy demands without destroying the natural world.

Government is not *the* solution, but it has to be part of the solution. Although international agreements such as the one sought by COP21 are useful in encouraging national governments to do the right thing, ultimately nations act on a national level. If the 20th century is any guide, once the government lays the foundations for new technologies, the private sector will step in to do what it does best, which is not to invent them but to sell them.

Above all, we have to reject the canard that addressing climate change threatens our liberty. Timothy Snyder—a foremost expert on the history of European fascism—reminds us that "a common American error is to believe that freedom is the absence of state authority." History shows that although state authority can be abused, its absence does not lead to liberty. On the contrary, its absence opens the door to tyranny and tragedy. Appropriate forms of authority are essential to the guarantee of liberty. As disruptive climate change unfolds, they will also be essential to the guarantee of life and the pursuit of happiness. SA

MORE TO EXPLORE

Deep Economy: The Wealth of Communities and the Durable Future. Bill McKibben. Times Books, 2007.

The Bridge at the Edge of the World: Capitalism, the Environment, and Crossing from Crisis to Sustainability. James Gustave Speth. Yale University Press, 2008.

Encyclical on Climate Change and Inequality: On Care for Our Common Home. Pope Francis. Introduction by Naomi Oreskes. Melville House, 2015.

Why Are We Waiting?: The Logic, Urgency, and Promise of Tackling Climate Change. Nicholas Stern. MIT Press, 2015.

FROM OUR ARCHIVES

Making Carbon Markets Work. David G. Victor and Danny Cullenward; December 2007.

scientificamerican.com/magazine/sa

RECOMMENDED

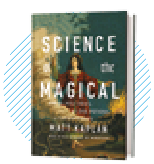
By Clara Moskowitz

MORE TO EXPLORE
FOR MORE BOOK RECOMMENDATIONS, VISIT **SCIENTIFICAMERICAN.COM/DEC2015/RECOMMENDED**

Extreme Earth
by Michael Martin. Abrams, 2015 ($85)

Landscapes of undulating sand dunes and barren ice fields, and the diverse and hardy people who populate such harsh environments, fill this large-format book. Photographer Martin traveled to some of Earth's most unforgiving terrains, making more than 40 trips between 2009 and 2015. He portrays here the vast beauty of four climate zones: the Arctic, the Antarctic, and the deserts of the Northern Hemisphere and the Southern Hemisphere. "I hope that this book will not only provide knowledge," Martin writes in the preface, "but also awaken an enthusiasm for and understanding of the extreme regions of Earth, many of which are still untouched and thus all the more necessary to preserve."

Science of the Magical: From the Holy Grail to Love Potions to Superpowers
by Matt Kaplan. Scribner, 2015 ($26)



Science and magical thinking might seem at odds, but science journalist Kaplan demonstrates that they can inform and even influence each other. In every chapter, Kaplan examines a putative supernatural phenomenon, such as an ability to predict events or heal someone with water from a sacred spring, through a scientific lens. He pulls back the curtain on the seeming magic, drawing on his own investigations and conversations with experts to determine whether tales of the supernatural have scientific explanations and what these stories reveal about human life and thought at the time and place of their origin. Kaplan also explores ways that the occult inspires scientific research and cases where new technologies are making "magical" capabilities, such as accelerating healing and controlling the weather, into real possibilities.

—Maria Temming

Pacific: Silicon Chips and Surfboards, Coral Reefs and Atom Bombs, Brutal Dictators, Fading Empires, and the Coming Collision of the World's Superpowers
by Simon Winchester. HarperCollins, 2015 ($28.99)

The Pacific Ocean is a place of superlatives: the oldest and largest, the most seismically active and biodiverse, and the site of the world's greatest mountains and deepest trenches. Journalist Winchester plumbs the ocean's science and its influence on people throughout time, writing, for example, of how the alluring geography of many Oceania islands has spurred imperial powers to usurp land from native peoples. And he explores the damage humanity has wreaked on the Pacific, polluting it with whirlpools of trash and destroying coral reefs, among other environmental insults. Ultimately Winchester shows that the Pacific has played a central part in history and is likely, through its ecological and geopolitical importance, to be just as vital to the future.

—Sabrina Imbler

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

Consilience and Consensus

Or why climate skeptics are wrong

By Michael Shermer

At some point in the history of all scientific theories, only a minority of scientists—or even just one—supported them, before evidence accumulated to the point of general acceptance. The Copernican model, germ theory, the vaccination principle, evolutionary theory, plate tectonics and the big bang theory were all once heretical ideas that became consensus science. How did this happen?

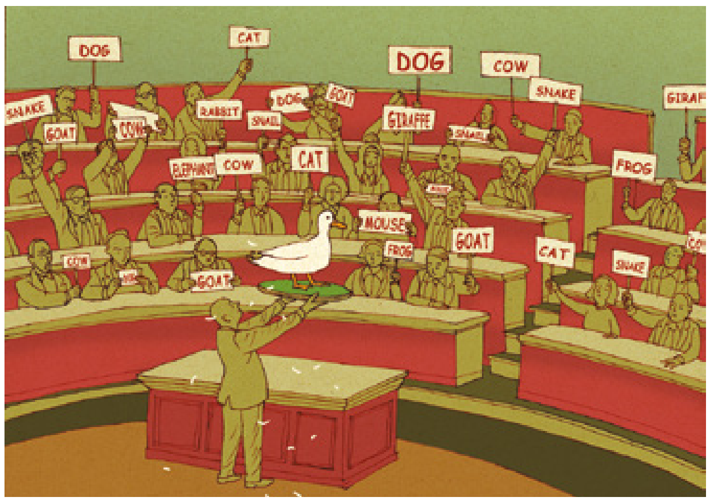
An answer may be found in what 19th-century philosopher of science William Whewell called a "consilience of inductions." For a theory to be accepted, Whewell argued, it must be based on more than one induction—or a single generalization drawn from specific facts. It must have multiple inductions that converge on one another, independently but in conjunction. "Accordingly the cases in which inductions from classes of facts altogether different have thus *jumped together,*" he wrote in his 1840 book *The Philosophy of the Inductive Sciences,* "belong only to the best established theories which the history of science contains." Call it a "convergence of evidence."

Consensus science is a phrase often heard today in conjunction with anthropogenic global warming (AGW). Is there a consensus on AGW? There is. The tens of thousands of scientists who belong to the American Association for the Advancement of Science, the American Chemical Society, the American Geophysical Union, the American Medical Association, the American Meteorological Society, the American Physical Society, the Geological Society of America, the U.S. National Academy of Sciences and, most notably, the Intergovernmental Panel on Climate Change all concur that AGW is in fact real. Why?

It is not because of the sheer number of scientists. After all, science is not conducted by poll. As Albert Einstein said in response to a 1931 book skeptical of relativity theory entitled *100 Authors against Einstein,* "Why 100? If I were wrong, one would have been enough." The answer is that there is a convergence of evidence from multiple lines of inquiry—pollen, tree rings, ice cores, corals, glacial and polar ice-cap melt, sea-level rise, ecological shifts, carbon dioxide increases, the unprecedented rate of temperature increase—that all converge to a singular conclusion. AGW doubters point to the occasional anomaly in a particular data set, as if one incongruity gainsays all the other lines of evidence. But that is not how consilience science works. For AGW skeptics to overturn the consensus, they would need to find flaws with all the lines of supportive evidence *and* show a consistent convergence of evidence toward a different theory that explains the data. (Creationists have the same problem overturning evolutionary theory.) This they have not done.

A 2013 study published in *Environmental Research Letters* by Australian researchers John Cook, Dana Nuccitelli and their colleagues examined 11,944 climate paper abstracts published from 1991 to 2011. Of those papers that stated a position on AGW, about 97 percent concluded that climate change is real and caused by humans. What about the remaining 3 percent or so of studies? What if they're right? In a 2015 paper published in *Theoretical and Applied Climatology,* Rasmus Benestad of the Norwegian Meteorological Institute, Nuccitelli and their colleagues examined the 3 percent and found "a number of methodological flaws and a pattern of common mistakes." That is, instead of the 3 percent of papers converging to a better explanation than that provided by the 97 percent, they failed to converge to anything.

"There is no cohesive, consistent alternative theory to human-caused global warming," Nuccitelli concluded in an August 25, 2015, commentary in the *Guardian*. "Some blame global warming on the sun, others on orbital cycles of other planets, others on ocean cycles, and so on. There is a 97% expert consensus on a cohesive theory that's overwhelmingly supported by the scientific evidence, but the 2–3% of papers that reject that consensus are



all over the map, even contradicting each other. The one thing they seem to have in common is methodological flaws like cherry picking, curve fitting, ignoring inconvenient data, and disregarding known physics." For example, one skeptical paper attributed climate change to lunar or solar cycles, but to make these models work for the 4,000-year period that the authors considered, they had to throw out 6,000 years' worth of earlier data.

Such practices are deceptive and fail to further climate science when exposed by skeptical scrutiny, an integral element to the scientific process. SA

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Illustration by Izhar Cohen

Steve Mirsky, who hosts the *Scientific American* podcast Science Talk, started writing the Anti Gravity column 20 years ago this month. He is taking this issue off. Here is one of our favorites—from June 2000.

Great Feets

Walking on water takes a man with mighty big shoes to fill

By Steve Mirsky

Fish gotta swim. Birds gotta fly. What doesn't gotta happen is what an Alsatian man named Rémy Bricka likes to do—walk on water. In March [2000] Bricka began what he hoped would be a walk, on buoyant ski-length footgear, across the Pacific Ocean. Because it is there, presumably.

Bricka already holds a place in the Guinness World Records by virtue of a previous tromp across the Atlantic in 1988. Normal journalistic practice would include an attempt to reach Bricka for a first-person account. That idea ground to a halt upon contemplation of the words of linguistic philosopher Ludwig Wittgenstein: "If a lion could talk, we would not understand it."

Just as the uniquely leonine experience imposes a worldview that would make meaningful communication impossible, the Bricka experience probably placed him beyond my comprehension. My father really is a carpenter who really is named Joseph, but any messiah complex I may have is too puny to help me figure out why somebody wants to walk on water. And I haven't even mentioned that Bricka takes leave from his job as a one-man band to take his walks.

Actually, lots of guys walk on water all the time. They are called hockey players. But restricting the discussion to water in the liquid phase, your average human makes a poor pond pedestrian. Bricka's passion, however, made me wonder about the creatures—none great, all small—that truly can keep their feet above water.

Such animals exploit various physical principles to stay afloat. Biologist Robert B. Suter has studied one such critter, the aptly named fishing spider. He explains that its legs produce tiny dimples on the water thanks to surface tension, the slight attraction of water molecules to one another that becomes a Brobdingnagian factor at Lilliputian scales. "What makes the dimple stay intact is surface tension, and a lot of the force that holds the spider up is surface tension," Suter says. Add the water's drag, and when the spider drives a leg against its dimple, voilà, it's walking.

Although there are characteristics of rowing involved here, and despite the fact that the dimples also act as hulls and impart an additional slight buoyancy, this process seems much like the kind of walking with which we humans are familiar. A leg pushes against a surface that pushes back. So while I hate to burst his bubble, Bricka's walks seem misclassified. He is actually a conventional sailor sailing unconventional vessels: two boats that happen to fit on his feet.

On the other hand, Bricka could become a genuine water walker through modified gear that would allow surface tension to work its magic. He needs to get edgier, the edge in question being where water, air and foot meet and where surface tension does its stuff. Calculations, for freshwater, by Mark W. Denny of Stanford University show that a 110-pound person could walk on water using footwear with a total perimeter of about 6.7 kilometers (4.2 miles). Laces surely sold separately. A bigger challenge than walking the Pacific would then be wearing both shoes at the same time.

An alternative noted by Steven Vogel of Duke University is severe weight reduction. Assuming Bricka wears about a size 9, his feet alone would support him on the water if he managed to slim down to about five grams, an accomplishment that would render the ensuing Pacific walk a mere footnote.

All this advice comes too late. Bricka's march on the sea, which he had estimated would take six months, was over almost before he could wave good-bye. On day one, a storm wrecked the catamaran he towed behind him, costing him food, supplies and bed. And so his *mare* trek came to an end. Fortunately, he escaped unscathed and continues to walk among us. Because he didn't sink. Like a bricka. SA

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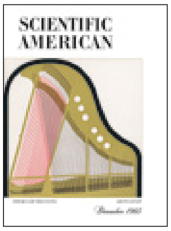
Illustration by Matt Collins

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Daniel C. Schlenoff



December 1965

The Life of the “Untouchables” of India

“Without violence or much notice from the outside world India is undergoing a profound social revolution. Religious sanctions as well as economic, social and legal ones have traditionally enforced the inferior position of the lower castes. Today the nation’s new constitution and its government are firmly committed to the overthrow of those traditions. For understandable reasons the people of India themselves have always avoided the term “untouchables.” Most people in India now call the former untouchables by the name Mahatma Gandhi gave them: Harijans, or ‘children of God.’ Under the law the Harijans are now free to adopt whatever style of life they choose; all the traditional taboos are legally abolished. The law says they may dress as they please, drink from any village well, enter any Hindu temple.”

Cigarettes and Atherosclerosis

“A direct association has been established between cigarette smoking and coronary atherosclerosis, the condition in which fatty deposits build up in the arteries of the heart and reduce their interior diameter. Earlier studies had shown that the risk of coronary disease and of death from heart attacks is higher among cigarette smokers than among nonsmokers. These studies told nothing about a smoker’s arteries, however; they could have meant merely that smoking imposes added burdens on the heart. Now researchers have reported that an advanced degree of coronary atherosclerosis is more common in cigarette smokers than in nonsmokers, and that it increases with the amount of smoking.”

December 1915

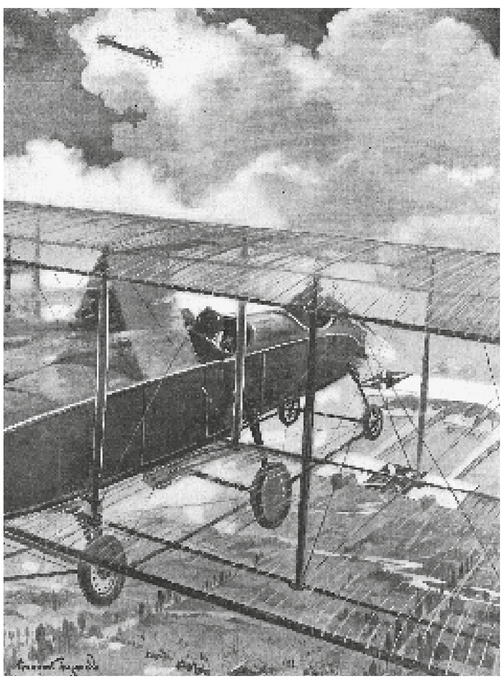
Dreams of Invisibility

“Military authorities await with great interest the development of the new French invisible aeroplane, which bids fair to revolutionize aerial warfare. The body and framework are constructed, as in ordinary machines, of aluminum braced with wire. Over the framework, instead of canvas, is stretched a transparent material which looks like a cross between mica and celluloid [*see illustration*]. It is called ‘cellon,’ and is a chemical combination of cellulose and acetic acid. Of almost the same transparency as glass, it does not crack or splinter and has the toughness and pliability of rubber.”

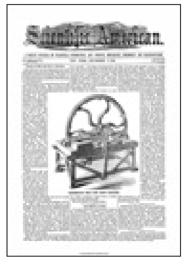
Images of advances in aviation in 1915 are at www.ScientificAmerican.com/dec2015/aviation

Radium for Crop Health

“A radium fertilizer is sold by a company recommending one pound to 50 square feet of soil. R. R. Ramsey estimates that this adds to the soil only one tenth the amount already there—an evident waste of good money. To double the amount of radium emanation available for crops, the farmer must sow seventy-five milligrams of radium to an acre at the trifling price of $7,500. It is evident that even the most modern farmer will remain satisfied with such stock of radium as is now locked up in his farm.”



TRANSPARENT AIRPLANE: In an early attempt at stealth, the material used was neither robust nor long lasting, **1915**



December 1865

Doubt on Geothermal

“At the last meeting of the Literary and Philosophical Society of Manchester, Mr. George Greaves read a paper embodying the suggestion that the ‘internal heat of the earth’ should itself be employed in place of fuel. He considers that the heat of the fiery ocean which he believes lies under our feet might supply us with all the mechanical power we want, and that one method of causing it to do this ‘might be by the direct production of steam power by bringing a supply of water from the surface in contact with sufficiently heated strata, by means of artesian borings or otherwise.’ He has yet to explain, however, how, supposing his ‘sufficiently heated strata’ to really exist, we could make ‘artesian borings’ deep enough to reach them.”

Science and Weather

“The daily record of meteorological observations telegraphed to the Imperial Observatory at Paris, and published in a lithographed sheet, continues to increase in interest and importance under the active and enlightened superintendence of M. Le Verrier, director of the observatory. The outline chart of Europe, with the curves of equal barometric pressure and direction of the wind at the different situations of the day of publication, and also a table of the estimated weather for the following day, continue to be inserted in every number.”

SCIENTIFIC AMERICAN, VOL. CXIII, NO. 25; DECEMBER 18, 1915

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FOR VIDEO ABOUT THE DUST AND FUNGI LURKING IN HOMES, GO TO SCIENTIFICAMERICAN.COM/DEC2015/GRAPHIC-SCIENCE

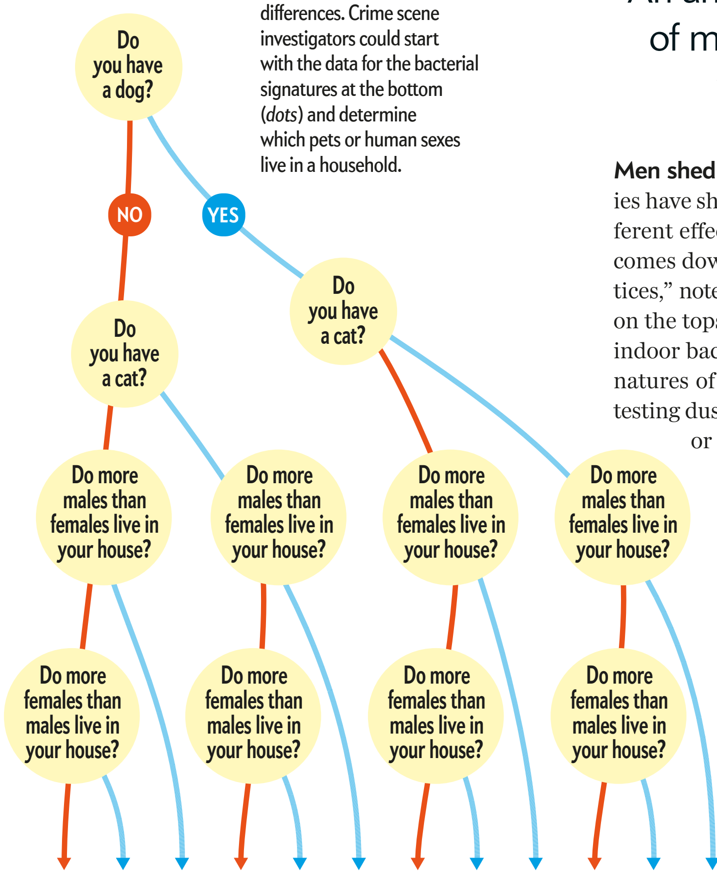
The Bacteria Game

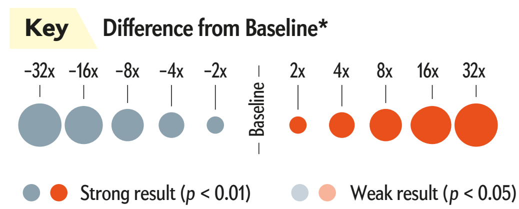
An analysis of dust reveals how the presence of men, women, dogs and cats affects the variety of bacteria in a household

Men shed more bacteria into their surroundings than women do, studies have shown. Now scientists have found that men and women have different effects on the variety of bacteria inside a home, too. The variation comes down to skin biology and "perhaps to body size and hygiene practices," note researchers who sequenced the genes in dust that had settled on the tops of doors in 1,200 homes across the U.S. Dogs apparently alter indoor bacteria more extensively than humans or cats. The bacterial signatures of each of these living beings are unique enough that by simply testing dust in a home, investigators can accurately predict if more women or men live there and if dogs or cats do as well. —*Mark Fischetti*

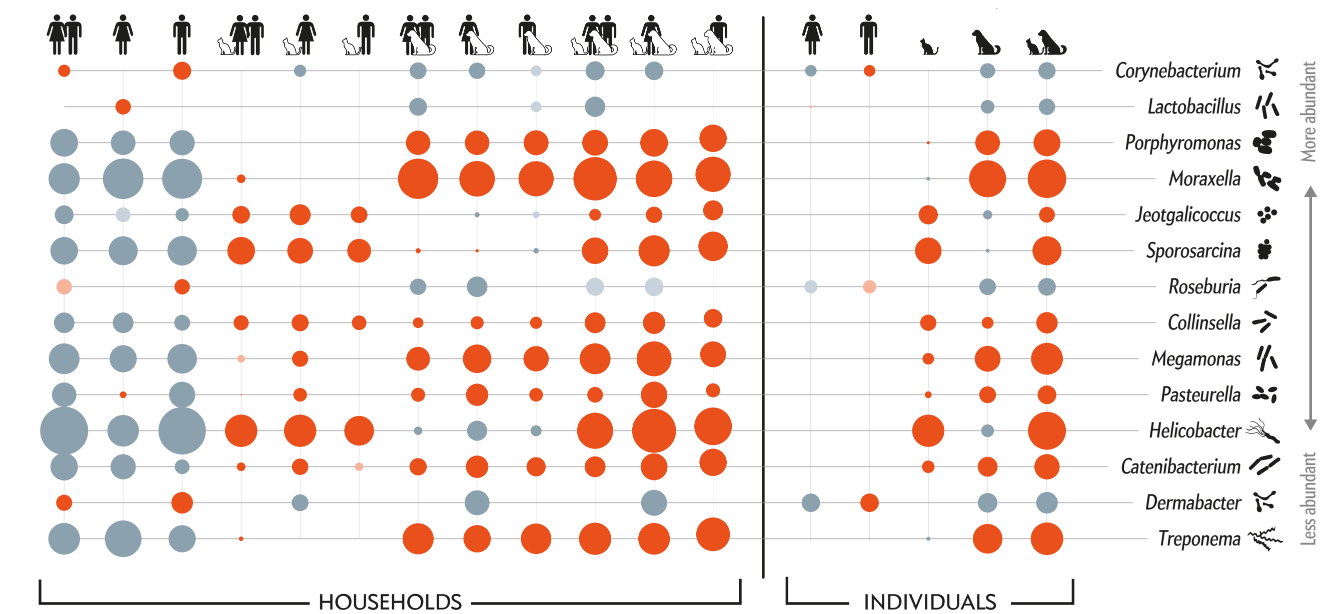
How to Play

Men, women, dogs and cats generate telltale sets of bacteria inside a home. Follow the questions (*circles*) from the top to find the differences. Crime scene investigators could start with the data for the bacterial signatures at the bottom (*dots*) and determine which pets or human sexes live in a household.





*The baseline for each category is the configuration opposite to the one shown. For example, the dots for a household with a majority of males and a cat (sixth from left) show the difference in bacteria relative to all households without a male majority or cats.



SOURCE: "THE ECOLOGY OF MICROSCOPIC LIFE IN HOUSEHOLD DUST," BY ALBERT BARBERÁN ET AL., IN PROCEEDINGS OF THE ROYAL SOCIETY B, VOL. 282; SEPTEMBER 2015

Graphic by Martin Krzywinski and B. Jeannie Hunnicutt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