SPECIAL ISSUE 100 YEARS OF GENERAL RELATIVITY

SCIENTIFIC AMERICAN

SEPTEMBER 2015

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# EINSTEIN

## HOW RELATIVITY CHANGED THE RULES OF OUR REALITY

A BRIEF HISTORY OF TIME TRAVEL

HIS LIFE, CRISES & "BOLDEST DREAMS"

THINGS HE GOT WRONG

NEW QUEST FOR A THEORY OF EVERYTHING


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BUT NEVER OUTSMARTED.

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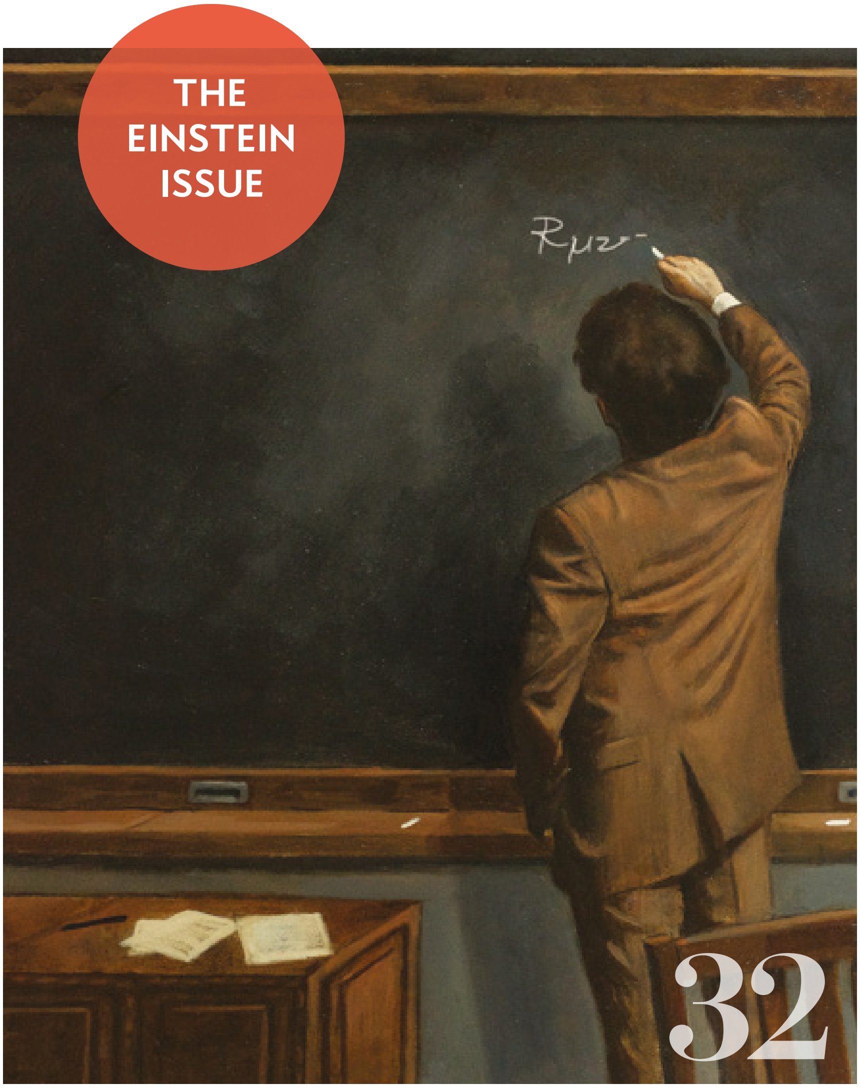
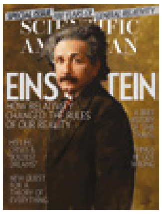
SEPTEMBER 2015

VOLUME 313, NUMBER 3





**ON THE COVER**
Albert Einstein's enigmatic face has captivated the world nearly as long as his theories have. The scientist's hallmark hair and soulful eyes have become an icon of genius. This special issue investigates the great man's life, legacy and the future of his ideas on the 100th anniversary of his greatest success, his general theory of relativity. **Illustration by Daniel Adel.**

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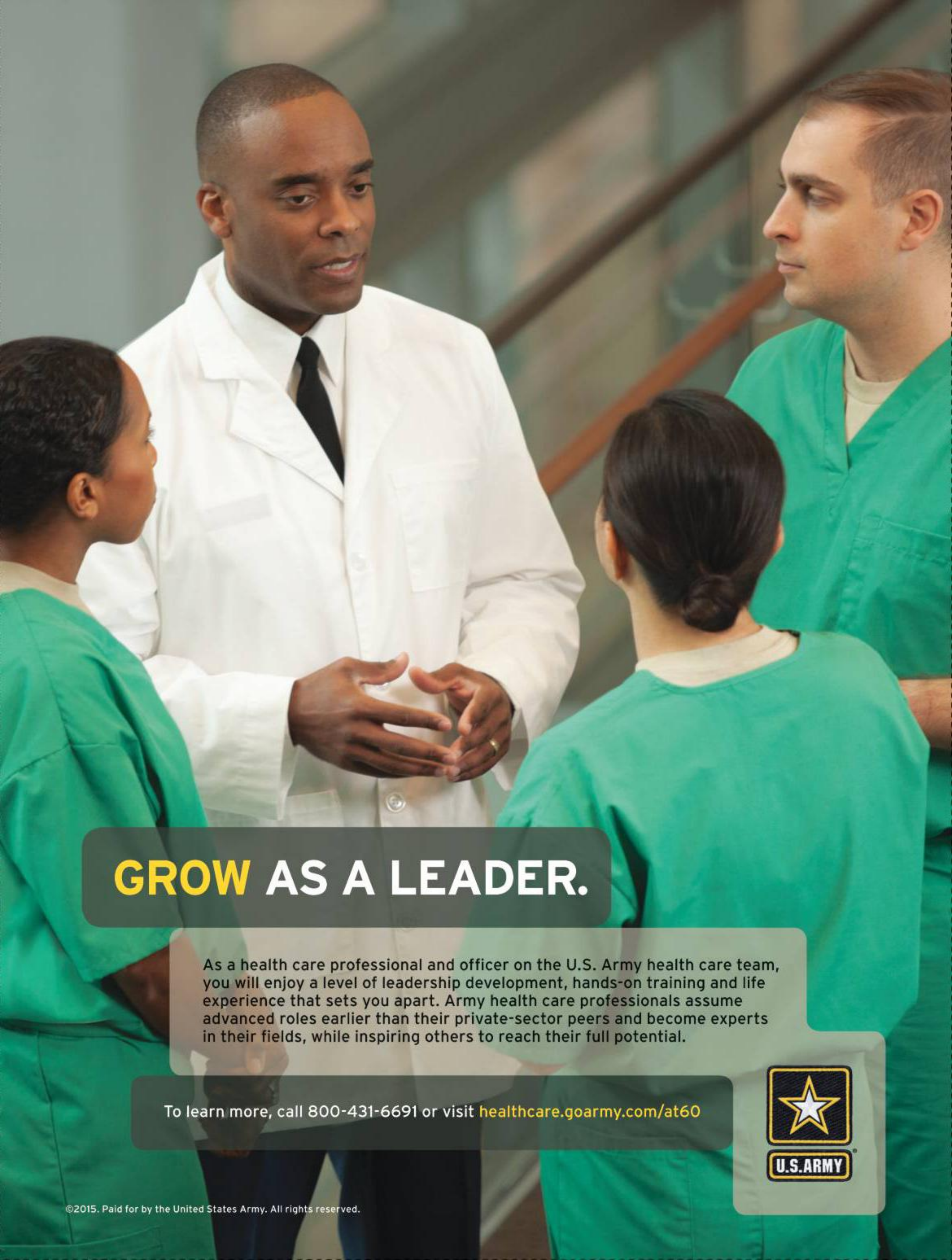
*Illustration by Bernard Lee*



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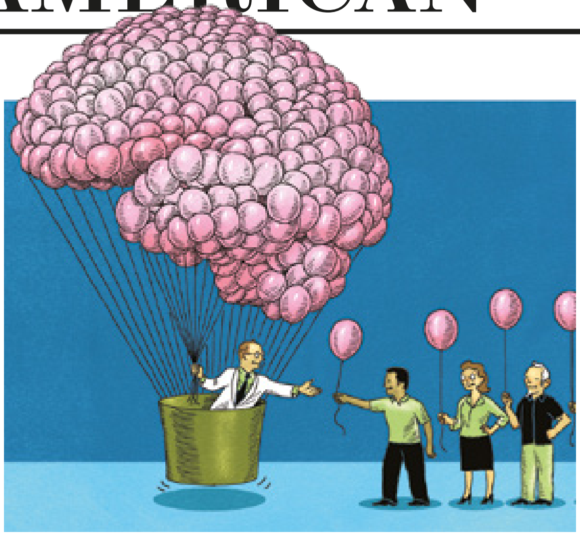

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*Go to www.ScientificAmerican.com/relativity*

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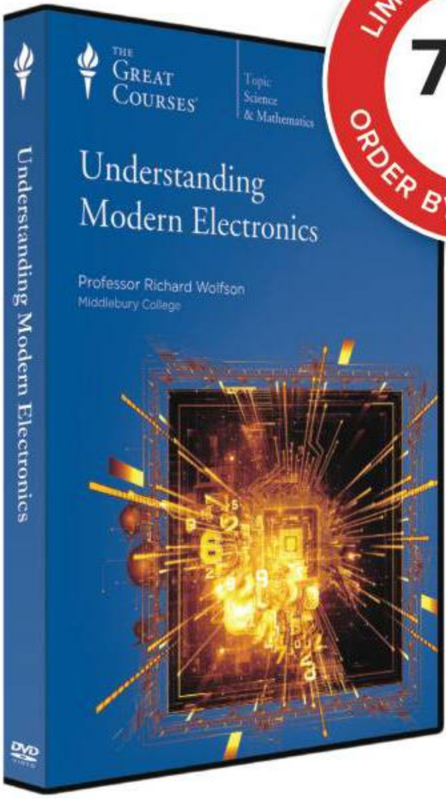
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**Mariette DiChristina** is editor in chief of *Scientific American.* Follow her on Twitter @mdichristina

# Editorial and Einstein

ALONG WITH HIS ARTICLE SUBMISSION, THE SCIENTIST included an apologetic note to the editors:

"The article is somewhat long and not quite easy to grasp. I should, therefore, not be astonished if you find it unsuited for publication in your magazine."

Despite the author's concern, the publisher, Gerard Piel, and the editor in chief, Dennis Flanagan, ran the article in *Scientific American.* They also framed the letter.

The author? Albert Einstein. His article, "On the Generalized Theory of Gravitation," appeared in the April 1950 issue (*right*).

I stumbled across this charming anecdote while paging through one of our old scrapbooks, which included a clipping from the November 19, 1961, edition of the *Chicago Sun-Times*, along with others about our publication of the feature submission from Einstein.

Of course, it wasn't our first encounter with Einstein. As you would expect from a magazine that is now celebrating its 170th year of reporting innovation, the editorial team and our scientist authors covered his theories as he published them. For example, Max Planck commented about the evolution of relativity theory in a 1910 article, "The Mechanical Theory of Nature": "The principle of relativity, despite its youth, appears very promising." He mentions Einstein, "who boldly generalized the principle and proclaimed the relativity of all intervals and epochs of time."

SCIENTIFIC AMERICAN

On the Gener

Theory of Gr

BEN SHAHN, COMMISSIONED BY *SCIENTIFIC AMERICAN*, VOL. 182, NO. 4; APRIL 1950

And in 1920—long before the world ever heard of "crowdsourcing," the magazine sought to rectify the paucity of lay explanations of the physics via a global essay contest. The editors explained: "Mr. Eugene Higgins offered, through the *Scientific American,* a prize of the extraordinary amount of $5,000 for the best popular essay on the Einstein Theories of Relativity." The contest drew exactly 300 essays from "all parts of Europe and North America, from India and South Africa and South America." With the agreement of the judges, Mr. L. Bolton of London got the award, with publication of his essay in a February 5, 1921, issue.

A century after Einstein's landmark December 2, 1915, publication of "*Die Feldgleichungen der Gravitation*" ("The Field Equations of Gravitation"), which we celebrate in this edition, we offer today's perspective on efforts to grasp the nature of spacetime. Issue editor Clara Moskowitz and the team have created a special report that is profound yet playful and sparkles with the wonder of discovery—rather like the great man himself. We hope you enjoy reading it as much as we did putting it together. SA

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*Illustration by Nick Higgins*

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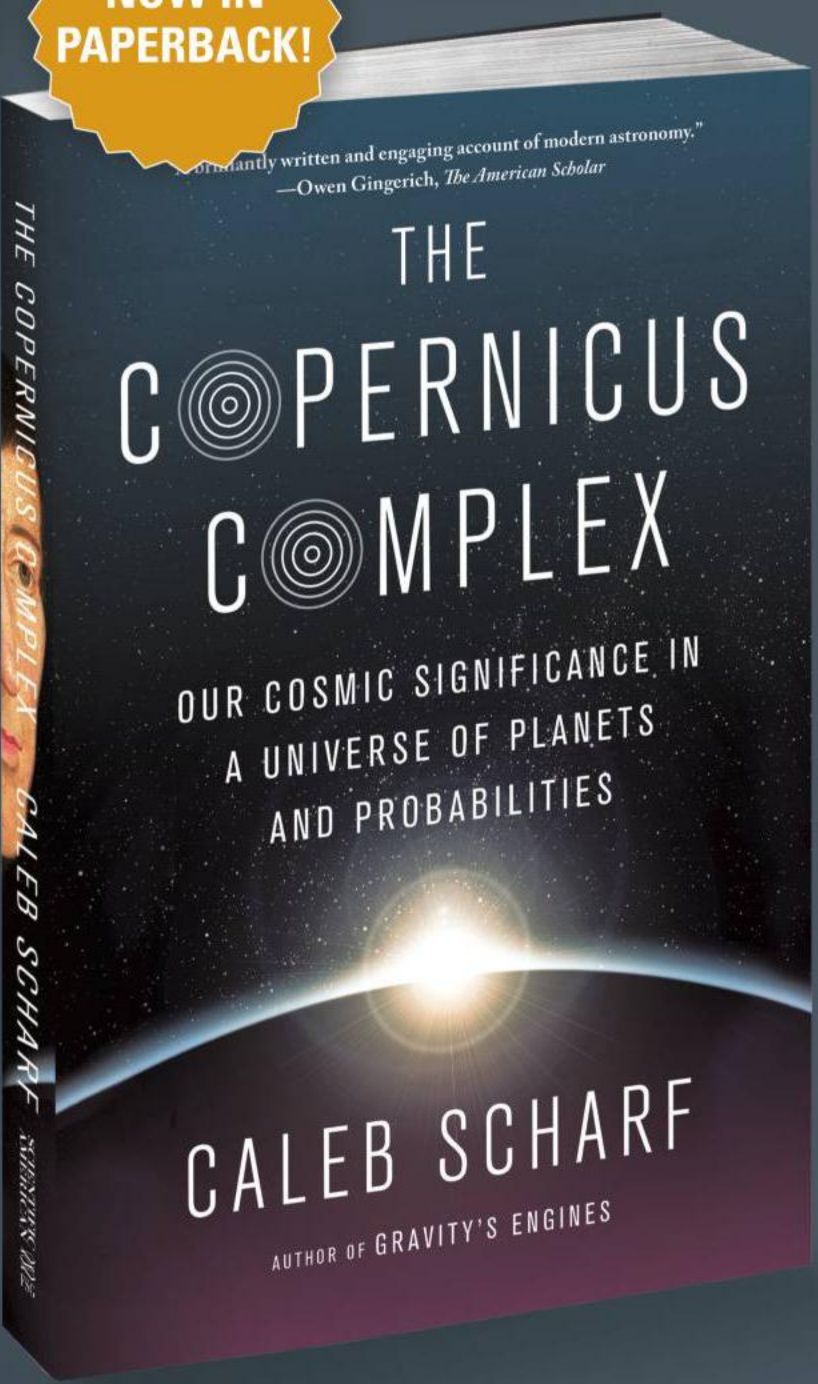
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*May 2015*

### VACCINATION STRATEGY

In "Wooing the Fence-sitters" [Science Agenda], the editors suggest that rather than "strong-arm tactics," we should use a more subtle social strategy of "little nudges" to convince parents to vaccinate their children. But strong-arm tactics are nothing new to public health. How is a law that mandates vaccinations for school-age children, such as the one recently passed in California, any different from, say, fluoridating drinking water? Although forming peer-advocacy groups and promoting pro-vaccine interactions with providers are part of the solution, I do not think these strategies alone are aggressive enough for a time-sensitive and life-threatening public health issue. California's law is a necessary measure to shift the immunization rate above the safety threshold.

Hannah Peckler
*University of California, San Francisco, School of Nursing*

> **"California's law mandating vaccinations for school-age children is a necessary measure."**
>
> HANNAH PECKLER *UNIVERSITY OF CALIFORNIA, SAN FRANCISCO, SCHOOL OF NURSING*

### DINOSAUR EXTINCTION

Stephen Brusatte refers to the extinction of the dinosaurs in "Rise of the Tyrannosaurs." What was so vulnerable in the dinosaurs that ensured their extinction while allowing mammals to survive and thrive?

Peter Stephen
*via e-mail*

*BRUSATTE REPLIES: The end-Cretaceous extinction is often viewed as a catastrophe that killed dinosaurs but spared mammals, allowing our ancestors to take over. But it wasn't so simple. Some dinosaurs did survive: birds. Yet it is a mystery why some (but not all) birds did so, but numerous very birdlike, feathered dinosaurs such as* Velociraptor *and its kin died. Many mammals did survive, particularly those that were smaller and had more general diets. Yet a number of other mammals perished. The late Cretaceous was the heyday of metatherians (living marsupials and close relatives), but this entire group almost went extinct when the asteroid that triggered the dinosaurs' demise hit. In the ensuing Paleogene, it was the placental mammals that took advantage of the metatherian demise and blossomed into the many familiar groups we know today, including our primate forebears.*

### RELATIVISTIC VOYAGE

In "The Glue That Binds Us," Rolf Ent, Thomas Ullrich and Raju Venugopalan state that "physicists think that when protons and neutrons reach extreme speeds, the gluons inside the protons split into pairs of new gluons."

But that would violate special relativity's tenet that the laws of physics are the same for all observers. Consider the perspective of a tiny physicist riding a proton in a vacuum, surrounded by a tube that races by at ever faster speeds. Our little physicist monitors his proton from time to time and always finds it the same. Which physicist's gluons are splitting—the tiny one or one observing from outside the tube?

Charles M. Bagley, Jr.
*Seattle*

*THE AUTHORS REPLY: Einstein's special theory of relativity holds true for the quantum foam of quark-antiquark and gluon pairs that continually pop in and out of existence inside the proton. Thus, in a proton moving at 0.99999 times the speed of light, the lifetime of this quantum foam is dilated long enough that its feature of splitting gluons is captured by an observer's quark-gluon femtoscope. Conversely, the physicist co-moving with the proton cannot observe these quantum fluctuations, because they are short-lived, relative to him or her. This person is therefore impervious to the seething cauldron of quarks and gluons existing within the proton (and all of us). Because the fluctuations exist in both frames, special relativity is upheld.*

### PUBERTY ONSET

After reading "Why Girls Are Starting Puberty Early," by Dina Fine Maron [The Science of Health], I was surprised that there was not a mention of the impact of growth hormones in milk production. Can these hormones bear some of the responsibility for the early onset of puberty in girls?

Vivian Fabbro Keenan
*St. Petersburg, Fla.*

Although it is clear that obesity is part of the picture—fat cells secrete estrogen, which is the major hormone involved in puberty in girls—I was astounded that Maron ignored what is most certainly the cause of both obesity and early-onset puberty: a diet rich in high-fat animal products, including dairy foods, which are themselves rich in estrogen.

Adam Dave
*via e-mail*

*MARON REPLIES: It is not simple to identify any one factor responsible for earlier puberty in girls. The bulk of evidence points to those outlined in the article (such as obesity), yet other theories abound.*

*Milk does contain some substances that have weak estrogenic effects in humans, but they probably are not big drivers of earlier puberty. Meanwhile although some cows are also treated with a hormone related to human growth hormone, there is little reason to think that it would affect humans, and according to pediatric endocrinologist Paul Kaplowitz, naturally occurring and added hormones in these products are quickly degraded in the stomach.*

*Instead environmental chemicals that act like hormones after being ingested appear to be of much greater concern.*

*Slashing consumption of red meat and high-fat dairy products is a good idea for a variety of health reasons. Yet it is hard to discern whether a more plant-based diet would influence puberty because that dietary change could also reduce obesity.*

## CELLULAR COMMUNICATION

My daughter and I were fascinated by the gap junctions—structures connecting cells to one another—described by Dale W. Laird, Paul D. Lampe and Ross G. Johnson in "Cellular Small Talk." Does cell communication via gap junctions occur with blood cells that are circulating through the body? And what about unicellular organisms, especially those that colonize?

James Wurzer
Mary-Elizabeth Wurzer
*Camas, Wash.*

*THE AUTHORS REPLY: Developing blood cells in the bone marrow make gap junctions and communicate by sharing small molecules with their neighbors. Yet for a long time we thought circulating blood cells did not do so: with gap junctions, groups of blood cells would stick together and potentially block small blood vessels. We now know that lymphocytes "activated" to combat an invading bacterium can form gap junctions with other cells. This might be an early step in blood cells crawling out of a vessel to fight infection.*

*Regarding unicellular organisms: single cells and even colonial organisms such as* Volvox *primarily communicate by releasing chemical signals. Gap junctions became necessary when cells began to develop different roles as they lived together with other cells. For example, cells in the coelenterate* Hydra *form them. Plant cells don't have gap junctions, but they do form connections that pass much larger molecules and complexes.*

## CLARIFICATION

"The Search for a New Machine," by John Pavlus, refers to Moore's law as indicating that halving transistor size doubles computing performance. It should have referred to doubling the number of transistors on a chip to increase performance.

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# Don't Blind NASA to Earth's Climate

## Budget meddling by Congress could cripple Earth science programs

**NASA was always** supposed to look close to home as well as out to the stars. In 1958 the U.S. Congress chartered the agency to focus on "phenomena in the atmosphere and space." Through Earth-observing satellites, NASA has vastly improved weather forecasting and natural disaster prediction and relief. It may have even helped save the world when it spotted a dangerous, growing hole in the planet's protective ozone layer in the 1980s. The data spurred the international community to ban ozone-destroying chlorofluorocarbon chemicals.

This year congressional Republicans seem to have decided they have had too much of a good thing and have moved to decrease NASA's Earth science budget. They have been egged on by Senator Ted Cruz of Texas, who has big ambitions—he announced his run for president this year—but little respect for science. Cruz, chair of the Senate Subcommittee on Space, Science, and Competitiveness, said in a hearing that Earth science was not part of the agency's "core mission" to space and, indeed, that it was not "hard science" at all. But this choice between our planet and others is a false one.

In June the House of Representatives, led by Republicans, passed a budget of $18.5 billion (which is what the White House had requested) but reshuffled where the money was to be spent. It slashed Earth science funding by $260 million and added extra money for planetary science that the agency did not ask for. For example, NASA requested $30 million for a robotic mission to Jupiter's icy moon, Europa, but the House gave it $140 million. The Senate Appropriations Committee, also pushed by the Republican majority, approved a version of NASA's budget that reduced total funding by $239 million. At press time, Congress needed to reconcile these competing bills.

Several Republicans, such as Cruz and Representative John Culberson of Texas, claim that funds used by the agency for gazing down at Earth would be better spent examining other worlds. The cuts, many say, actually pare back years of Earth science largesse from the Obama administration that underfunded other agency initiatives.

This argument is misleading. The current administration did increase NASA's Earth science budget but only to redress a nearly 40 percent cut such science suffered between 2001 and 2006, during the George W. Bush administration. Then, as now, actions were driven in large part by antiscientific opposition to evidence that global warming has a human trigger.

Another agency, the National Oceanic and Atmospheric Administration, also has eyes on Earth. But neither Republicans nor Democrats in Congress have supported NOAA with much fervor. For instance, in 2012 Democratic Senator Barbara Mikulski of Maryland tried to move several NOAA satellites to NASA. And in the Obama administration's 2016 budget, NOAA requested $30 million for a study of ocean acidification, which is driven by climate change. The House granted $8.4 million, cut NOAA's total budget by about 5 percent and gave NASA's Europa project that $110-million boost. "Don't tell me that there isn't money available," fumed Democratic Representative Sam Farr of California during a House debate. "It is just the priority where you give it. Are you going to save this planet or put all the money into the moon of Jupiter?"

NASA researchers have successfully placed rovers on Mars and tracked the depletion of groundwater that is exacerbating the current drought in the American West. Of all federal agencies, this one is best positioned to study the heavens and the major environmental changes that affect our lives on Earth. Political extremists need to back off from their budgetary meddling and let the agency do both its jobs. The clock is ticking: the new fiscal year starts in October. SA

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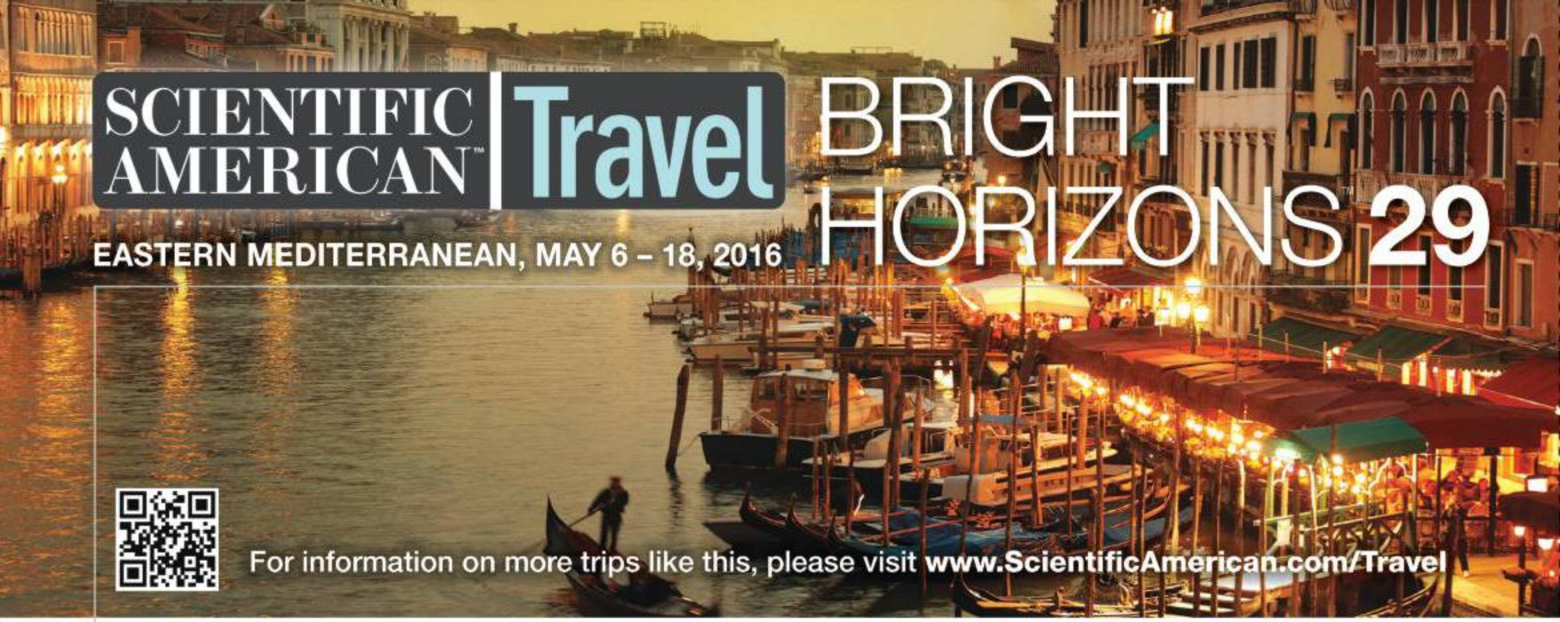
*Illustration by Morgan Schweitzer*



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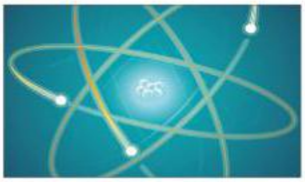

## THEORETICAL PHYSICS

**The Power of Symmetry**

**The Particle Physics World**

**Antimatter**

**Toward an Ultimate Theory of the Universe**

## SPEAKERS

**Diana McDonald, Ph.D.**
**Kenneth W. Harl, Ph.D.**
**Tara C. Shears, Ph.D.**
**Stephen Ressler, Ph.D.**

## A REVIEW OF THE ANCIENT MEDITERRANEAN CIVILIZATIONS

**Sea Power in the Ancient Mediterranean**

**Struggle for the Mastery of Greece, 480–338 B.C.**

**Constantinople to Kostantiniyye**

**Markets, Trade, and Money in the Mediterranean World**

**Religious and Cultural Change in Anatolia**

## ARCHITECTURE IN THE ANCIENT WORLD

**Building in Stone: From Quarry to Temple**

**Stone Masonry Perfected: The Greek Temple**

**Roman Engineering at Ephesus**

**The Church of Hagia Sophia**

**Reconstructing the Trireme**

## INSIDER'S TOUR OF CERN

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**Daniel Goodwin** is a doctoral researcher in the Synthetic Neurobiology Group at the Massachusetts Institute of Technology. This piece was written while he was a research scientist at the Simons Center for Data Analysis in New York City.

# Neuroscience Needs Hackers

## Brain researchers are overwhelmed with data. Hackers can help

**There was a time** when neuroscientists could only dream of having such a problem. Now the fantasy has come true, and they are struggling to solve it. Brilliant new exploratory devices are overwhelming the field with an avalanche of raw data about the nervous system's inner workings. The trouble is that even starting to make sense of this bonanza of information has become a superhuman challenge.

Just about every branch of science is facing a similar disruption. As laboratory-bench research migrates into the digital realm, programming is becoming an indispensable part of the process. At the same time, previously dependable sources of financial support are drying up. The result has been a painful scarcity of jobs and grants—which, in turn, is impelling far too many gifted researchers to focus on their narrow areas of specialization rather than investing time and energy into acquiring new, computer-age skills. In fields where data growth is especially out of control, such as neuroscience, the demand for computer expertise is growing as quickly as the information itself.

Science urgently needs hackers—hackers in the original, Tech Model Railroad Club of the Massachusetts Institute of Technology sense of the word. Their engineering and design skills will be useful, but what is most desirable is the true hacker's resourcefulness, curiosity and appetite for fresh challenges. Particularly in a field like neuroscience, helpers could be invaluable in exploring the daunting wilderness of newly revealed neural networks.

A few pioneers are leading the way. One is H. Sebastian Seung, a professor at the Neuroscience Institute and in the department of computer science at Princeton University. A few years ago he and his collaborators set out to map the retina's neural connections. As they collected an overwhelming mass of electron microscopy data, the question was how they would ever manage to interpret it all. Seung's familiarity with state-of-the-art computing told him that no artificial-intelligence algorithm in existence could possibly handle the task alone.

The solution—then almost unheard of in lab science—was to enlist thousands of human volunteers alongside a state-of-the art AI and harness their collective brainpower. On December 10, 2012, Seung and his team launched the online game EyeWire, in which players score points by helping to improve a neural map. About a year and a half later the game's creators published their first discoveries in *Nature,* together with a note sharing coveted co-author credit with the 2,183 players who had reached the game's top ranks and made the paper possible. (*Scientific American* is part of Springer Nature.)

Hackers are finding their own routes into neuroscience. In late 2013 Brooklyn, N.Y.–based designers Joel Murphy and Conor Russomanno introduced OpenBCI, an "open-source brain-computer interface"—basically a home-brewed electroencephalographic device. Kits and plans are available from their Web site for just a fraction of a standard EEG's cost, and by all accounts it works just as well as the big-budget models. Their two-month-long Kickstarter campaign sold nearly 1,000 units and caught the attention of academic research labs. It's just another example of how traditional barriers are crumbling between institutional science and individuals with new ideas. In fact, some labs have begun posting research challenges with cash prizes on crowdsourcing sites such as Kaggle and InnoCentive. These days if a research entity chooses not to explore such collaborative approaches, it is in danger of being left behind.

The software-design community has demonstrated over the past 20 years that massive online collaborations can work wonders. Today the physical sciences are only beginning to discover that potential. Established scientists would do well to recognize that true hackers are motivated by challenge and honest pride in seeing what they can do.

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*Illustration by Wesley Bedrosian*

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# ADVANCES

A colorized micrograph of a black-legged tick, which can carry up to five diseases.

**INSIDE**

- Airplanes face a new collision risk: personal drones
- A plot of basil flourishes 20 feet underwater
- Is the sun a thief?
- A toy car powered by evaporation

GETTY IMAGES

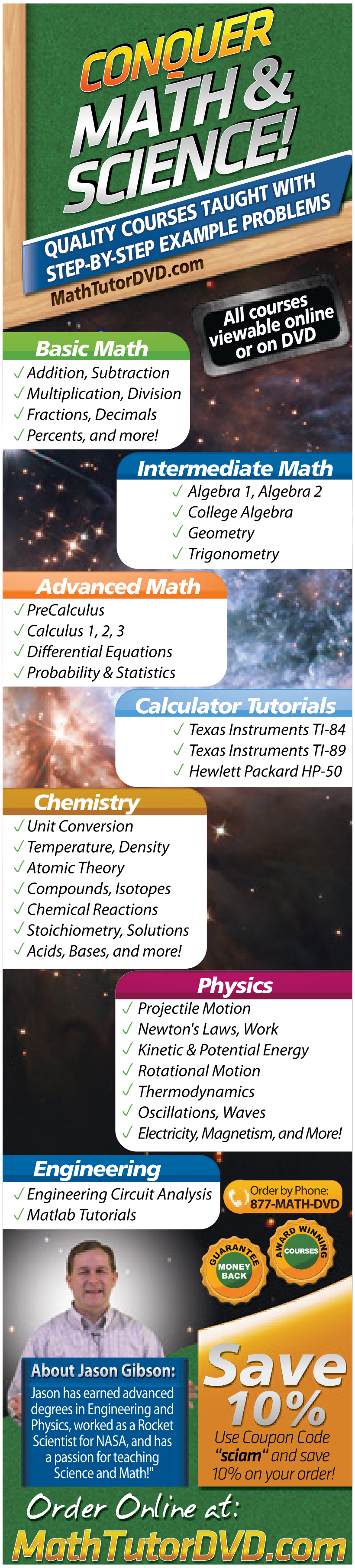
HEALTH

# Lingering Lyme

A new theory about long-lasting Lyme disease symptoms suggests treatment options

**Lyme disease** is a truly intractable puzzle. Scientists used to consider the tick-borne infection easy to conquer: patients, diagnosed by their bull's-eye rash, could be cured with a weeks-long course of antibiotics. But in recent decades the U.S. Centers for Disease Control and Prevention has realized that up to one in five Lyme patients exhibits persistent debilitating symptoms such as fatigue and pain, known as post-treatment Lyme disease syndrome, and no one understands why. The problem is growing. The incidence of Lyme in the U.S. has increased by about 70 percent over the past decade. Today experts estimate that at least 300,000 people in the U.S. are infected every year; in areas in the Northeast, more than half of adult black-legged ticks carry the Lyme bacterial spirochete, *Borrelia burgdorferi*. Although the issue is far from settled, new research lends support to the controversial notion that the disease lingers because these bacteria evade antibiotics—and that timing drug treatments differently could eliminate some persistent infections.

These ideas stem from the observation of a few rogue bacterial cells. Kim Lewis,



director of the antimicrobial discovery center at Northeastern University, and his colleagues grew *B. burgdorferi* in the laboratory, treated them with various antibiotics and found that whereas most of the bacteria died within the first day, a small percentage—called persister cells—managed to survive the drug onslaught. Scientists first discovered persister cells in 1944 in *Staphylococcus aureus*, the agent of staph infections, and Lewis and others have observed them in other species of bacteria, too—but the observations that *B. burgdorferi* also form persisters is new.

"These are some of the most robust persisters we've seen," says Lewis, whose results were published online in May in *Antimicrobial Agents and Chemotherapy*. "Over days, in the presence of antibiotic, their numbers don't decline." Researchers at Johns Hopkins University similarly identified *B. burgdorferi* persister cells this past spring.

Persisters are not antibiotic-resistant mutants; they are genetically identical to their vulnerable counterparts. Instead they are bacteria that have gone into a dormant state, ceasing the types of cellular activities that antibiotics typically thwart. Previous research has shown that when persisters of other bacterial species are removed from a bath of antibiotics, they begin to grow again. This fact prompted Lewis and his colleagues to try treating *B. burgdorferi* with antibiotics in pulsed doses—administering the drugs, stopping and then administering them again—to see if they could kill the persisters once they began to regrow. It worked, which suggests that if persisters are responsible for lasting infections in people, treating patients on and off with antibiotics could help. Lewis and his colleagues, as well as the Johns Hopkins scientists, are also exploring other treatment options, such as different drugs and drug combinations.

Not everyone agrees that persister cells play a role in Lyme's lingering symptoms. "There's been no evidence that this persister phenomenon has any relevance for animals or humans," says Gary Wormser, chief of the division of infectious diseases at New York Medical College. First, he says, lab studies of *B. burgdorferi* cannot account for the potential effects of the body's immune system, which might be able to eliminate persisters once the brunt of the infection has cleared. Second, labs have yet to grow *B. burgdorferi* isolated from people treated with antibiotics, and that raises questions about whether the persisters are even viable and capable of making someone sick.

Identifying the causes of and treatments for post-treatment Lyme disease syndrome is "one of the highest priority research needs in the field," said C. Ben Beard, chief of the bacterial diseases branch at the CDC's Division of Vector-Borne Diseases, at a CDC event in May 2014. So although it is as yet unclear whether *B. burgdorferi* persister cells drive some of these enduring symptoms, Lewis and his colleagues will take their research to the next level—they will test whether pulse dosing helps to clear *B. burgdorferi* infections in mice—in an attempt to move one step toward a much needed answer.

—*Melinda Wenner Moyer*

GERALD C. KELLEY *Science Source*

### LYME ON THE RISE

Lyme disease is expanding its geographical reach in almost every direction from its epicenters in the Northeast and upper Midwest, according to a study published in August by CDC scientists. The reasons remain uncertain. Ongoing forest fragmentation could contribute to the problem: as people chop forests into smaller pieces, they unwittingly create landscapes well suited for the deer and small mammals that ticks tend to feed on.

Climate change may also foster new suitable habitats for the arachnids and change the timing of tick feedings in ways that make young ticks—and humans—more vulnerable to infection. Nearly every known tick-borne disease in the U.S. has become more prevalent over the past decade. Scientists have identified four new ones since 2013, bringing the total up to an estimated 16. —M.W.M.

PSYCHOLOGY

# Fibs with Friends

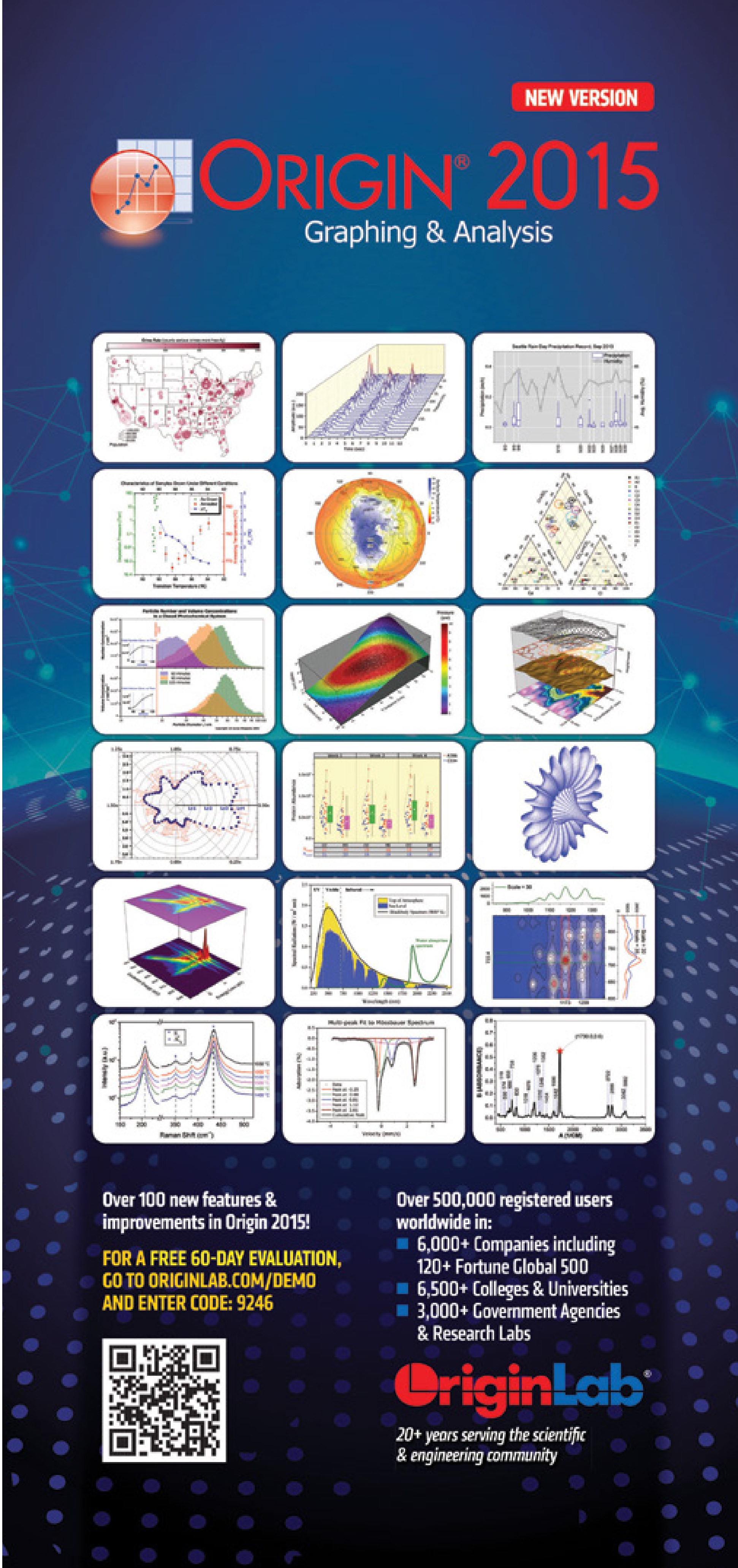
Groups spot lies more often than individuals do

**A shifty gaze,** fidgety stance or sweaty palms signal a liar in classic film noirs. In real life, however, it is surprisingly difficult to recognize when someone is telling a tall tale. Even among trained professionals, the lie-detection accuracy rate is only slightly better than pure chance. And courts tend to reject polygraph evidence because the tests lack standardized questions for determining falsehoods. For better odds, discussions of questionable claims appear to be the way to go. Psychologists at the University of Chicago have found that groups of people are consistently more reliable at rooting out fabrications than chance or individual judges.

For the study, participants were shown videotaped statements, either by themselves or with other people present, and then asked to guess whether the speakers were telling the truth or white lies. After 36 rounds, the researchers found that groups of evaluators scored just as well as individuals in determining truths but were up to 8.5 percent more accurate in exposing lies. Groups of three or six were equally reliable at pinpointing falsehoods. The slight edge arises as a result of insights that emerge from conversations, says Nadav Klein, one of the study's authors. By talking out their observations with others, people gain new perspectives, improving their understanding. The results were published in June in the *Proceedings of the National Academy of Sciences USA.*

The scales of justice could be recalibrated accordingly. For instance, judges could explicitly instruct juries to evaluate witnesses for honesty, in addition to asking them to consider the evidence objectively, says R. Scott Tindale, a psychologist at Loyola University Chicago. With that direction, deliberations might be more likely to include conversations about credibility and thus to defeat deception. No one advocates for mob mentality, but when gauging mendacity, it is apparently wise to compare notes. *—Kat Long*

*Illustration by Thomas Fuchs*



RICHARD NEWSTEAD Getty Images

TECHNOLOGY

# Cloudy with a Chance of Drones

Civilian multicopters raise collision risks for jet airliners

**A near miss** with a personal drone forced a Shuttle America flight to pull up while on final approach to land at LaGuardia Airport in New York City earlier this year. It wasn't the first such incident. The U.S. Federal Aviation Administration currently receives about 60 reports from pilots every month that represent potential drone sightings. No one knows exactly the type or extent of damage that a collision with a small drone could cause to a jet airliner's engine or airframe, but the agency plans to research that possibility in the next fiscal year. Meanwhile technologies and policies that could deter such collisions remain up in the air.

The current prevention tactic is to stop repeat offenders. The FAA works with local law enforcement to contact drone operators who carry out an "unauthorized [unmanned aerial system] operation" to educate them about flight safety regulations. The agency can also tack on civil penalties for "careless or reckless operation" of drones.

But the FAA needs to do more to avert collisions than educate citizens, says Ben Berman, a Boeing 737 pilot for a major U.S. airline. "Most near-collision courses are going to be misses," he explains. "But if we roll the dice on near collisions with drones enough times a year, eventually you'll come up snake eyes."

Small drones—classified by the FAA as weighing less than 55 pounds—cannot carry the relatively heavy traffic collision and avoidance system used by larger aircraft to track the locations of nearby planes. As an alternative, Berman, a former chief investigator for the National Transportation Safety Board, thinks drone manufacturers should program their craft to avoid flying above certain altitudes or into restricted airspace. The FAA has also mentioned such "geo-fencing" software updates as a potential short-term fix but does not require them for small drone makers.

One best-selling-drone manufacturer has already taken such steps. DJI, a company based in Shenzhen, China, makes the world's most popular small drones, with its Phantom models costing about $1,000 apiece. Since 2014, DJI has pushed out drone firmware updates to clearly show operators the restricted airspaces around airports, Washington, D.C., or national borders. Operators who ignore the software warnings about restricted airspace and try flying forward will find their drones simply refusing to move. "It's like flying into an invisible wall," DJI's Michael Perry says.

Several other tactics could be hovering just over the horizon. In February the FAA proposed rules for small drones that include speed and altitude restrictions and access limits to airspace where manned planes typically fly. Such rules could be finalized as early as 2016. On the technology side, NASA has been working with industry partners to develop an unmanned air traffic system that could track small drones at low altitudes. The space agency also has tested a detect-and-avoid system for larger unmanned aircraft such as its Ikhana drone, a civilian version of the military's Predator drone. Such technology could eventually scale down for smaller drones.

These solutions have become more incumbent as growing numbers of drones find their way into the hands of ordinary consumers. This year China exported 160,000 civilian drones worth $120 million from January to May, according to the Xinhua News Agency. "We're in the process of going from these very niche hobby products to mass consumer products," Perry says. "Many consumers just entering this space don't know the rules and regulations in the way that model aircraft hobbyists used to." *—Jeremy Hsu*

COMMENT AT ScientificAmerican.com/sep2015

AGRICULTURE

# Sunken Strawberries

## The produce aisle goes undersea in a new approach to farming

**In transparent** plastic bubbles 20 feet beneath the surface of the Mediterranean Sea, an experimental garden grows. The strawberries, basil, beans and tomatoes within these air-filled biospheres thrive in their submerged homes. Surrounding water provides the constant temperature and humidity elusive at most terrestrial farms, and freshwater trickles down the spheres' interiors after the seawater below evaporates and then condenses.

These marine greenhouses, located off the coast of Italy, represent a foray into underwater farming by Ocean Reef Group, a diving and scuba gear company. Company president Sergio Gamberini chose to grow his crops hydroponically after noticing, during an early trial, that soil brought along stowaway insect pests. He hopes to introduce this gardening approach to coastal developing countries with arid lands. In fact, Gamberini has received requests for biospheres from nations ranging from the Maldives to Saudi Arabia. His son, Luca Gamberini, admits a long path lies ahead: "Our dream is, on a large scale, utopic." *—Sabrina Imbler*

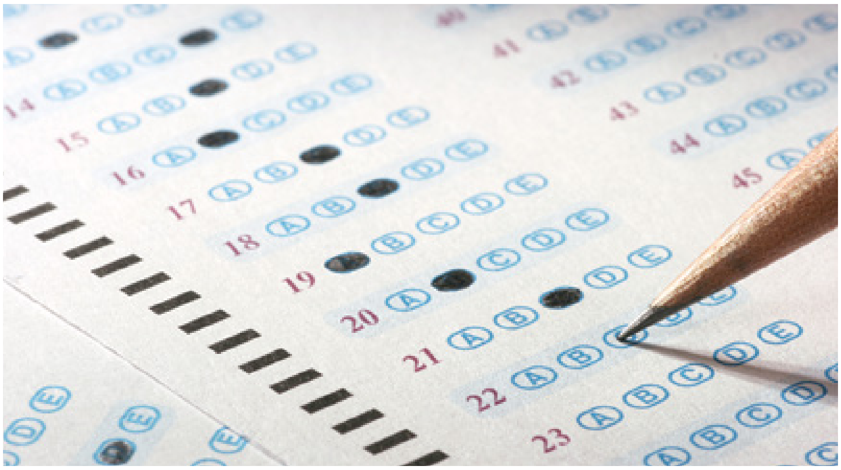
The air temperature inside the underwater greenhouses stays close to a balmy 84 degrees Fahrenheit, with a humidity of 90.5 percent.

COURTESY OF SERGIO GAMBERINI (top); OLIVIER MORIN *Getty Images* (middle and bottom)

EDUCATION

# SAT Charts New Territory

## The revamped test puts a stronger emphasis on graphic literacy



RYAN BALDERAS *Getty Images*

**"Fortune favors the prepared mind,"** as Louis Pasteur once said. So as school revs up this month, so do SAT prep classes. Students might be surprised, however, at the amount of time dedicated to visual literacy skills. The increased focus on graphics is designed to prepare an estimated 1.6 million college-bound pupils for the first redesign of the standardized college admissions test in more than a decade. Along with other updates, test takers of the March 2016 exam will encounter graphics not only in the math section as in past years but also in the reading and writing and language portions. Students will be asked to interpret information presented in tables, charts and graphs and to correct text so it accurately describes data found in accompanying figures.

Mounting evidence indicates that such literacy is a key skill for success in college, careers and daily life in general. In an increasingly data-rich world, graphics now pop up routinely in formats ranging from political campaign literature to household bills. "Being a literate consumer of that information is valuable regardless of your career," says Jim Patterson, an executive director at the College Board, the nonprofit corporation that owns and publishes the SAT.

Education experts agree that students in many developed nations, including the U.S., lack experience with visual data. "Apart from basic *x*- and *y*-axis graphs, educators [around the world] don't sufficiently teach students how to represent information graphically," says Emmanuel Manalo, a professor of education psychology at Kyoto University in Japan. The SAT's new focus most likely will nudge educators to shift their lesson plans accordingly. Students, in other words, won't be the only ones with bubble charts or scatter plots on the mind this fall—teachers will, too.

*—Rachel Nuwer*

### BIG DATA DEMANDS

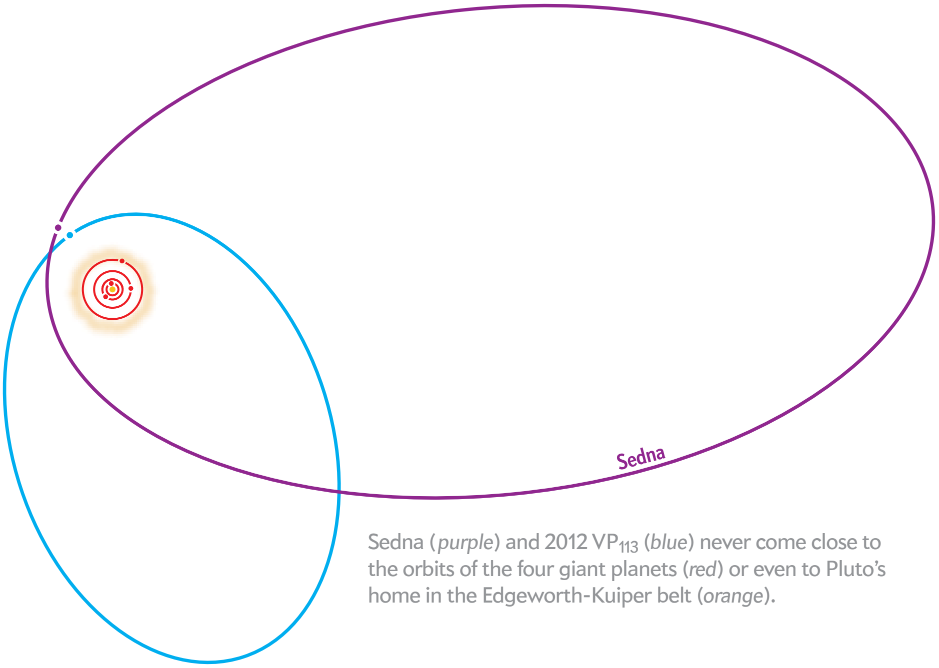
**The intellectual work** required to interpret a graph taxes our brain more than the effort involved in reading the same information presented as text, according to a new study by Manalo and two researchers at the University of Twente in the Netherlands. The team measured neurological activity in students and found that graphs elicited roughly 60 percent more electrical activity than text or equations and 40 to 50 percent more than pictures and tables. Manalo will next examine whether practice diminishes the amount of tapped brainpower. *—R.N.*

COMMENT AT ScientificAmerican.com/sep2015

ASTRONOMY

# Solar Swindle

The sun may have swiped Sedna from a neighboring star



Sedna (*purple*) and 2012 VP$_{113}$ (*blue*) never come close to the orbits of the four giant planets (*red*) or even to Pluto's home in the Edgeworth-Kuiper belt (*orange*).

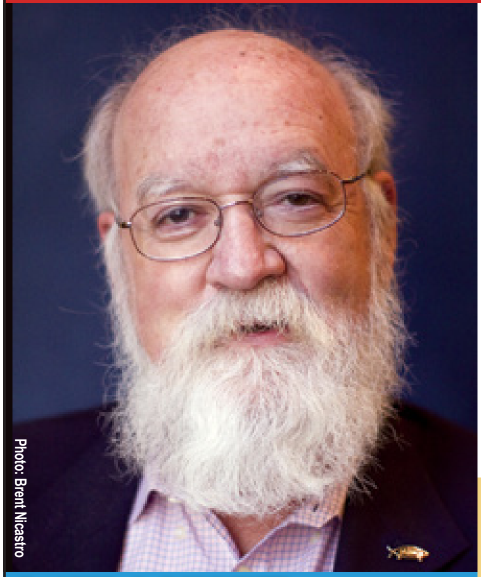
SOURCE: SCOTT S. SHEPPARD *Carnegie Institution for Science*

**At the time of** Sedna's discovery in 2003, it was the farthest body ever seen in our planetary club. Its peculiar path—it never ventures near the giant planets—suggested an equally peculiar history. How did it get there? The sun may have snatched Sedna away from another star, new computer simulations show.

A clue to Sedna's past came in 2012, when observers spotted a second and even smaller object with a similarly elongated and remote orbit. Astronomers Lucie Jílková and Simon Portegies Zwart of Leiden Observatory in the Netherlands and their colleagues decided to investigate whether interstellar robbery could produce the orbits of both Sedna and its sidekick, 2012 VP$_{113}$. "We show that it's possible," Jílková says. Moreover, the researchers reconstructed the crime scene and even the likely properties of the victim star, which they dubbed "Star Q." In work submitted to *Monthly Notices of the Royal Astronomical Society,* the astronomers say Star Q was originally about 80 percent more massive than the sun. It passed within 34 billion kilometers of us—just 7.5 times greater than the distance from the sun to Neptune. This proximity means the star arose in the same stellar group or cluster as the sun. Although Star Q still exists, its fiercest light probably burned out long ago because of its greater mass. As a dim white dwarf, it will be hard to find.

The new work makes a "pretty convincing case" that Sedna could be captured, says astronomer Scott Kenyon of the Harvard-Smithsonian Center for Astrophysics. But Sedna discoverer Mike Brown of the California Institute of Technology contends that the object most likely is native to our solar system and got yanked outward by the gravitational tug of the sun's siblings—a simpler scenario.

The issue may remain unresolved until more objects with odd orbits are found in the outer reaches of our solar system. "When we have something like a dozen, I think we'll probably know," Brown says. If the sun stole these objects from Star Q, they should all come closest to Earth on the same side of the sun. But if their orbits differ, the sun probably is innocent of theft. —*Ken Croswell*



*Graphic by Amanda Montañez*

ANIMAL BEHAVIOR

# From the Pages of *Aesop's Fables*

A seven-gram bird deceives a predator 40 times its size by crying wolf

Pied currawongs are fearsome birds but have enemies of their own.

B. G. THOMSON *Science Source*

**In the classic story,** a boy tries to repeatedly fool his town into believing that there is a wolf on the prowl. This morality tale ends poorly for the boy, but a small Australian bird can do one better. When a pied currawong goes looking for brown thornbill nestlings to eat, the thornbill parents call wolf—or, actually, they call hawk. The false alarms fool the currawong into thinking that its own predator, the brown goshawk, is nearby. The tiny thornbill thus effectively outsmarts its large enemy.

To explore how this sophisticated ruse works, biologist Branislav Igic, then at the Australian National University, and his colleagues positioned a taxidermied currawong near thornbill nests while broadcasting nestling distress calls. The thornbills sounded their hawk alarm calls and even mimicked the alarms of other species. Igic also tested 18 currawongs by broadcasting the sounds of the thornbills' mimetic and nonmimetic hawk calls. He found that the playback discouraged the currawongs from hunting. The results were published this past spring in the *Proceedings of the Royal Society B.*

The researchers think that alarm calls from what sounds like multiple callers might make the warning seem more reliable. "Birds can adapt some very interesting and unique strategies to protect their young," says Igic, who is now at the University of Akron. The thornbills' own hawk calls fooled the currawongs for 8.3 seconds on average, but when Igic included the mimicked calls, too, the currawongs were distracted twice as long. That padding may provide enough time for the nestlings to escape the nest.

Visual mimicry, exemplified by harmless king snakes that resemble venomous coral snakes, is well known to animal behaviorists, but vocal mimicry has remained more mysterious. "This is further evidence of the benefits some vocal mimics gain from their unusual vocal behavior," says University of Cape Town ornithologist Tom Flower, who was not involved in this study. He ultimately would like to see proof that deception actually increases nestling survival. For now, unlike the fabled townspeople, the currawongs have yet to catch on to the thornbills' lies. *—Jason G. Goldman*

IN THE NEWS

# Quick Hits

**U.S.**

Google will add every railroad crossing in the country to its Maps application. Visual and audio alerts will signal these potential hazards to users. The Federal Railroad Administration has asked Apple, TomTom and other companies that provide GPS services to do the same after a large year-over-year increase in crossing accidents in 2014.

**UNITED ARAB EMIRATES**

Dubai will house the first fully functional 3-D-printed building, announced the city's Museum of the Future. A 20-foot-tall printer will construct the 2,000-square-foot office.

**RUSSIA**

Scuba divers helped an international team of physicists install a spherical neutrino detector more than 4,000 feet below the surface of icy Lake Baikal in Siberia.

**MEXICO**

A deep-sea submarine discovered a 0.25-mile-long field of hydrothermal vents along a fault in the Gulf of California's seafloor. At 12,500 feet, they are the deepest high-temperature vents ever found in the Pacific.

**CUBA**

The World Health Organization certified the island nation as the first country to eliminate the transmission of HIV and syphilis from mother to baby.

**INDONESIA**

A plane dumped several tons of cloud-seeding salt over central Sumatra in a government-supported effort to induce rain and relieve a seasonal heat wave. The attempt failed to produce any showers.

For more details, visit www.ScientificAmerican.com/sep2015/advances

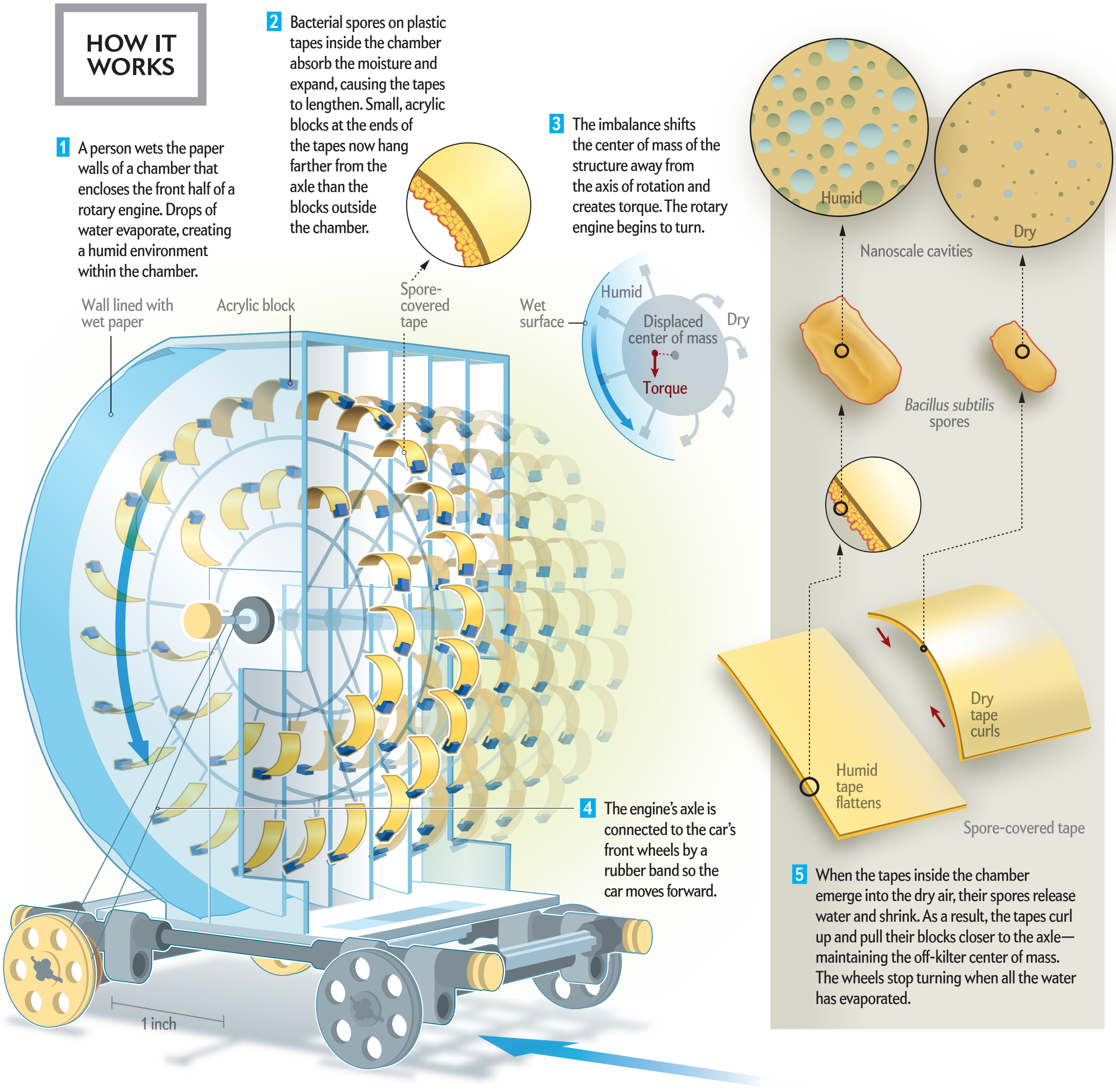
ENGINEERING

# Water, Water Everywhere

A toy car runs on the energy of evaporation

**The first vehicle** powered by evaporation frequently zooms along a laboratory bench these days at Columbia University. The 100-gram car relies on spore-coated tapes that expand and contract like tiny muscles as they move through environments of varying humidity. It can take up to 10 minutes to cross a table at the moment, but the biologists, chemists and engineers on the project think upgrades to the engine could enable it to power a wide range of technologies, including robotics systems and generators. For now the focus is on the small: another prototype can power two tiny LED lights. —*Maria Temming*

## HOW IT WORKS



1 A person wets the paper walls of a chamber that encloses the front half of a rotary engine. Drops of water evaporate, creating a humid environment within the chamber.

2 Bacterial spores on plastic tapes inside the chamber absorb the moisture and expand, causing the tapes to lengthen. Small, acrylic blocks at the ends of the tapes now hang farther from the axle than the blocks outside the chamber.

3 The imbalance shifts the center of mass of the structure away from the axis of rotation and creates torque. The rotary engine begins to turn.

4 The engine's axle is connected to the car's front wheels by a rubber band so the car moves forward.

5 When the tapes inside the chamber emerge into the dry air, their spores release water and shrink. As a result, the tapes curl up and pull their blocks closer to the axle—maintaining the off-kilter center of mass. The wheels stop turning when all the water has evaporated.

SOURCE: "SCALING UP NANOSCALE WATER-DRIVEN ENERGY CONVERSION INTO EVAPORATION-DRIVEN ENGINES AND GENERATORS," BY XI CHEN ET AL., IN *NATURE COMMUNICATIONS*, VOL. 6, ARTICLE NO. 7346; JUNE 16, 2015

*Illustration by 5W Infographics*

## OLD MOLD SOLD

**A small sample** of Sir Alexander Fleming's original penicillin culture (*above*) was put up for sale by a London auction house in July. In 1955 Fleming had given the fungus to a neighbor to thank him for foiling a robbery at the famed microbiologist's home. Fleming stumbled on the antibiotic properties of *Penicillium* mold in 1928, and over the course of the following decade University of Oxford bacteriologists and others expanded on his findings to develop the first antibiotic drug. Mass production of penicillin during World War II cured millions of people of bacterial infections that would have been fatal otherwise. Today antibiotics are considered one of the greatest discoveries in medical history—thus the auction of a crusty petri dish that would have been thrown out long ago. In a letter accompanying the sample, the microbiologist's housekeeper warned its recipient that the contents were "not to be confused with Gorgonzola cheese!!!" —*Kat Long*

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**$20**

Cost per 100,000 units of penicillin in 1943. With mass production, that price fell to less than 10 cents by 1949.

**6.8 trillion**

Units of the antibiotic produced by U.S. companies in 1945.

**1**

Percentage of deaths attributed to bacterial pneumonia in World War II, down from 18 percent in World War I.

**20+**

Classes of antibiotics introduced since penicillin became available.

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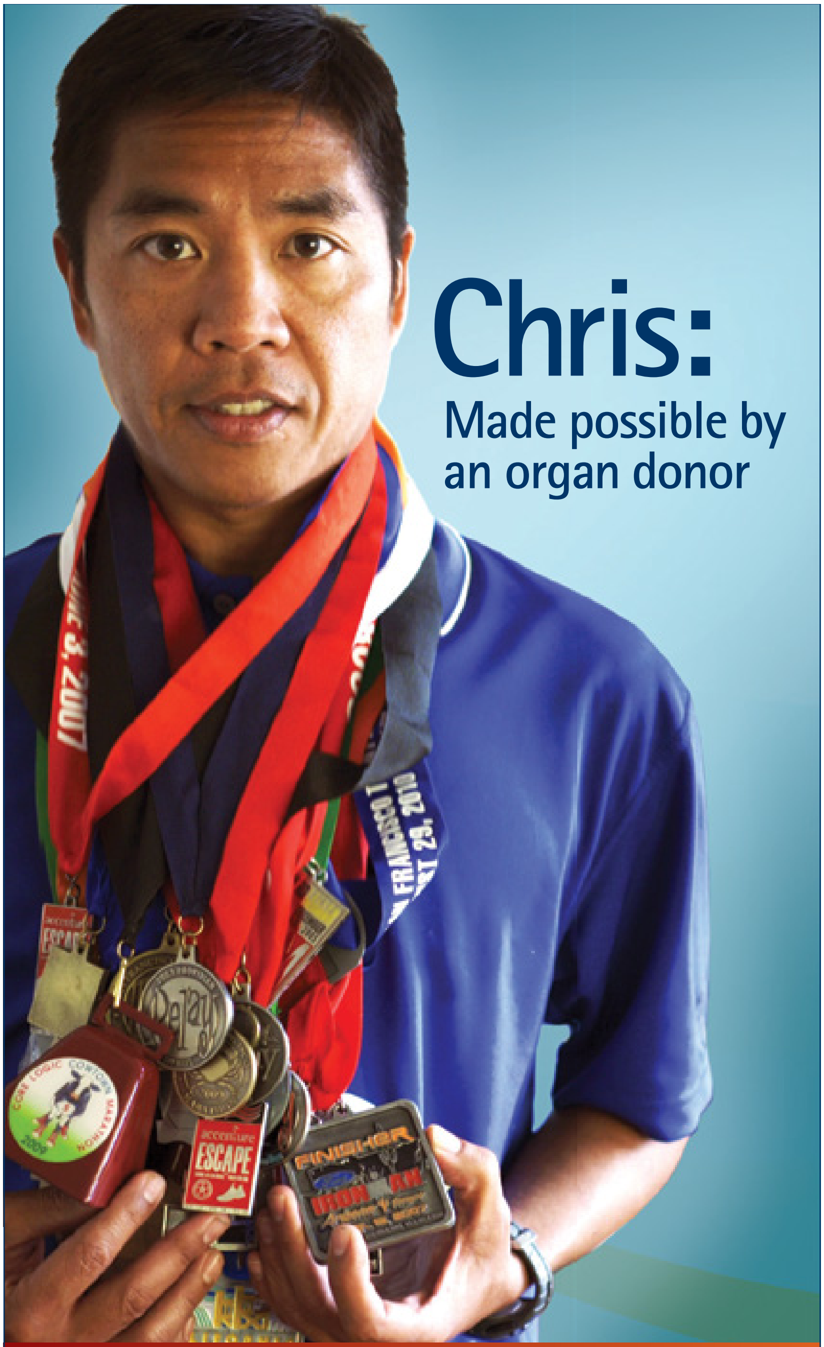
COURTESY OF CATHERINE SOUTHON AUCTIONEERS & VALUERS (*top*); SOURCES FOR STATISTICS: DISCOVERY AND DEVELOPMENT OF PENICILLIN, IN AMERICAN CHEMICAL SOCIETY'S INTERNATIONAL HISTORIC CHEMICAL LANDMARKS *www.acs.org/content/acs/en/education/whatischemistry/landmarks/flemingpenicillin.html* (*first two items*); "THE REAL STORY BEHIND PENICILLIN," BY HOWARD MARKEL, IN *PBS NEWSHOUR'S* "THE RUNDOWN." PUBLISHED ONLINE SEPTEMBER 27, 2013 *www.pbs.org/newshour/rundown/the-real-story-behind-the-worlds-first-antibiotic* (*third item*); "NEW BUSINESS MODELS FOR ANTIBIOTIC INNOVATION," BY ANTHONY D. SO AND TEJEN A. SHAH, IN *UPSALA JOURNAL OF MEDICAL SCIENCES*, VOL. 119, NO. 2; MAY 2014 (*fourth item*); CATHERINE SOUTHON AUCTIONEERS & VALUERS (*fifth item*)

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# Brain Food

## A Mediterranean-style diet may slow memory loss, even if adopted late in life

**Whenever the fictional character** Popeye the Sailor Man managed to down a can of spinach, the results were almost instantaneous: he gained superhuman strength. Devouring any solid object similarly did the trick for one of the X-Men. As we age and begin to struggle with memory problems, many of us would love to reach for an edible mental fix. Sadly, such supernatural effects remain fantastical. Yet making the right food choices may well yield more modest gains.

A growing body of evidence suggests that adopting the Mediterranean diet, or one much like it, can help slow memory loss as people age. The diet's hallmarks include lots of fruits and vegetables and whole grains (as opposed to ultrarefined ones) and a moderate intake of fish, poultry and red wine. Dining mainly on single ingredients, such as pumpkin seeds or blueberries, however, will not do the trick.

What is more, this diet approach appears to reap brain benefits even when adopted later in life—sometimes aiding cognition in as little as two years. "You will not be Superman or Superwoman," says Miguel A. Martínez González, chair of the department of preventive medicine at the University of Navarra in Barcelona. "You can keep your cognitive abilities or even improve them slightly, but diet is not magic." Those small gains, however, can be meaningful in day-to-day life.

### FROM FORK TO BRAIN

SCIENTISTS LONG BELIEVED that altering diet could not improve memory. But evidence to the contrary started to emerge about 10 years ago. For example, Nikolaos Scarmeas of Columbia University and his colleagues collected information about the dietary habits and health status of about 2,000 Medicare-eligible New Yorkers—typically in their mid-70s—over the course of four years on average. In 2006 the investigators reported that tighter adherence to a Mediterranean diet, which had previously been linked to a lower risk of cardiovascular disease, was associated with slower cognitive decline and a lower likelihood of acquiring Alzheimer's disease. Because the researchers merely observed dietary patterns and did not control them—as would be the case in a clinical trial—doubts lingered, however. It was still possible that the apparent brain benefit was the result of chance or some other trait common to folks who consistently follow a Mediterranean diet in the U.S., such as educational achievement or particular life choices.

Seven years later researchers pinned down some answers. In 2013 Martínez González and his colleagues published findings on their massive PREDIMED study, an experiment that included almost 7,500 people in Spain. (PREDIMED stands for Prevention with Mediterranean Diet.) The investigators randomly assigned study subjects to one of two experimental groups. In the first, participants followed the Mediterranean diet with an additional helping of mixed nuts; in the second, they also adhered to the Mediterranean diet but were given additional extra virgin olive oil. (Researchers felt that providing extra nuts and oils at no cost to participants would guarantee that certain healthy fats were eaten in quantities large enough to have measurable effects on the study's outcomes.) The control group, against which the results of the experimental groups would be compared, was in-

*Illustration by Aleks Sennwald*

structed generally on how to lose weight. Its members were given advice on eating vegetables, meat and high-fat dairy products that jibed with the Mediterranean diet, but they were discouraged from using olive oil for cooking and from consuming nuts.

As expected, the results showed that either of the experimental Mediterranean diet options led to significantly better cardiovascular outcomes. But when the scientists tested cognition in a subset of study members, they also discovered that individuals in either of the Mediterranean diet groups performed better than the weight-instruction group in a battery of widely accepted cognitive tests. "This is surprising, of course," Martínez González says.

As intriguing as these findings are, they are still not conclusive; the researchers had not gathered any cognitive information at the beginning of the study. Therefore, the possibility remains that there was something different between the two experimental groups and the control group—beyond their diet interventions—that could account for the findings.

Martínez González sought to quiet such criticisms with a new study his team published in July in *JAMA Internal Medicine*. Drawing from a group of more than 300 participants who were also part of PREDIMED but at a specific site with more financial resources, the researchers conducted baseline cognitive measurements and compared them with that same group's results four years later. On average, people were 67 years old at the start of the study. The newest findings, Martínez González says, are consistent with what he found in his earlier studies. These results are also not definitive, however, because this substudy was relatively small. Yet, he notes, it is the first time scientists have seen improvements in cognitive function from a randomized trial of the Mediterranean diet.

Can Americans, whose standard diet and way of life are often substantially different from that of adults living in Spain, benefit from the approach? That remains to be seen. The normal diet of the people in the study's control group was still closer to a Mediterranean diet than that of most Americans, so they already had years of relatively healthy eating under their belts, which could have helped their overall health. But Martínez González believes that the diet might provide even greater benefits for Americans because they have so much more room for improvement. Still, nutrition expert Martha Morris of Rush University says, only a randomized trial in the U.S. can truly answer the question—something she hopes to spearhead in the coming years.

### BEYOND DIET

PROVING THAT A PARTICULAR CUISINE affects cognitive health is one thing. Getting a lot of Americans to eat more fruits, vegetables, fish and olive oil is another matter altogether. Two major obstacles are cost and ingrained habits. For PREDIMED, study participants were supplied with expensive extra virgin olive oil and told how to prepare meals. "To transfer this knowledge to the American population, you can't just show them food items," Martínez González says. "You have to show them how to shop for them, cook with them and prepare them to keep all the nutrients in line with the traditional Mediterranean diet." The first step in the right direction, he says, would be for Americans to slash their consumption of red meats and use poultry instead. But that still leaves a lot of other steps to go before they are eating a Mediterranean diet.

Adhering to the exact diet laid out in PREDIMED may not be the only way to gain cognitive benefits from food. In February, Morris and her colleagues published online a study recommending a modified diet largely consistent with the Mediterranean diet but one cheaper to adopt in the U.S. Morris's so-called MIND diet emphasizes green, leafy plant and whole grain consumption. Its staples include two veggie servings a day, two berry servings a week and, instead of the almost daily fish consumption required in the Mediterranean diet, fish only once a week.

Morris found that even moderate adherence to the MIND diet for an average of 4.5 years appeared to reduce Alzheimer's risk compared with the Mediterranean and another diet. She and her colleagues judged that outcome by counting the number of cases of clinically diagnosed Alzheimer's among each group during the study period. (The comparison diets required stricter adherence to get the same cognitive benefit.) Better yet, the MIND diet may be more achievable for the average person's wallet and for American culture. In the bigger picture, this finding suggests that "people improving their diet can make a difference for their memory," says Francine Grodstein, a professor focusing on healthy aging at Brigham and Women's Hospital in Boston and Harvard Medical School, who was not involved with the work.

Why certain food choices might help the brain function better remains unclear. Perhaps these regimens' known cardiovascular benefits, which promote a good flow of blood and oxygen to the brain, are key. But other factors may be at work. Of course, questions about when these dietary changes need to happen or how diet stacks up against other factors, such as physical activity, sleep patterns and genetics also remain unanswered.

Recently some researchers have begun broadening their focus beyond food alone. In the European Union, a multicountry randomized trial beginning this year is designed to provide further insights into how diet, exercise and better control of blood pressure could work together to promote brain health. (Hypertension is a leading cause of stroke, which can seriously harm mental processing.) Although the study will not allow scientists to pinpoint which factor offers the greatest benefit, it should give them a better understanding of how significant a role life changes can play.

There is reason to be hopeful. A pilot study published in June in the *Lancet* found that making changes in diet and habits later in life can slow the course of cognitive decline. Scandinavian researchers divided a group of 1,260 people in Finland either to receive standard nutrition and diet advice or to follow a specified exercise plan and eat a modified Mediterranean diet—all while their blood pressure and other health indicators were monitored and, if necessary, treated. Subjects in the experimental group ended up doing significantly better on standard tests of cognition. "We could really see that [the intervention] can protect against or at least delay cognitive impairments," says lead study author Miia Kivipelto, director of research and education at the geriatric clinic at the Karolinska Institute in Stockholm. Unexpectedly, she says, those changes were visible within just two years. And best of all, superpowers are not required. SA

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

# Super Siri

## A new breed of virtual assistant is almost here. And it is scary smart

**Virtual voice-controlled** assistants such as Siri, Cortana and Google Now are magical. You can say things such as “Will I need an umbrella in Dallas this weekend?” or “What flights are overhead?”—or even jokey things like “Is Santa Claus real?” Each time, you get an accurate (or witty) answer.

Behind the scenes, though, all their responses were scripted in advance by writers and programmers. (In fact, Apple employs a team of comedy writers exclusively for drafting Siri’s wisecracks.) Their underlying software is still, in essence, a passel of if/then statements.

Soon, though, your voice assistant will be much, much smarter. After leaving Apple, three of Siri’s creators—Dag Kittlaus, Adam Cheyer and Chris Brigham—started a company called Viv Labs.

Whereas a Siri or a Cortana might know how to handle requests about weather, sports and about 20 other areas, Viv’s knowledge and vocabulary will be extensible and unlimited. They will tap into the databases of thousands of online services—stores, flight-booking sites, car-sharing services, flight trackers, restaurants, florists, dating sites—and understand how everything all fits together.

“You can ask Siri, ‘Where does my sister live?’ and ‘What’s the weather in Boston?’” Cheyer explained to me, “but you can’t say, ‘What’s the weather where my sister lives?’ because that integration hasn’t been written by a human. But Viv will weave things together.”

Viv will also learn a huge portfolio about you—your preferences, credit-card numbers, addresses, and so on (with your permission, of course). As a result, Viv can answer queries such as “Book me an appointment with a French-speaking optometrist whose office is on my way home from work,” “Find me a good place to go take my kids to the Caribbean in the last week of February,” and “I want to pick up a great bottle of wine on the way to my brother’s house—something that goes well with lasagna.”

In that last example, Viv consults one Web service that knows the inventory of the wine in various stores, one that plots the route to your brother’s home and one that knows the ingredients of lasagna. And in the case of the Caribbean trip, Viv can suggest a resort package for you, which you can book on the spot—no searching required.

It would be convenient for the consumer. And a boon for Viv. Every time that you confirm one of Viv’s proposed purchases, the corresponding service (say, Uber, Hotels.com or Orbitz) will pay Viv a cut.

Will this system level the playing field for smaller companies—that Francophone optometrist—or further cement the dominance of the world’s Amazons and Ubers? Will Viv’s product selections be the final nail in the coffin of browsing and serendipity?

And just how smart will Viv be? When you book a flight, will it take into account how bad traffic will be on your way to the airport that time of day? Will it know that a layover at Chicago’s O’Hare airport during the holidays is a fate worse than death?

And what about jobs? What happens to all the travel agents, florists and sommeliers that AI assistants such as Viv will displace?

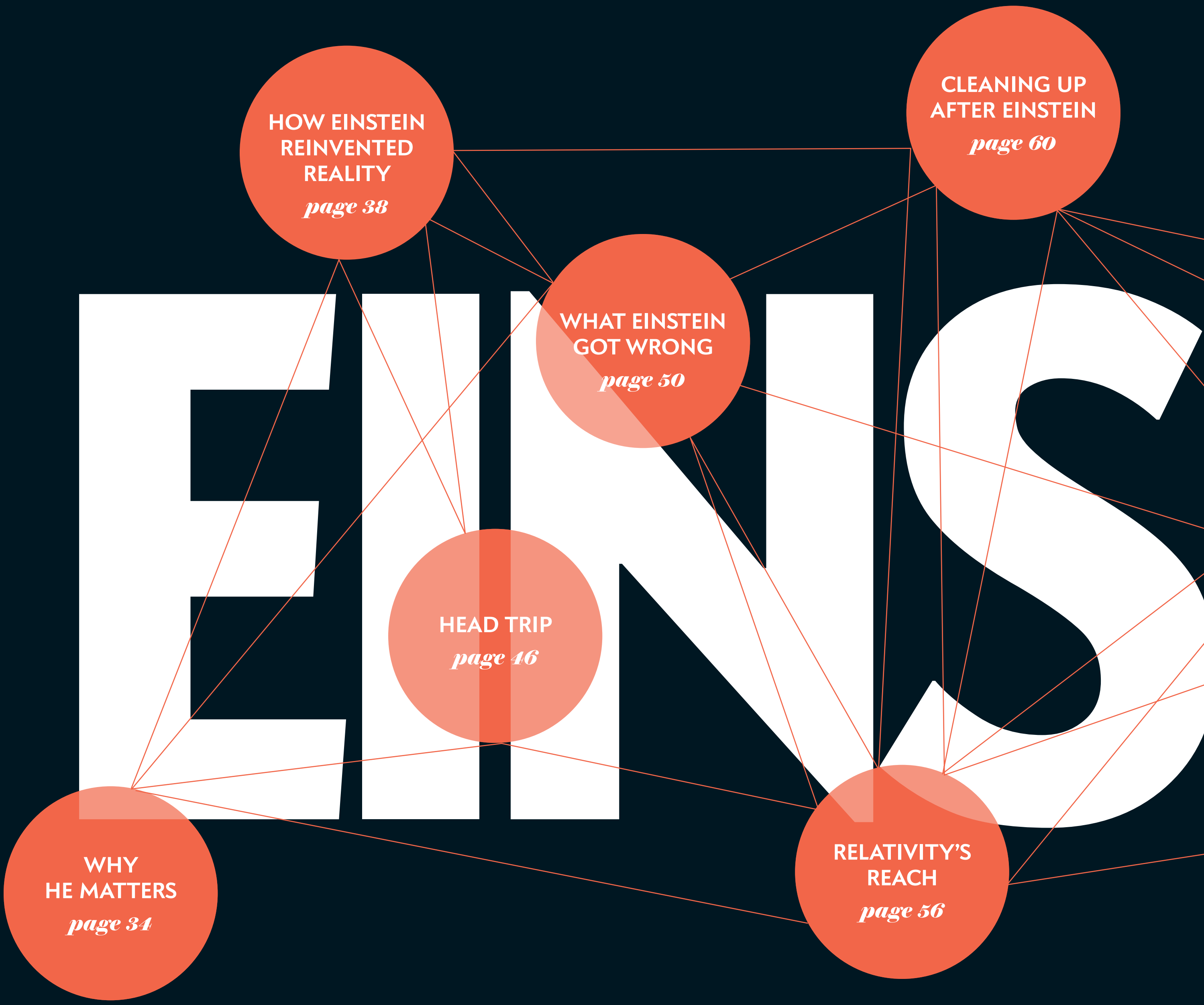
“Historically the economy adapts,” Kittlaus replies. Most of the U.S. population used to work on farms—now it’s a tiny minority. “It’s only when people’s skills can’t keep up with the rate of change that you run into trouble.”

The user interface isn’t done yet, so the company hasn’t released pictures or videos. But Viv works well, even now. Kittlaus demoed Viv with a bunch of commands (for example: “Send my mom a dozen roses” and “Book me two first-class seats on the first flight from SFO to JFK, returning Tuesday”). Each time, Viv presented a list of options, ranked by price or rating; Kittlaus could execute the transaction with one more tap.

Viv is a year away from public release. But Viv’s competitors aren’t sitting still; in the past few months Microsoft, Google and Apple all announced upgrades to the intelligence of their existing voice assistants. And SoundHound’s Hound is still in beta but already beating out the big dogs in complex voice searches and ultraspecific transaction requests. Although they don’t quite approach the sophistication and integration of Viv’s smarts, the direction these voice apps are taking is already clear: they’re growing smarter, faster and more disruptive every day.

**SCIENTIFIC AMERICAN ONLINE**
10 ways to streamline Siri commands: ScientificAmerican.com/sep2015/pogue

*Illustration by Peter and Maria Hoey*



# 100 YEARS OF GENERAL RELATIVITY

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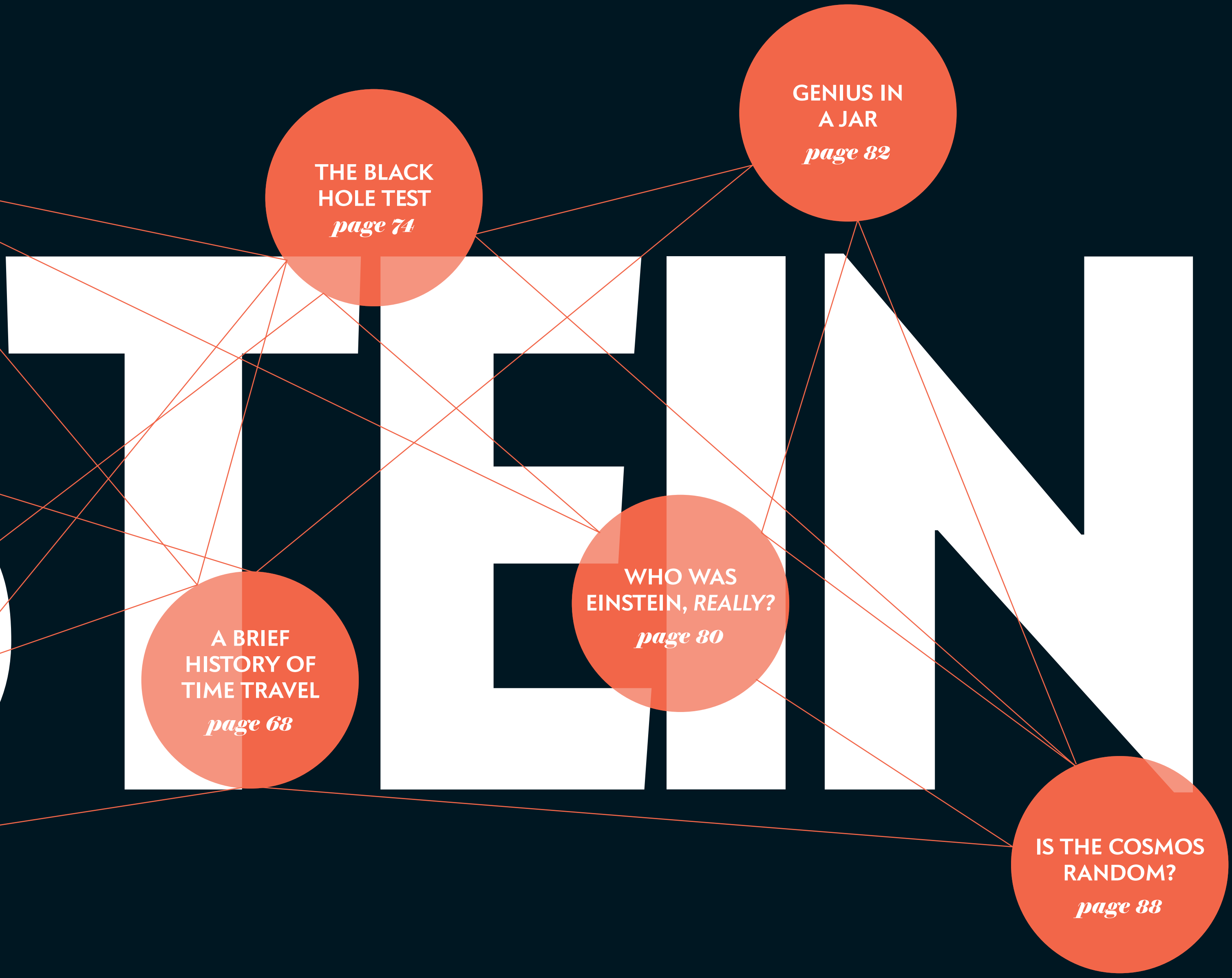
**Everyone knows what gravity is.** A baby at three months will express surprise if a box does not topple as expected; a one-year-old knows whether a precarious object will fall or not depending on its shape. Scientists came to think of gravity as a pull to Earth and later, in a more generalized way, as a force of attraction between any two masses.

Then came Albert Einstein. In 1915 he revealed in his general theory of relativity that gravity is not a force so much as the by-product of a curving universe. In other words, what we think we know about gravity from everyday experience is wrong.

The publication of "*Die Feldgleichungen der Gravitation*" ("The Field Equations of Gravitation") on December 2, 1915, at first got little notice beyond academe. A few years later a solar eclipse expedition led by Sir Arthur Eddington made an observation that vaulted the theory to fame overnight. Starlight, as Einstein predicted, appeared to bend as it passed the sun, and Eddington con-



**firmed this bending firsthand. The *New York Times* famously declared: “Men of Science More or Less Agog over Results of Eclipse Observations.”**

**They were right to be agog. It would be hard to overstate how disruptive the idea of general relativity was a century ago to prevailing notions of the universe and our physical world. All of a sudden, space and time were no longer a mere backdrop to the real action of the cosmos. Spacetime, rather, had its own geometry, and its curvature dictated the movements of the heavenly bodies and kept our feet planted firmly on the ground. Even light, the theory suggested, had to follow its contours.**

**The relativity revolution went on to shape much of the 20th century. It influenced philosophy, art, politics and pop culture. Its inventor’s name became synonymous with genius and inaugurated Einstein as the world’s greatest scientific celebrity. He used his stature to play a major role in global events—he famously advocated for the development of the atomic bomb and then spent decades bemoaning the mistake. He lobbied for the protection of the Jewish people and was an outspoken critic of racism and an activist for civil rights. Even more, the fame surrounding Einstein and his great idea marked a turning point in the public perception of science, establishing the 20th century as the scientific age and ushering in a technological transformation that we are still living through.**

**The 100th anniversary of general relativity provides an opportunity to survey the incredible pace of science and its effect on society. In the following pages we look back at what we learned from**

Einstein's achievement and forward to the secrets it may yet reveal. An illuminating graphic shows the multitude of new fields of research the theory has spawned (*page 56*). We examine the first moment of inspiration that led the genius on the path to relativity (*page 38*) and celebrate his ability to expose such truths through the power of pure thought (*page 46*). Even Einstein's mistakes often proved fruitful (*page 50*), and we see that what is commonly thought to be one of his greatest faults—his perceived intolerance of quantum mechanics—is misunderstood (*page 88*). And we explore our obsession with genius by investigating the misguided attempts to locate the source of Einstein's brilliance in his brain anatomy (*page 82*).

The passage of 100 years of general relativity is also important because of what the idea still has not done: unite with the other forces of nature to build a unified theory of everything. Einstein spent his last years questing for a deeper set of rules that would reign not just over the realm of the cosmos—general relativity's domain—but also the world inside the atom, where quantum mechanics rules. He thought this dream was in reach, but a century of toil by generations of physicists has not accomplished a single theory of nature. Relativity and quantum mechanics are just as incompatible as they ever were.

Lately scientists have begun to take a new tack, probing some of the mysteries of the universe that have popped up since Einstein's age, such as dark matter and dark energy, in hopes that these paths will eventually lead to the realization of Einstein's dream (*page 60*). Other researchers are attempting to poke holes in general relativity by testing it in the extreme realm of black holes (*page 74*). And one of relativity's weirdest consequences—the possibilities it introduces for time travel—may also offer an avenue for uncovering deeper secrets of nature (*page 68*).

Ultimately it is clear that no other scientific theory has been more important in shaping the course of 20th-century physics, and no other scientist's legacy looms larger over the 21st century than Einstein's. At this milestone anniversary, physics is waiting for the next general relativity. We could use another Einstein. —*The Editors*

ESSAY

# WHY HE MATTERS

## The fruits of one mind shaped civilization more than seems possible

*By Brian Greene*

**Albert Einstein once said** that there are only two things that might be infinite: the universe and human stupidity. And, he confessed, he wasn't sure about the universe.

When we hear that, we chuckle. Or at least we smile. We do not take offense. The reason is that the name "Einstein" conjures an image of a warm-hearted, avuncular sage of an earlier era. We see the good-natured, wild-haired scientific genius whose iconic portraits—riding a bike, sticking out his tongue, staring at us with those penetrating eyes—are emblazoned in our collective cultural memory. Einstein has come to symbolize the purity and power of intellectual exploration.

Einstein shot to fame within the scientific community in 1905, a year christened as his annus mirabilis. While working eight hours days, six days a week at the Swiss patent office in Bern, he wrote four papers in his spare time that changed the course of physics. In March of that year he argued that light, long described as a wave, is actually composed of particles, called photons, an observation that launched quantum mechanics. Two months later, in May, Einstein's calculations provided testable predictions of the atomic hypothesis, later confirmed experimentally, cinching the case that matter is made of atoms. In June he completed the special theory of relativity, revealing that space and time behave in astonishing ways no one had ever anticipated—in short, that

IN BRIEF

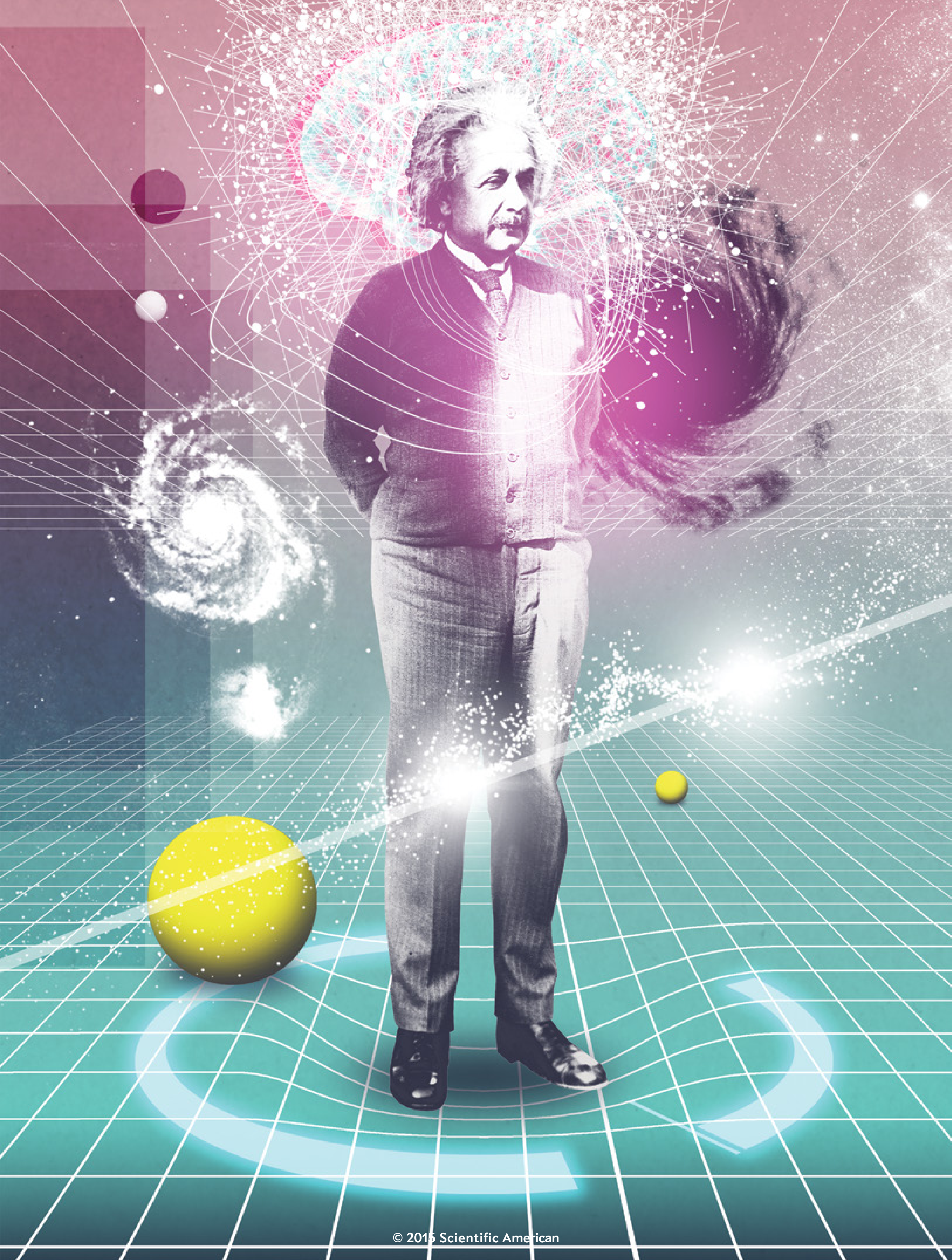
**Einstein's first major achievements** came in 1905, when he published four groundbreaking papers, including his completion of special relativity.

**Ten years later** he expanded that theory to include gravity, creating general relativity. The idea toppled Isaac Newton's physics and redefined our notion of space and time. It launched new strands of research that scientists are still pursuing and made its creator a star.

**Over the past century** Einstein's ideas have intermingled with culture and art and shaped our world in infinite, indelible ways.

GETTY IMAGES (*Einstein photograph*)

*Illustration by Mario Wagner*



distances, speeds and durations are all relative depending on the observer. And to cap it off, in September 1905 Einstein derived a consequence of special relativity, an equation that would become the world's most famous: $E = mc^2$.

Science usually progresses incrementally. Few and far between are contributions that sound the scientific alert that a radical upheaval is at hand. But here one man in one year rang the bell four times, an astonishing outpouring of creative insight. Almost immediately, the scientific establishment could sense that reverberations of Einstein's work were shifting the bedrock understanding of reality. For the wider public, however, Einstein had not yet become Einstein.

That would change on November 6, 1919.

In special relativity, Einstein established that nothing can travel faster than the speed of light. This set the stage for a confrontation with Newton's theory of gravity, in which gravity exerts its influence across space instantaneously. Driven by this looming contradiction, Einstein brazenly sought to rewrite the centuries-old rules of Newtonian gravity, a daunting task that even his ardent supporters considered quixotic. Max Planck, the dean of German science, intoned, "As an older friend, I must advise you against it.... You will not succeed, and even if you succeed, no one will believe you." Never one to yield to authority, Einstein pressed on. And on. For nearly a decade.

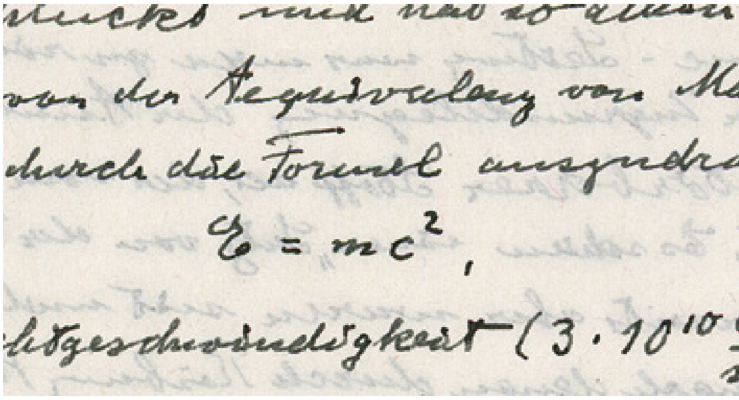
Finally, in 1915, Einstein announced his general theory of relativity, which offered a profound recasting of gravity in terms of a startling new idea: warps and curves in space and time. Instead of Earth grabbing hold of a teacup that slips from your hand and pulling it to an untimely demise on the floor, general relativity says that the planet dents the surrounding environment, causing the cup to slide along a spacetime chute that directs it to the floor. Gravity, Einstein declared, is imprinted in the geometry of the universe.

During the 100 years since Einstein proposed the theory, physicists and historians have pieced together a coherent, if complex, story of its genesis [see "How Einstein Reinvented Reality," by Walter Isaacson, on page 38]. In some of my own general-level writings, I've had the pleasure of retracing Einstein's climb, from elegant maneuvers to *pieds en canard* to his final summit. Far from demystifying Einstein's creative leaps, however, perusing his process only adds luster to the astonishing novelty and overwhelming beauty of the proposal.

On November 6, 1919, four years after Einstein completed the general theory of relativity, newspapers the world over trumpeted just released astronomical measurements establishing that the positions of stars in the heavens were slightly different than what Newton's laws would have us expect, just as Einstein had predicted. The results triumphantly confirmed Einstein's theory and rocketed him to icon status overnight. He became the man who had toppled Newton and who, in the process, had ushered our species one giant step closer to nature's eternal truths.

To top it off, Einstein made for great copy. While squinting in the limelight and paying lip service to an ardent desire for solitude, he knew how to entice the world's interest in his mysterious but momentous dominion. He would throw out clever quips ("I am a militant pacifist") and gleefully play the public part of the bemused genius of geniuses. At the premiere of *City Lights,* while the cameras on the red carpet flashed, Charlie Chaplin whispered to Einstein something along the lines of, "The people applaud me because everybody understands me, and they applaud you because no one understands you." It was a role Einstein wore well. And the wider public, weary from World War I, embraced him wholeheartedly.

**Brian Greene** is a professor of physics and mathematics at Columbia University who researches superstring theory. He is author of numerous books and co-founder and chairman of the board of the World Science Festival.



von der Aequivalenz von
durch die Formel ausgedr
$\mathcal{E} = mc^2$,
chtgeschwindigkeit $(3 \cdot 10^{10}$

**EINSTEIN'S FAMOUS EQUATION,** $E = mc^2$**, can be seen in his own handwriting from a later paper, published in 1946.**

ALBERT EINSTEIN ARCHIVES, HEBREW UNIVERSITY OF JERUSALEM

As Einstein glided through society, his ideas about relativity, at least the version broadly reported, seemed to resonate with other cultural upheavals. James Joyce and T. S. Eliot were splintering the sentence. Pablo Picasso and Marcel Duchamp were cleaving the canvas. Arnold Schoenberg and Igor Stravinsky were shattering the scale. Einstein was unshackling space and time from outmoded models of reality.

Some have gone further, portraying Einstein as the central inspiration for the avant-garde movement of the 20th century, the scientific wellspring that necessitated a cultural rethink. It's romantic to believe that nature's truths set off a tidal wave that swept away the dusty vestiges of an entrenched culture. But I've never seen convincing evidence pinning these upheavals to Einstein's science. A widespread misinterpretation of relativity—that it eliminated objective truth—is responsible for many unjustified invocations of Einstein's theories in the realm of culture. Curiously, Einstein himself had conventional tastes: he preferred Bach and Mozart to modern composers and refused a gift of new Bauhaus furniture in favor of the well-worn traditional decor he already owned.

It is fair to say that many revolutionary ideas were wafting through the early 20th century, and they surely commingled. And just as surely, Einstein was a prime example of how breaking from long-held assumptions could uncover breathtaking new landscapes.

A century later the landscapes Einstein revealed remain remarkably vibrant and fertile. General relativity gave birth in the 1920s to modern cosmology, the study of the origin and evolution of the entire universe. Russian mathematician Aleksandr Friedmann and, independently, Belgian physicist and priest Georges Lemaître used Einstein's equations to show that space should be expanding. Einstein resisted this conclusion and even modified the equations by inserting the infamous "cosmological constant" to ensure a static universe. But subsequent observations by Edwin Hubble showing that distant galaxies are all rushing away convinced Einstein to return to his original equations and accept that space is stretching. An expanding universe today means an ever smaller universe in the past, implying that the cosmos emanated from the swelling of a primordial speck, a "primeval atom" as Lemaître called it. The big bang theory was born.

In the decades since, the big bang theory has been substantially developed (today the most widely held version is inflationary theory) and, through various refinements, has aced a spectrum of observational tests. One such observation, which received the 2011 Nobel Prize in Physics, revealed that for the past seven billion years not only has space been expanding, but the rate of expansion has been speeding up. The best explanation? The big bang theory augmented by a version of Einstein's long-ago-discarded cosmological constant. The lesson? If you wait long enough, even some of Einstein's wrong ideas turn out to be right [see "What Einstein Got Wrong," by Lawrence M. Krauss, on page 50].

An even earlier insight from general relativity originated in an analysis carried out by German astronomer Karl Schwarzschild during his stint at the Russian front in the midst of World War I. Taking a break from calculating artillery trajectories, Schwarzschild derived the first exact solution of Einstein's equations, giving a precise description of the warped spacetime produced by a spherical body like the sun. As a by-product, Schwarzschild's result revealed something peculiar. Compress any object to a sufficiently small size—the sun, say, to three miles across—and the resulting spacetime warp will be so severe that anything approaching too closely, including light itself, will be trapped. In modern language, Schwarzschild had revealed the possibility of black holes.

At the time, black holes seemed far-fetched, a mathematical oddity that many expected to have no relevance to reality. But observation, not expectation, dictates what is right, and astronomical data have now established that black holes are real and plentiful. They are too far away for direct exploration at the moment, but as theoretical laboratories, black holes are indispensable. Beginning with Stephen Hawking's influential calculations in the 1970s, physicists have become increasingly convinced that the extreme nature of black holes makes them an ideal proving ground for attempts to push general relativity forward and, most notably, to meld it with quantum mechanics [see "The Black Hole Test," by Dimitrios Psaltis and Sheperd S. Doeleman, on page 74]. Indeed, one of today's most hotly debated issues concerns how quantum processes may affect our understanding of the outer edge of a black hole—its event horizon—as well as the nature of a black hole's interior.

Which is all just to say that the centenary of general relativity is a far cry from a backward glance of historical interest. Einstein's general relativity is tightly woven into the tapestry of today's leading-edge research.

> **The centenary of general relativity is a far cry from a backward glance of historical interest. Einstein's general relativity is tightly woven into the tapestry of today's leading-edge research.**

How, then, did Einstein do it? How did he contribute so much of such lasting importance? Whereas we can dismiss Einstein as the source of Cubism or atonal music, he *is* why we imagine that someone can, in the privacy of his or her own mind, think hard and reveal cosmic truths. Einstein was social as a scientist, but his big breakthroughs were solitary aha! moments. Did those insights emerge because his brain had an unusual architecture? Because of a nonconformist perspective? Because of a tenacious and uncompromising ability to focus? Maybe. Yes. Probably. The reality, of course, is that no one knows. We can tell stories of why someone may have had this or that idea, but the bottom line is that thought and insight are shaped by influences too numerous to analyze.

Eschewing hyperbole, the best we can say is that Einstein had the right mind at the right moment to crack a collection of deep problems of physics. And what a moment it was. His numerous but comparatively modest contributions in the decades after the discovery of general relativity suggest that the timeliness of the particular intellectual nexus he brought to bear on physics had passed.

With all that he accomplished, and the continuing legacy he spawned, there's an urge to ask another speculative question: Could there be another Einstein? If one means another über genius who will powerfully push science forward, then the answer is surely yes. In the past half a century since Einstein's death, there have indeed been such scientists. But if one means an über genius to whom the world will look not because of accomplishments in sports or entertainment but as a thrilling example of what the human mind can accomplish, well, that question speaks to us—to what we as a civilization will deem precious.

### MORE TO EXPLORE

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HISTORY

# HOW EINSTEIN REINVENTED REALITY

Albert Einstein created his most famous theory amid personal strife, political tension and a scientific rivalry that almost cost him the glory of his discovery

*By Walter Isaacson*

**The general theory of relativity** began with a sudden thought. It was late 1907, two years after the "miracle year" in which Albert Einstein had produced his special theory of relativity and his theory of light quanta, but he was still an examiner in the Swiss patent office. The physics world had not yet caught up with his genius. While sitting in his office in Bern, a thought "startled" him, he recalled: "If a person falls freely, he will not feel his own weight." He would later call it "the happiest thought in my life."

The tale of the falling man has become an iconic one, and in some accounts it actually involves a painter who fell from the roof of an apartment building near the patent office. Like other great tales of gravitational discovery—Galileo dropping objects from the Leaning Tower of Pisa and the apple falling on Isaac Newton's head—it was embellished in popular lore. Despite Einstein's propensity to focus on science rather than the "merely personal," even he was not likely to watch a real human plunging off a roof and think of gravitational theory, much less call it the happiest thought in his life.

Einstein soon refined his thought experiment so that the falling man was in an enclosed chamber, such as an elevator, in free fall. In the chamber, he would feel weightless. Any objects he dropped would float alongside him. There would be no way for him to tell—no experiment he could do to determine—if the chamber was falling at an accelerated rate or was floating in a gravity-free region of outer space.

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Then Einstein imagined that the man was in the same chamber way out in space, where there was no perceptible gravity, and a constant force was pulling the chamber up at an accelerated rate. He would feel his feet pressed to the floor. If he dropped an object, it would fall to the floor at an accelerated rate—just as if he stood on Earth. There was no way to make a distinction between the effects of gravity and the effects of being accelerated.

Einstein dubbed this “the equivalence principle.” The local effects of gravity and of acceleration are equivalent. Therefore, they must be manifestations of the same phenomenon, some cosmic field that accounts for both acceleration and gravity.

It would take another eight years for Einstein to turn his falling-man thought experiment into the most beautiful theory in the history of physics. He would go from his sedate life as a married father working at the Swiss patent office to living alone as a professor in Berlin, estranged from his family and increasingly alienated from his Prussian Academy of Sciences colleagues there by the rise of anti-Semitism. The decision last year by the California Institute of Technology and Princeton University to put an archive of Einstein’s papers online for free permits a glimpse of him juggling the cosmic and the personal throughout this period. We can relish his excitement in late 1907 as he scribbled down what he called “a novel consideration, based on the principle of relativity, on acceleration and gravitation.” Then we can sense his grumpy boredom, a week later, as he rejected an electric company’s patent application for an alternating-current machine, calling the claim “incorrectly, imprecisely and unclearly prepared.” The coming years would be full of human drama, as Einstein raced against a rival to give mathematical expression to relativity while struggling with his estranged wife over money and his right to visit his two young boys. But by 1915 his work climaxed in a completed theory that would change our understanding of the universe forever.

**Einstein faced two ticking clocks: he could sense that Hilbert was closing in on the correct equations, and he had agreed to give a series of four formal Thursday lectures on his theory.**

### BENDING LIGHT

FOR ALMOST FOUR YEARS after positing that gravity and acceleration were equivalent, Einstein did little with the idea. Instead he focused on quantum theory. But in 1911, when he had finally breached the walls of academia and become a professor at the German Charles-Ferdinand University in Prague, he turned his attention back to coming up with a theory of gravity that would help him generalize special relativity—the relation between space and time that he defined in 1905.

As Einstein developed his equivalence principle, he realized that it had some surprising ramifications. For example, his chamber thought experiment indicated that gravity would bend light. Imagine that the chamber is being accelerated upward. A light beam comes in through a pinhole on one wall. By the time it reaches the opposite wall, the light is a little closer to the floor because the chamber has shot upward. And if you could plot the beam’s trajectory across the chamber, it would be curved because of the upward acceleration. The equivalence principle says that this effect should be the same whether the chamber is accelerating upward or is resting still in a gravitational field. In other words, light should bend when passing through a gravitational field.

In 1912 Einstein asked an old classmate to help him with the complicated mathematics that might describe a curved and warped four-dimensional spacetime. Until then, his success had been based on his talent for sniffing out the underlying physical principles of nature. He had left to others the task of finding the best mathematical expressions of those principles. But now Einstein realized that math could be a tool for discovering—and not merely describing—nature’s laws.

Einstein’s goal as he pursued his general theory of relativity was to find the mathematical equations describing two interwoven processes: how a gravitational field acts on matter, telling it how to move, and how matter generates gravitational fields in spacetime, telling spacetime how to curve.

For three more years Einstein wrestled with drafts and outlines that turned out to have flaws. Then, beginning in the summer of 1915, the math and the physics began to come together.

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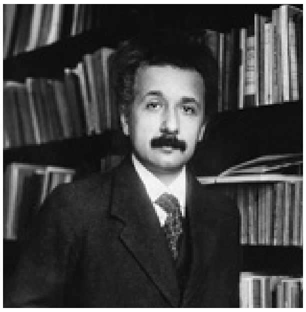
IN BRIEF

**Einstein’s realization** that gravity and acceleration are equivalent put him on an eight-year path to generalize his special theory of relativity.

**He raced to discover** the correct mathematical formulas for his theory before a rival, mathematician David Hilbert, could do so first. Einstein simultaneously struggled on the home front, as he went through a divorce from his first wife and a separation from his sons while he courted a cousin whom he would later marry.

**Despite these challenges,** Einstein triumphed and delivered one of the world’s supreme scientific works in his general theory of relativity.



# Road to Relativity

Einstein faced difficulties, both scientific and personal, while formulating general relativity

**1907**
Einstein realizes that a person falling freely would not feel his weight—an insight that set him on the path to general relativity

**1911**
Now a professor at the German Charles-Ferdinand University in Prague, Einstein starts working to expand his special theory of relativity to include gravity

**1912**
The physicist begins an affair with his cousin, Elsa Löwenthal, whom he later marries

**1914**
Einstein and his first wife, Mileva Marić, separate. She moves from Berlin, where they had been living, to Zurich with their two sons

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## PERSONAL UNRAVELING

BY THEN, HE HAD MOVED TO BERLIN to become a professor and member of the Prussian Academy. But he found himself working pretty much without support. Anti-Semitism was rising, and he formed no coterie of colleagues around him. He split with his wife, Mileva Marić, a fellow physicist who had been his sounding board in formulating special relativity in 1905, and she moved back to Zurich with their two sons, ages 10 and four. He was having an affair with his cousin Elsa, whom he would later marry, but he lived by himself in a sparsely furnished apartment in central Berlin, where he ate intermittently, slept randomly, played his violin and waged his solitary struggle.

Throughout 1915 his personal life began to unravel. Some friends were pressing him to get a divorce and marry Elsa; others were warning that he should not be seen with her or let her come near his two boys. Marić repeatedly sent letters requesting money, and at one point Einstein replied with unbridled bitterness. "I find such a demand beyond discussion," he responded. "I find your constant attempts to lay hold of everything that is in my possession absolutely disgraceful." He tried hard to maintain a correspondence with his sons, but they rarely wrote back, and he accused Marić of not delivering his letters to them.

Yet amid this personal turmoil, Einstein was able to devise, by late June 1915, many elements of general relativity. He gave a weeklong series of lectures at the end of that month on his evolving ideas at the University of Göttingen in Germany, the world's preeminent center for mathematics. Foremost among the geniuses there was David Hilbert, and Einstein was particularly eager—perhaps too eager, it would turn out—to explain all the intricacies of relativity to him.

## A RIVALRY

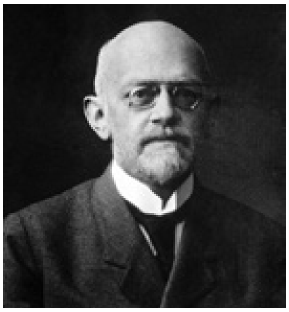
THE VISIT TO GÖTTINGEN WAS A TRIUMPH. A few weeks later Einstein reported to a scientist friend that he "was able to convince Hilbert of the general theory of relativity." In a letter to another colleague, he was even more effusive: "I am quite enchanted with Hilbert!"

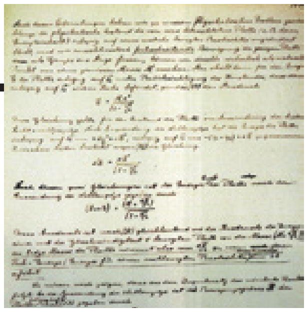
Hilbert was likewise enchanted with Einstein and with his theory, so much so that he soon set out to see if he could do what Einstein had so far not accomplished: produce the mathematical equations that would complete the formulation of general relativity.

Einstein began hearing Hilbert's footsteps in early October 1915, just as he realized that his current version of the theory—which was based on an *Entwurf,* or outline, he had been refining for two years—had serious flaws. His equations did not account properly for rotating motion. In addition, he realized that his equations were not generally covariant, meaning that they did not really make all forms of accelerated and nonuniform motion relative, nor did they fully explain an anomaly that astronomers had observed in the orbit of the planet Mercury. Mercury's perihelion—its point of closest approach to the sun—had been gradually shifting in a way not accounted for by Newtonian physics or by Einstein's then current version of his own theory.

Einstein faced two ticking clocks: he could sense that Hilbert was closing in on the correct equations, and he had agreed to give a series of four formal Thursday lectures on his theory in November to the members of the Prussian Academy. The result was an exhausting monthlong whirlwind during which Einstein wrestled with a succession of equations, corrections and updates that he rushed to complete.

**JUNE 1915**
Mathematician David Hilbert attends a lecture where Einstein describes his ideas about general relativity. Hilbert begins to race Einstein to devise the mathematics of the theory





**NOVEMBER 1915**
During his fourth lecture that month at the Prussian State Library, Einstein finally delivers a paper reporting his field equations for general relativity

**SUMMER AND FALL OF 1915**
Einstein lives alone, eats and sleeps intermittently, and consoles himself with his violin while he struggles to produce equations to formalize general relativity

Even as he arrived at the grand hall of the Prussian State Library on November 4 to deliver the first of his lectures, Einstein was still wrestling with his theory. "For the last four years," he began, "I have tried to establish a general theory of relativity." With great candor, he detailed the problems he had encountered and admitted that he still had not come up with equations that fully worked.

Einstein was in the throes of the one of the most concentrated frenzies of scientific creativity in history. At the same time, he was dealing with personal crises within his family. Letters continued to arrive from his estranged wife that pressed him for money and discussed the guidelines for his contact with their two sons. Through a mutual friend, she demanded that he not ask that his children come visit him in Berlin where they might discover his affair. Einstein assured the friend that in Berlin he was living alone and that his "desolate" apartment had "an almost churchlike atmosphere." The friend replied, referring to Einstein's work on general relativity, "Justifiably so, for unusual divine powers are at work in there."

On the very day that he presented his first paper, he wrote a painfully poignant letter to his elder son, Hans Albert, who was living in Switzerland:

> *Yesterday I received your dear little letter and was delighted with it. I was already afraid you didn't want to write me at all anymore.… I shall press for our being together for a month every year so that you see that you have a father who is attached to you and loves you. You can learn a lot of fine and good things from me as well that no one else can offer you so easily.… In the last few days I completed one of the finest papers of my life; when you are older, I will tell you about it.*

He ended with a small apology for seeming so distracted. "I am often so engrossed in my work that I forget to eat lunch," he wrote.

Einstein also engaged in an awkward interaction with Hilbert. He had been informed that the Göttingen mathematician had spotted the flaws in the *Entwurf* equations. Worried about being scooped, he wrote Hilbert a letter saying that he himself had discovered the flaws, and he sent along a copy of his November 4 lecture.

In his second lecture, delivered on November 11, Einstein imposed new coordinate conditions that allowed his equations to be generally covariant. As it turned out, the change did not greatly improve matters. He was close to the final answer but making little headway. Once again, he sent his paper off to Hilbert and asked him how his own quest was going. "My own curiosity is interfering with my work!" he wrote.

Hilbert sent him a reply that must have unnerved Einstein.

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He said he had a “solution to your great problem,” and he invited Einstein to come to Göttingen on November 16 and have the dubious pleasure of hearing it. “Since you are so interested, I would like to lay out my theory in very complete detail this coming Tuesday,” Hilbert wrote. “My wife and I would be very pleased if you stayed with us.” Then, after signing his name, Hilbert felt compelled to add a tantalizing and disconcerting postscript. “As far as I understand your new paper, the solution given by you is entirely different from mine.”

### COMING TO A HEAD

EINSTEIN WROTE FOUR LETTERS on November 15, a Monday, that give a glimpse into his intertwined personal and professional dramas. To Hans Albert, he suggested that he would like to travel to Switzerland at Christmas to visit him. “Maybe it would be better if we were alone somewhere,” such as at a secluded inn, he said to his son. “What do you think?”

He then wrote his estranged wife a conciliatory letter that thanked her for her willingness not “to undermine my relations with the boys.” And he reported to a friend, “I have modified the theory of gravity, having realized that my earlier proofs had a gap.... I shall be glad to come to Switzerland at the turn of the year to see my dear boy.”

He also replied to Hilbert and declined his invitation to visit Göttingen the next day. His letter did not hide his anxiety: “The hints you gave in your messages awaken the greatest of expectations. Nevertheless, I must refrain from traveling to Göttingen.... I am tired out and plagued by stomach pains.... If possible, please send me a correction proof of your study to mitigate my impatience.”

Einstein was in the throes of the one of the most concentrated frenzies of scientific creativity in history. At the same time, he was dealing with personal crises within his family.

As he hurriedly rushed to come up with the precise formulation of his theory, Einstein made a breakthrough that turned his anxiety into elation. He tested a set of revised equations to see if they would yield the correct results for the anomalous shift in Mercury’s orbit. The answer came out right: his equations predicted the perihelion should drift by about 43 arc seconds per century. He was so thrilled that he had heart palpitations. “I was beside myself with joy and excitement for days,” he told a colleague. To another physicist, he exulted, “The results of Mercury’s perihelion movement fill me with great satisfaction. How helpful to us is astronomy’s pedantic accuracy, which I used to secretly ridicule!”

The morning of his third lecture, November 18, Einstein received Hilbert’s new paper and was dismayed by how similar it was to his own work. His response to Hilbert was terse and clearly designed to assert priority. “The system you furnish agrees—as far as I can see—exactly with what I found in the last few weeks and have presented to the Academy,” he wrote. “Today I am presenting to the Academy a paper in which I derive quantitatively out of general relativity, without any guiding hypothesis, the perihelion motion of Mercury. No gravitational theory has achieved this until now.”

Hilbert responded kindly and generously the following day, claiming no priority for himself. “Cordial congratulations on conquering perihelion motion,” he wrote. “If I could calculate as rapidly as you, in my equations the electron would have to capitulate, and the hydrogen atom would have to produce its note of apology about why it does not radiate.” The next day, however, Hilbert sent a paper to a Göttingen science journal describing his own version of the equations for general relativity. The title he picked for his piece was not a modest one: “The Foundations of Physics,” he called it.

It is not clear how carefully Einstein read Hilbert’s paper or if it affected his thinking as he prepared his climactic fourth lecture at the Prussian Academy. Regardless, he produced in time for his final lecture on November 25—entitled “The Field Equations of Gravitation”—a set of covariant equations that described a general theory of relativity.

It was not nearly as vivid to the layperson as, say, $E = mc^2$. Yet using the condensed notations of tensors, in which sprawling mathematical complexities can be compressed into little subscripts, the crux of the final Einstein field equation is compact enough to be emblazoned on T-shirts worn by physics geeks. In one of its many variations, it can be written as:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu}R = -8 \pi G T_{\mu\nu}$$

The left side of the equation—which is now known as the Einstein tensor and can be written simply as $G_{\mu\nu}$—describes how the geometry of spacetime is warped and curved by massive objects. The right side describes the movement of matter in the gravitational field. The interplay between the two sides shows how objects curve spacetime and how, in turn, this curvature affects the motion of objects.

Both at the time and to this day, there has been a priority dispute over which elements of the mathematical equations of general relativity were discovered first by Hilbert rather than by Einstein. Whatever the case, it was Einstein’s theory that was being formalized by these equations, one that he had explained to Hilbert during their time together in Göttingen that summer of 1915. Hilbert graciously noted this in the final version of his paper: “The differential equations of gravitation that result are, as it seems to me, in agreement with the magnificent theory of general relativity established by Einstein.” As he later summed it up, “Einstein did the work and not the mathematicians.”

Within a few weeks Einstein and Hilbert were repairing their relationship. Hilbert proposed Einstein for membership in the Royal Society of Sciences in Göttingen, and Einstein wrote back with an amiable letter saying how two men who had glimpsed transcendent theories should not be diminished by earthly emotions. “There has been a certain ill-feeling between us, the cause of which I do not want to analyze,” Einstein wrote. “I have struggled against the feeling of bitterness attached to it, and this with complete success. I think of you again with unmixed geniality and ask you to try to do the same with me. Objectively it is a shame when two real fellows who have extricated themselves from this shabby world do not afford each other mutual pleasure.”

### “THE BOLDEST DREAMS”

EINSTEIN’S PRIDE WAS UNDERSTANDABLE. At age 36, he had produced a dramatic revision of our concept of the universe. His general theory of relativity was not merely the interpretation of some experimental data or the discovery of a more accurate set of laws. It was a whole new way of regarding reality.

With his special theory of relativity, Einstein had shown that space and time did not have independent existences but instead formed a fabric of spacetime. Now, with his general version of the theory, this fabric of spacetime became not merely a container for objects and events. Instead it had its own dynamics that were determined by, and in turn helped to determine, the motion of objects within it—like the way that the fabric of a trampoline will curve as a bowling ball and some billiard balls roll across it and in turn that the dynamic curving of the trampoline fabric will determine the path of the rolling balls and cause the billiard balls to move toward the bowling ball.

The curving and rippling fabric of spacetime explained gravity, its equivalence to acceleration and the general relativity of all forms of motion. In the opinion of Paul Dirac, the Nobel laureate pioneer of quantum mechanics, it was “probably the greatest scientific discovery ever made.” And Max Born, another giant of 20th-century physics, called it “the greatest feat of human thinking about nature, the most amazing combination of philosophical penetration, physical intuition and mathematical skill.”

The entire process had exhausted Einstein. His marriage had collapsed, and war was ravaging Europe. But he was as happy as he would ever be. “The boldest dreams have now been fulfilled,” he exulted to his best friend, engineer Michele Besso. “*General* covariance. Mercury’s perihelion motion wonderfully precise.” He signed himself “contented but quite worn-out.”

Years later, when his younger son, Eduard, asked why he was so famous, Einstein replied by using a simple image to describe his fundamental insight that gravity was the curving of the fabric of spacetime. “When a blind beetle crawls over the surface of a curved branch, it doesn’t notice that the track it has covered is indeed curved,” he said. “I was lucky enough to notice what the beetle didn’t notice.”

#### MORE TO EXPLORE

**The Field Equations of Gravitation.** A. Einstein in *Preussische Akademie der Wissenschaften, Sitzungsberichte,* pages 844–847; December 2, 1915.

**Einstein: His Life and Universe.** Walter Isaacson. Simon & Schuster, 2007.

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scientificamerican.com/magazine/sa

THE BASICS

## Relativity Primer

**General relativity redefined** the concept of gravity—rather than a force pulling masses together, the theory exposed it as a simple consequence of the geometry of space and time. The notion grew out of a revelation from the more limited special theory of relativity, which Albert Einstein conceived 10 years earlier. This theory established space and time as a single entity, spacetime (*below*). In his general theory of relativity, Einstein described what happens when mass is present in spacetime (*top right*), causing it to curve and forcing objects traveling through it to follow a bent path. If enough mass is packed into a very small region, spacetime becomes infinitely curved, creating a black hole (*bottom right*).

### Spacetime without Mass

The special theory of relativity first established that the universe as we know it has four dimensions—three of space and one of time. In the absence of mass, spacetime is essentially a grid, and the shortest path for an object to travel through it is a straight line. Because we cannot portray four dimensions on this two-dimensional page, we show a simplified diagram of the three spatial dimensions with the position of an object at various times standing in for the missing fourth dimension.

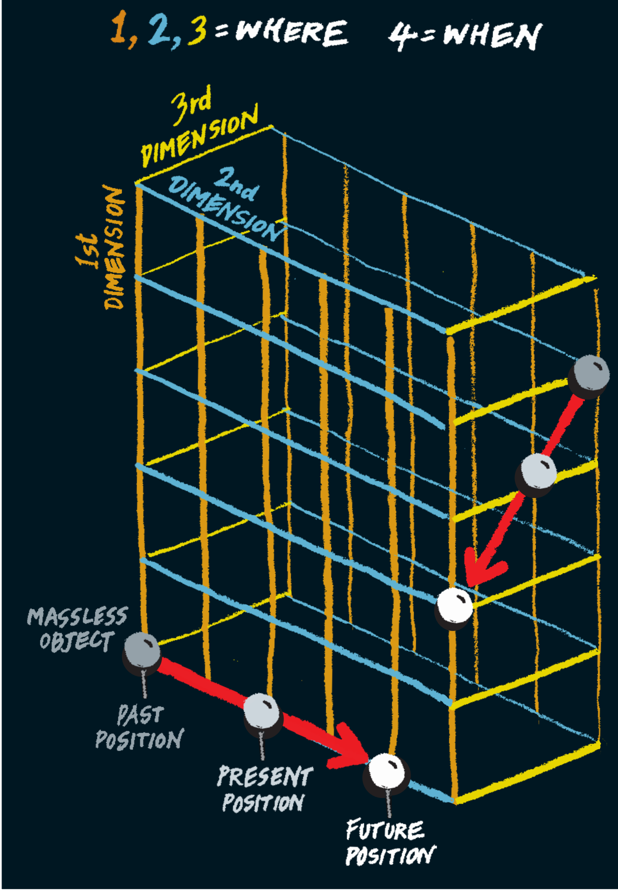
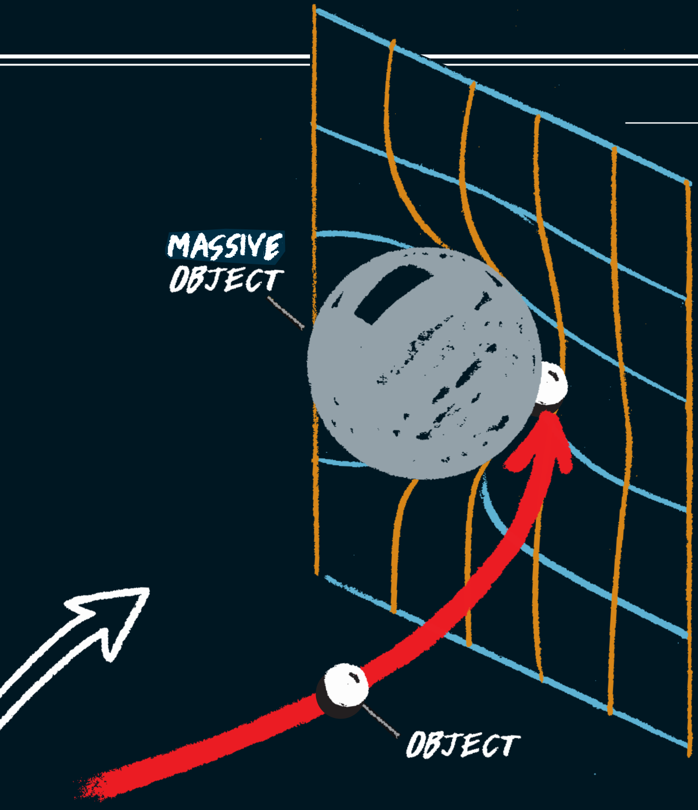
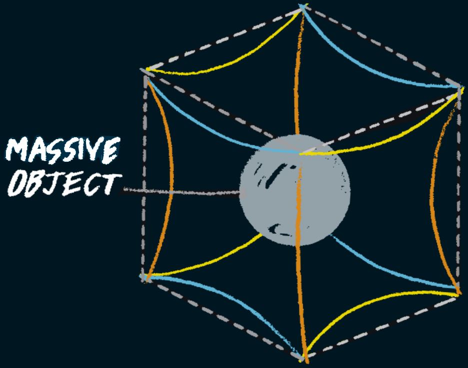


Illustration by Nigel Holmes



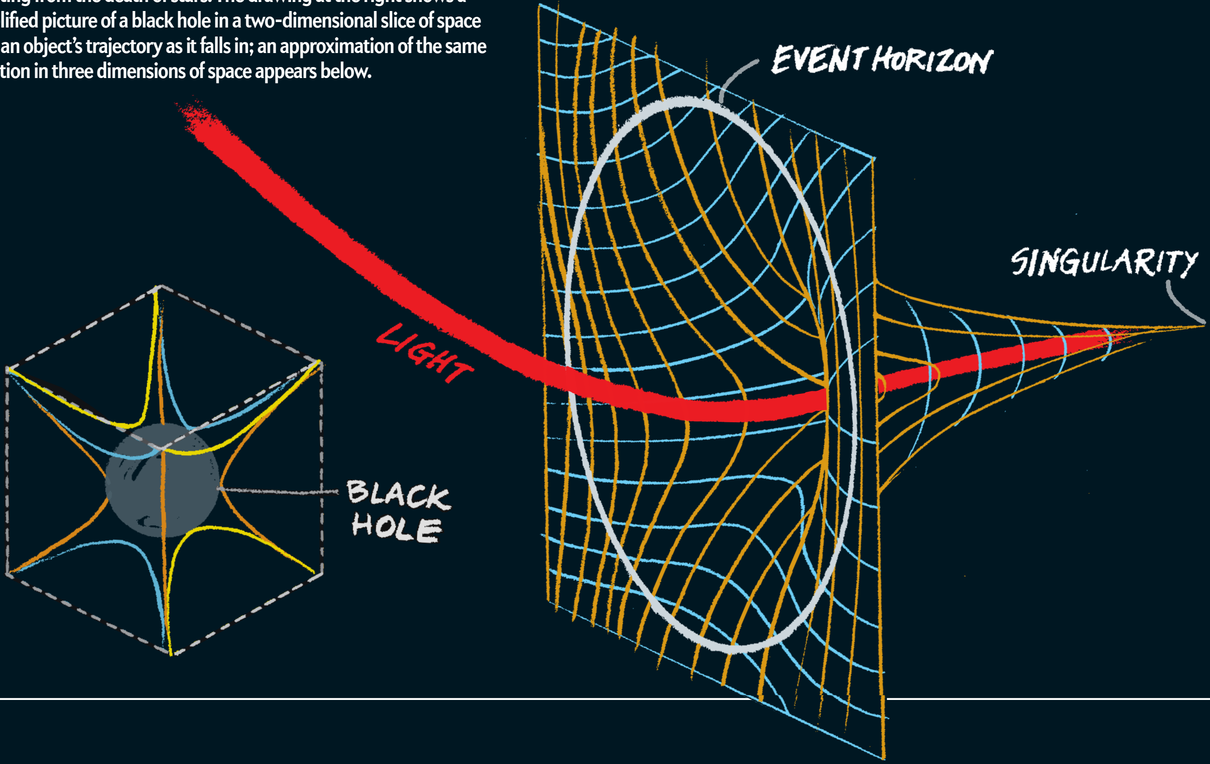
## Spacetime with Mass

When mass—be it a star, a planet or a human being—is present, spacetime bends around it so that an object traveling nearby must follow a rounded trajectory that takes it closer to the mass. Just as it is impossible to move in a straight line on the surface of a sphere, it is likewise impossible to move in a straight line through curved spacetime. This effect produces gravity, which we observe as an attraction between two masses. On the left is a simplified two-dimensional diagram of spacetime curvature, and below is an approximation of the same situation in three dimensions.



## Spacetime with Extreme Mass

One of the most startling consequences of general relativity is the idea of black holes. These occur when mass is dense enough to form a so-called singularity—a point where spacetime is infinitely curved. The black hole defines the region around the singularity where gravity is so strong that nothing that enters can exit again. Physicists now think that black holes are ubiquitous in the universe, often resulting from the death of stars. The drawing at the right shows a simplified picture of a black hole in a two-dimensional slice of space with an object's trajectory as it falls in; an approximation of the same situation in three dimensions of space appears below.



THOUGHT EXPERIMENTS

# HEAD TRIP

## Einstein's thought experiments left a long and somewhat mixed legacy of their own

*By Sabine Hossenfelder*

***Gedankenexperiment,*** German for "thought experiment," was Albert Einstein's famous name for the imaginings that led to his greatest breakthroughs in physics. He traced his realization of light's finite speed—the core idea of special relativity—to his teenage daydreams about riding beams of light. General relativity, his monumental theory of gravitation, has its origins in his musings about riding up and down in an elevator. In both cases, Einstein crafted new theories about the natural world by using his mind's eye to push beyond the limitations of laboratory measurements.

Einstein was neither the first nor the last theorist to do this, but his remarkable achievements were pivotal in establishing the gedankenexperiment as a cornerstone of modern theoretical physics. Today physicists regularly use thought experiments to craft new theories and to seek out inconsistencies or novel effects within existing ones.

But the modern embrace of thought experiments raises some uncomfortable questions. In the search for a grand unified theory that would wed the small-scale world of quantum mechanics with Einstein's relativistic description of the universe at large, the most popular current ideas are bereft of observational support from actual experiments. Can thought alone sustain them? How far can we trust logical deduction? Where is the line between scientific intuition and fantasy? Einstein's legacy offers no certain answers: On one hand, his reliance on the power of thought was a spectacular success. On the other, many of his best known thought experiments were based on data from real experimentation, such as the classic Michelson-Morley experiment that first measured the constancy of the speed of light. Moreover, Einstein's fixation on that which can be measured at times blinded him to deeper layers of reality—although even his mistakes in thought experiments contributed to later breakthroughs.

Here we will walk through some of Einstein's most iconic thought experiments, highlighting how they succeeded, where they failed and how they remain vital to questions now at the frontiers of theoretical physics.

### THE WINDOWLESS ELEVATOR

IN HIS THOUGHT EXPERIMENTS, Einstein's genius was in realizing which aspects of experience were essential and

*Illustration by Sam Falconer*

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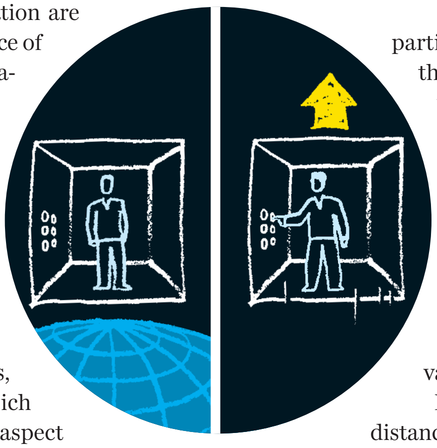
which could be discarded. Consider his most famous one: the elevator thought experiment, which he began devising in 1907. Einstein argued that inside a windowless elevator, a person cannot tell whether the elevator is at rest in a gravitational field or is instead being hauled up with constant acceleration. He then conjectured that the laws of physics themselves must be identical in both situations. According to this "principle of equivalence," locally (in the elevator), the effects of gravitation are the same as that of acceleration in the absence of gravity. Converted into mathematical equations, this principle became the basis for general relativity. In other words, the elevator thought experiment motivated Einstein to make the daring intellectual leap that ultimately led to his greatest achievement, his geometric description of gravity.



## SPOOKY ACTION

LATER IN HIS CAREER, Einstein fought hard against the tenets of quantum mechanics, particularly the uncertainty principle, which dictates that the more you know about one aspect of a fundamental particle, such as its position, the less you can know about another related aspect of that particle, such as its momentum—and vice versa. Einstein thought that the uncertainty principle was a sign that quantum theory was deeply flawed.

During a years-long exchange with Danish quantum theorist Niels Bohr, Einstein conceived of a series of thought experiments meant to demonstrate that it is possible to violate the uncertainty principle, but Bohr dissected every one of them. This exchange bolstered Bohr's conviction that quantum uncertainty was a fundamental aspect of nature. If not even the great Einstein could devise a way to precisely measure both the position and the momentum of a particle, then certainly there must be something to the uncertainty principle!

In 1935, along with his colleagues Boris Podolsky and Nathan Rosen, Einstein published what was meant to be his most potent critique of the uncertainty principle. Perhaps because Podolsky, not Einstein, drafted the actual text of the paper, this Einstein-Podolsky-Rosen (EPR) thought experiment was presented not as an easy-to-imagine scenario of boxes, clocks and light beams but as an abstract series of equations describing interactions between two generalized quantum systems.

The simplest version of the EPR experiment studies the paradoxical behavior of "entangled" particles—pairs of particles that share a common quantum state. It unfolds as follows: imagine an unstable particle with a spin of zero decaying into two daughter particles, which speed off in opposite directions. (Spin is a measure of a particle's angular momentum, but counterintuitively, it has little to do with a particle's rate of rotation.) Conservation laws dictate that the spins of those two daughter particles must add up to zero; one particle, then, could possess a spin value of "up," and the other could have a spin value of "down." The laws of quantum mechanics dictate that in the absence of measurement, neither of the particles possesses a definite spin until one of the two speeding entangled particles is measured. Once a measurement of one particle is made, the state of the other changes *instantaneously,* even if the particles are separated by vast distances!

Einstein believed this "spooky action at a distance" was nonsense. His own special theory of relativity held that nothing could travel faster than light, so there was no way for two particles to communicate with each other instantaneously from opposite sides of the universe. He suggested instead that the measurement outcomes must be determined prior to measurement by "hidden variables" that quantum mechanics failed to account for. Decades of discussion followed until 1964, when physicist John Stewart Bell developed a theorem quantifying exactly how the information shared between entangled particles differs from the information that Einstein postulated would be shared through hidden variables.

Since the 1970s lab experiments with entangled quantum systems have repeatedly confirmed that Einstein was wrong, that quantum particles indeed share mutual information that cannot be accounted for by hidden variables. Spooky action at a distance is real, but experiments have demonstrated that it cannot be used to transmit information faster than light, making it perfectly consistent with Einstein's special relativity. This counterintuitive truth remains one of the most mysterious conundrums in all of physics, and it was Einstein's stubborn, mistaken opposition that proved crucial to confirming it.

## ALICE AND BOB

TODAY SOME OF THE MOST SIGNIFICANT thought experiments in physics explore how to reconcile Einstein's clockwork, relativistic universe with the fuzzy uncertainties inherent to quantum particles.

Consider, for instance, the widely discussed black hole information paradox. If you combine general relativity and quantum field theory, then you find that black holes evaporate, slowly radiating away their mass because of quantum effects. You also find that this process is not reversible: regardless of what

### IN BRIEF

**One of Einstein's enduring** contributions to physics was his use of *gedankenexperiments,* or thought experiments.

**His intuition about falling elevators,** for example, led to his greatest achievement, the general theory of relativity.

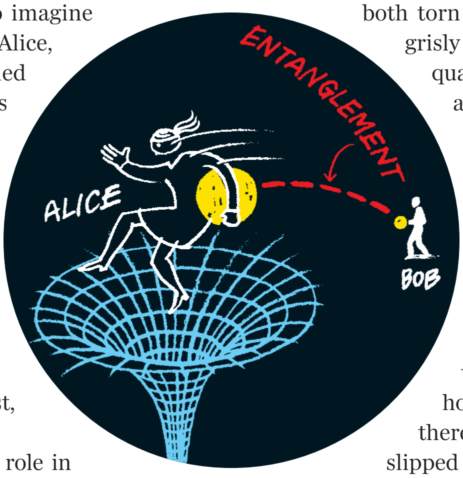
**Today some of the most important** questions in theoretical physics involve thought experiments about black holes.

**Yet there is a problem:** these thought experiments may be so far removed from empirical data as to be untestable.

*Illustrations by Nigel Holmes*

formed the black hole, the evaporating black hole always produces the same featureless bath of radiation from which no information about its contents can be retrieved. But such a process is prohibited in quantum theory, which states that any occurrence can, in principle, be reversed in time. For instance, according to the laws of quantum mechanics, the leftovers of a burned book still contain all the information necessary to reassemble that book even though this information is not easily accessible. Not so for evaporating black holes. And so we arrive at a paradox, a logical inconsistency. A union of quantum mechanics and general relativity tells us that black holes must evaporate, but we conclude that the result is incompatible with quantum mechanics. We must be making some mistake—but where?

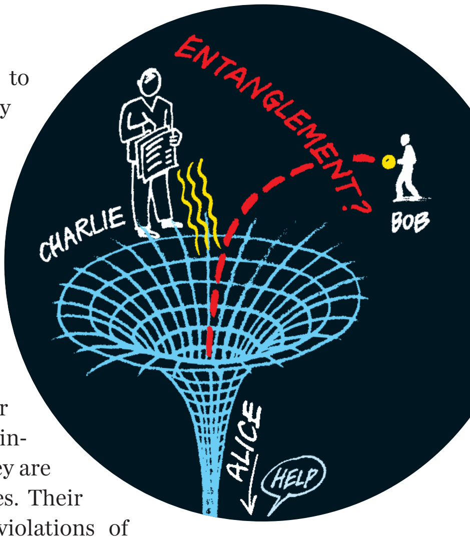
The thought experiments created to explore this paradox typically ask us to imagine a pair of observers, Bob and Alice, who share a pair of entangled particles—those spooky entities from the EPR experiment. Alice jumps into the black hole, carrying her particle with her, whereas Bob stays outside and far away with his. Without Alice, Bob's particle is just typical, with a spin that might measure up or down—the information that it once shared with its entangled partner is lost, along with Alice.



Bob and Alice play a central role in one of the most popular proposed solutions to the paradox, called black hole complementarity. Proposed in 1993 by Leonard Susskind, Lárus Thorlacius and John Uglum, all then at Stanford University, black hole complementarity rests on Einstein's golden rule for a gedankenexperiment: a strict focus on that which can be measured. Susskind and his colleagues postulated that the information falling in with Alice must come out later with the evaporating black hole's radiation. This scenario would usually create another inconsistency because quantum mechanics allows only pair-wise entanglement with one partner at a time, a property called monogamy of entanglement. That is, if Bob's particle is entangled with Alice's, it cannot be entangled with anything else. But black hole complementarity requires that Bob's particle be entangled with Alice's *and* with the radiation the black hole later emits even though this violates monogamy. At first sight, then, black hole complementarity seems to exchange one inconsistency with another.

But like a perfect crime, if no one actually *witnesses* this inconsistency, perhaps it can subvert nature's otherwise strict laws. Black hole complementarity relies on the argument that it is physically impossible for any observer to see Alice and Bob's entangled particles breaking the rules.

To envision how this perfect quantum-mechanical crime could unfold, imagine a third observer, Charlie, hovering near the black hole, keeping an eye on Alice and Bob. He watches as Bob stays outside and as Alice falls in, measuring the black hole's emitted radiation all the while. In theory, information encoded in that radiation could tip off Charlie that Bob and Alice had violated the monogamy of their entanglement. To know for certain, however, Charlie would have to compare his observations not only with Bob's measurement but also with Alice's—*inside* the black hole. So he must hover at the horizon, measure the emitted radiation, then jump in to tell Alice what he has found. Amazingly enough, Susskind and Thorlacius showed that no matter how hard Charlie tries, it is impossible for him to enter the black hole and compare his information with Alice's before they are both torn apart by tidal forces. Their grisly fate suggests no violations of quantum mechanics can ever be measured by anybody around a black hole, and so theorists can commit this crime against nature with impunity.



Suffice it to say, not all theorists are convinced that this argument is valid. One criticism of black hole complementarity is that it might violate Einstein's equivalence principle—the one that grew out of his elevator thought experiment. Einstein's general relativity predicts that just as the elevator's passenger cannot distinguish between gravity and acceleration, an observer crossing a black hole's horizon should not notice anything unusual; there is no way an observer can tell that he or she has slipped past the point of no return.

Now let us return to the entanglement of Alice and Bob. If the radiation that Bob sees from far outside the hole contains all the information that we thought vanished with Alice behind the horizon, then this radiation must have been emitted with an extremely high energy; otherwise, it would not have escaped the strong gravitational pull near the horizon. This energy is high enough to vaporize any infalling observer before he or she slips past the black hole's horizon. In other words, black hole complementarity implies that black holes have a "firewall" just outside the horizon—and yet the firewall directly contradicts the predictions of Einstein's equivalence principle.

At this point, we have ventured deep into the realm of theory. Indeed, we might never know the solutions to these puzzles. But because those solutions could lead to an understanding of the quantum nature of space and time, these puzzles are, for better or worse, some of the most vibrant areas of research in theoretical physics. And it all goes back to Einstein's musings about falling elevators.

### MORE TO EXPLORE

**Einstein's Dice and Schrödinger's Cat: How Two Great Minds Battled Quantum Randomness to Create a Unified Theory of Physics.** Paul Halpern. Basic Books, 2015.

### FROM OUR ARCHIVES

**Black Holes and the Information Paradox.** Leonard Susskind; April 1997.
**A Quantum Threat to Special Relativity.** David Z Albert and Rivka Galchen; March 2009.
**Burning Rings of Fire.** Joseph Polchinski; April 2015.

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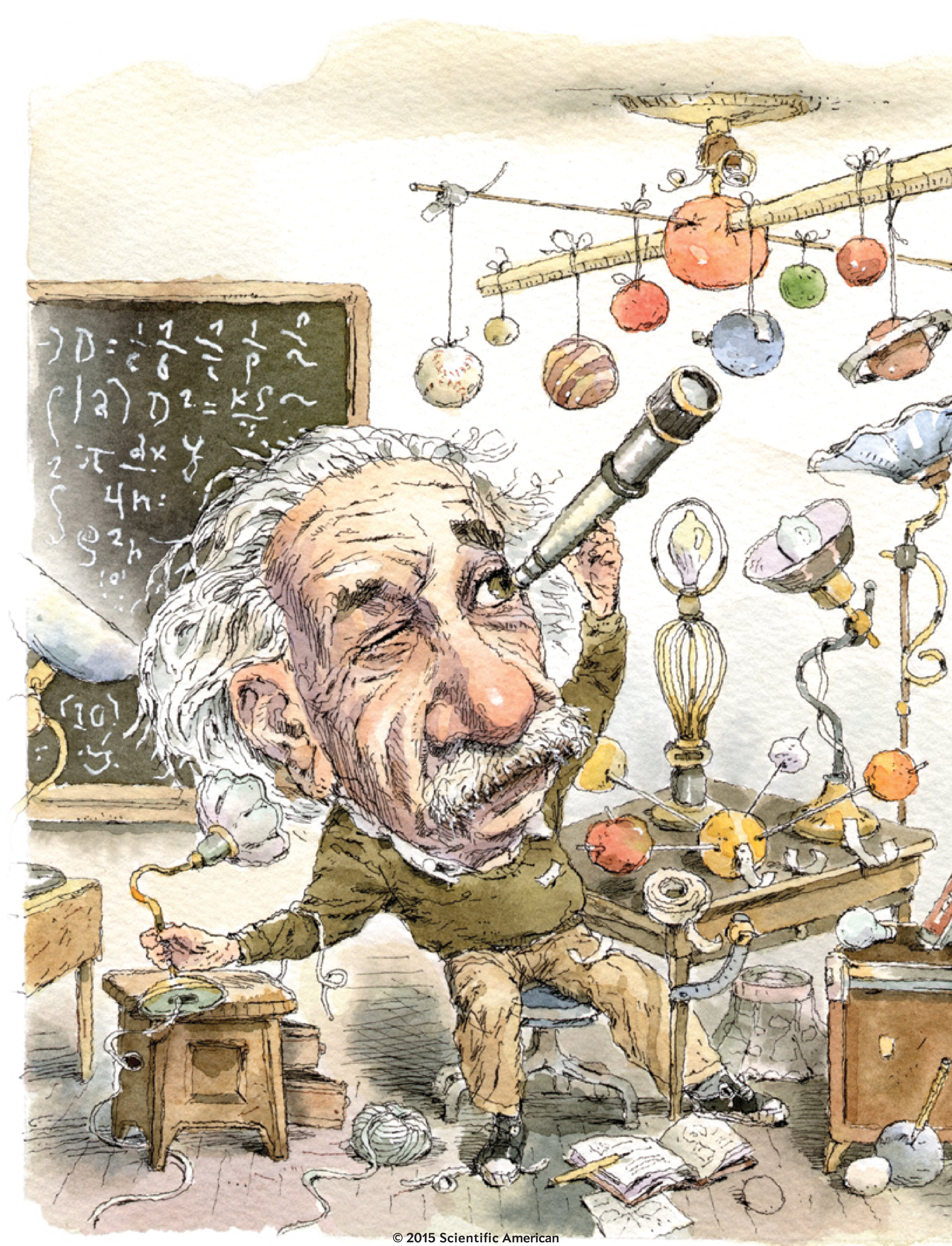


COSMOLOGY

# WHAT EINSTEIN GOT WRONG

## Everyone makes mistakes. But those of the legendary physicist are particularly illuminating

*By Lawrence M. Krauss*

**Like all people,** Albert Einstein made mistakes, and like many physicists he sometimes published them. For most of us, the times when we go astray are happily forgettable. In Einstein's case, even the mistakes are noteworthy. They offer insight into the evolution of his thinking and with it the surrounding shifts in scientific conceptions of the universe. Einstein's errors also lay bare the challenges of discovery at the leading edge. When pushing the limits of understanding, it is difficult to know whether ideas written down on paper correspond to real phenomena and whether a radically new idea will lead to profound insights or will fizzle out.

Over the years Einstein—the man who brazenly redefined the meaning of space and time—underestimated his discoveries and second-guessed himself surprisingly often. Today three whole flourishing areas of cosmology are built on ideas he misjudged: gravitational lensing, gravitational waves and the accelerating expansion of our universe.

IN BRIEF

**Despite his immense powers** of perception, Einstein repeatedly failed to grasp the meaning of some of his own most significant ideas or else overlooked their importance.

**As a result,** he dismissed the importance of gravitational lensing, initially doubted the reality of gravitational waves and failed to anticipate the discovery of the expanding universe.

**Examining Einstein's errors** offers insight into his thought process, as well as a new perspective on the history behind three of the most exciting areas of modern cosmology.

*Illustrations by John Cuneo*

### EINSTEIN'S DISTORTED LENS

IN THE CASE OF GRAVITATIONAL LENSING, Einstein's crucial error was to downplay one of his most famous results: his prediction that light bends in a gravitational field. In December 1936 he published a short paper in the journal *Science,* with the title "Lens-Like Action of a Star by the Deviation of Light in the Gravitational Field." It began with a kind of innocence that would be impossible to find in modern academic literature: *"Some time ago, R. W. Mandl [a Czech engineer] paid me a visit and asked me to publish the results of a little calculation which I had made at his request. This note complies with his wish."*

The "little calculation" examined the possibility of extreme deflections of light caused by gravity. It was a simple matter for Einstein to show that given a massive enough intervening object and a sufficiently close approach, light rays originating from well behind the object would be bent so strongly by gravity that they could converge, producing a magnified image or multiple images of the distant source—akin to the bending of light through a lens, hence the name gravitational lensing. Lensing has developed into one of the most important observational tools in modern cosmology because it offers a way to deduce the distribution of mass in the universe even in places where the matter is invisible.

Einstein did not recognize either the magnitude or the importance of the lensing effect, however. Rather he concluded in his 1936 paper that the splitting of images caused by light passing a nearby star would be so small as to be essentially immeasurable, which undoubtedly explains the self-deprecating nature of the introduction to his paper. He was technically correct, but apparently it did not occur to him that stars are not the only objects that could produce such bending.

Einstein's obliviousness is all the more surprising given the huge impact of gravitational lensing on his scientific reputation. Deflection of light by a massive object was a key observational prediction of general relativity. In 1919 an expedition led by physicist Arthur Eddington observed a solar eclipse and determined that starlight passing by the sun bent just as Einstein expected. News of the confirmation appeared on the front pages of newspapers around the world, with the drama of a British expedition confirming the work of a German scientist right at the end of World War I no doubt contributing to the public's fascination. Einstein rapidly attained a level of scientific fame unequaled ever since.

There is a further twist to the story. Einstein had done the same light-bending calculation years earlier, in 1912. He had not recognized the cosmological importance of his result then, either. Even worse, he had made a near-disastrous mathematical error: he performed his calculation using an early version of general relativity that predicted a light deflection by gravity half as big as the true value. An expedition had been planned to search for the bending of starlight by the sun during a 1914 solar eclipse, but it was preempted by the outbreak of World War I. Einstein was lucky that the observation never happened. If it had, the first prediction of Einstein's emerging theory of gravity would have disagreed with the data. How that would have affected his life, and the subsequent history of science, is anyone's guess.

After the 1936 article was published, Einstein wrote to the editor with a charmingly incorrect assessment of his research: *"Let me also thank you for your cooperation with the little publication, which Mister Mandl squeezed out of me. It is of little value, but it makes the poor guy happy."*

**Lawrence Krauss** is director of the Origins Project at Arizona State University and also Foundation Professor in the School of Earth and Space Exploration and the physics department there. He is author of nine books (including best sellers *The Physics of Star Trek* and *A Universe from Nothing*) and a producer of *The Unbelievers,* a documentary film on science and reason.

What Einstein missed—as the irascible but brilliant California Institute of Technology astronomer Fritz Zwicky pointedly argued in a paper he submitted to the *Physical Review* within months of Einstein's publication—was that stars combine to form galaxies. Individual stars might produce unobservably small lensing effects, Zwicky noted, but lensing by massive galaxies, containing perhaps 100 billion stars, might be observable.

Zwicky's one-page paper, published in 1937, was remarkable. In it he proposed three uses for gravitational lensing that presage almost all the applications that astronomers have managed to achieve in the intervening decades: testing general relativity, using lensing by galaxies to magnify more distant objects that would otherwise be unobservable, and using lensing to measure the masses of the largest structures in the universe. Zwicky missed a fourth application that has turned out to be equally important, using the lensing by galaxies to probe the geometry and evolution of the universe on its largest scales.

It is hard to imagine a larger underestimation of the significance of any calculation in physics.

### STYMIED BY IMAGINARY SINGULARITIES

IN THE CASE OF GRAVITATIONAL WAVES—ripples in spacetime—Einstein understood early on that they were implied by his theory but for a time backtracked from his original, correct claims for their existence. Today the detection of gravitational waves from colliding black holes and exploding stars or from the inflationary era (an epoch of hyperfast expansion immediately after the big bang) promises to open a vast new window on the universe.

Einstein first predicted gravitational waves shortly after he finalized his general theory of relativity in 1916. Although the mathematics behind the waves is complex, the line of reasoning he employed is not. According to the laws of electromagnetism, if we move an electrical charge back and forth, we generate an oscillating disturbance that manifests itself as an electromagnetic wave such as light. Likewise, if we move a pebble back and forth across the surface of a pond, we generate a pattern of water waves. Einstein had demonstrated that matter curves space, so matter in motion should produce an analogous, oscillating disturbance of space. But then he started to doubt whether such disturbances were physically real.

Einstein announced this change of heart in a 1936 paper submitted to *Physical Review* (the same prestigious American journal that published Zwicky's lensing paper). The tale of how he made the error and later discovered his mistake is almost comically twisted. He had moved to the U.S. from Germany three years earlier, and clearly he was still not used to the way things were done in the new world. Around the time he submitted his paper, entitled "Do Gravitational Waves Exist?" Einstein wrote a letter to his colleague Max Born, stating, *"Together with a young collaborator, I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty to the first approximation. This shows us that the non-linear general relativistic field equations can tell us more or, rather, limit us more than we have believed up to now."*

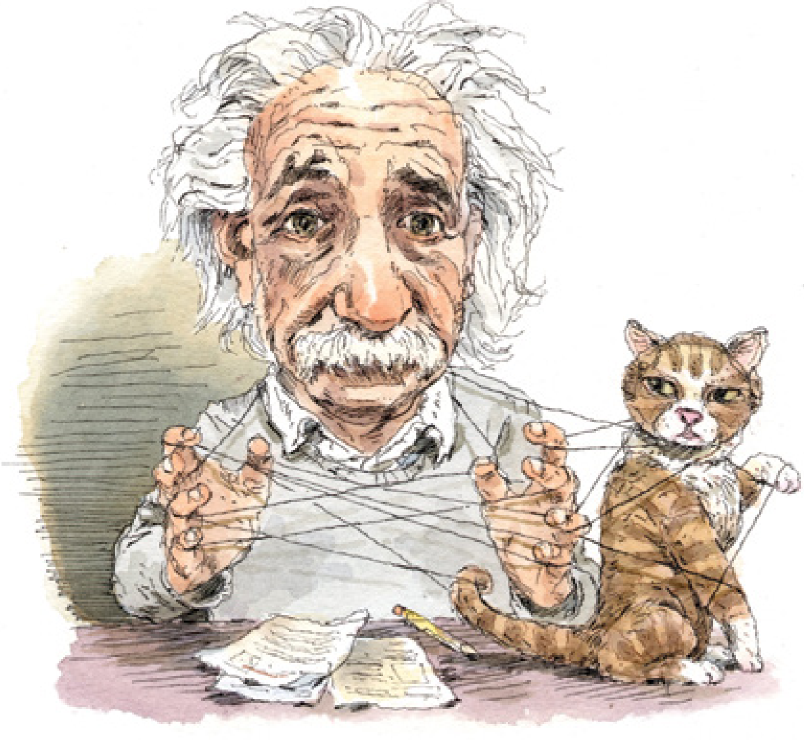
The paper that Einstein sent to the *Physical Review* no longer exists because it was never published there. Following normal procedure, the editor of the journal had sent his paper (coauthored with Nathan Rosen, then Einstein's research assistant at the Institute for Advanced Study in Princeton, N.J.) out for peer review. A critical report came back from an anonymous referee and was forwarded to Einstein for a response. He was stunned to have had his work subject to review, given that this policy was not the norm in the German publications he previously had submitted to.

In response, Einstein wrote a haughty letter to the editor: *"We (Mr. Rosen and I) had sent you our manuscript for publication and had not authorized you to show it to specialists before it is printed. I see no reason to address the—in any case erroneous—comments of your anonymous expert. On the basis of this incident I prefer to publish the paper elsewhere."* He never again submitted a paper to the *Physical Review*. Apparently he also never read the referee's report, written by the distinguished U.S. cosmologist Howard Percy Robertson, which correctly explained the crucial error in his thinking.

Einstein and Rosen had tried to write a formula for gravitational plane waves (flat, evenly spaced waves, analogous to pond ripples from a rock that was dropped extremely far away), but in doing so they encountered a singularity—a place where quantities become infinitely large. That nonsensical result led them to infer that such waves could not exist. In reality, Einstein misunderstood the mathematics of his own theory. General relativity tells us that nature is independent of the particular way that scientists choose to define coordinates in space; many seemingly bizarre results that come out of solving relativity's equations are now understood as mere artifacts of using the wrong coordinate system. For example, around a black hole there is a radius, called the event horizon, inside of which one can never escape the pull of the black hole. When writing down the geometry around a black hole, many quantities—including distance and time—seem to blow up at the event horizon. These infinities are unphysical, however. In another set of coordinates, defined by the way that light moves through space, they disappear. The same is true for gravitational waves. There is no single coordinate system in which planar gravitational waves can be described without apparent singularities, but these are not real. By using two different, overlapping coordinates, the singularities disappear.

Still convinced of his argument, Einstein resubmitted his paper to the *Journal of the Franklin Institute,* but before it could be published, he, too, realized his mistake and informed the editors he had discovered errors. The final published form, retitled "On Gravitational Waves," presents a solution to the general relativity equations that use a different coordinate system—one appropriate for cylindrical rather than planar gravitational waves—in which no singularities appear, just as Robertson had suggested.

How did Einstein come to the correct conclusion in the end? According to his later assistant, Leopold Infeld, Robertson sought out Infeld and kindly explained to him both the error in the original paper and the possible resolution, which Infeld related to Einstein. Robertson apparently never revealed that he was the paper's referee, nor did Einstein ever mention the original referee's report. The upshot is that Einstein never published his erroneous claim disputing the existence of gravitational waves, but only thanks to the intervention of a particularly diligent peer reviewer.



Einstein did not fare as well with regard to black holes. He remained confused by the unphysical singularity at the event horizon and assumed that nature must prohibit it somehow. He argued that conservation of angular momentum would cause particles in a collapsing object to stabilize in orbits of finite radius, making it impossible for an event horizon to form. He never accepted black holes as physically real objects.

### A BRILLIANT BLUNDER?

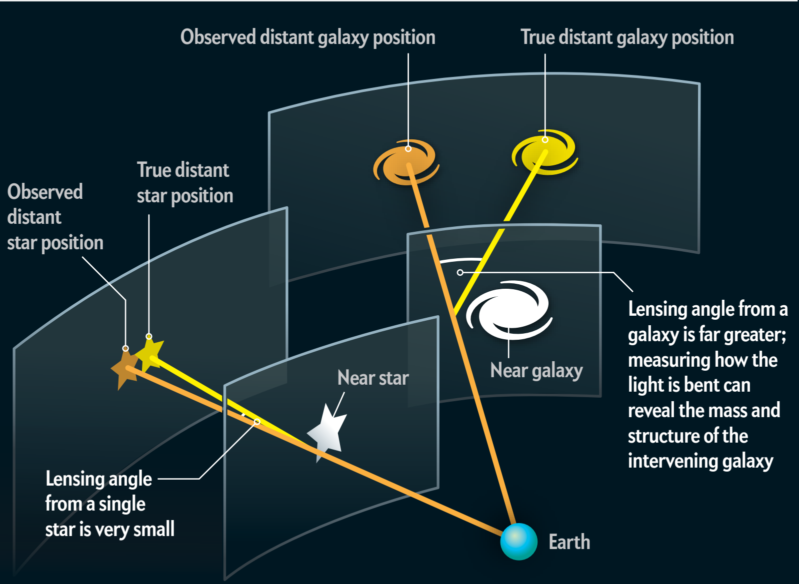
THE MOST FAMOUS OF EINSTEIN'S ERRORS is his modification of general relativity to allow a universe that is not expanding. It became widely known because he reportedly denounced it himself as a "blunder." When he completed general relativity in 1915, the prevailing wisdom held that our galaxy, the Milky Way, was surrounded by an infinite void that was both static and eternal. But Einstein recognized that the gravitational force caused by matter in general relativity (as in Newton's theory) is universally attractive, making a static solution impossible. Gravity should cause the matter to collapse inward.

# Einstein's Blunders

**In three major cases,** Einstein shockingly underestimated the value of his findings or decided that a valid discovery was incorrect. His discarded ideas have proved crucial to modern cosmology. Gravitational lensing is used to map galaxy clusters; gravitational waves offer insights into the first moments of the big bang; the cosmological constant may regulate the evolution of the universe.

## Gravitational Lensing

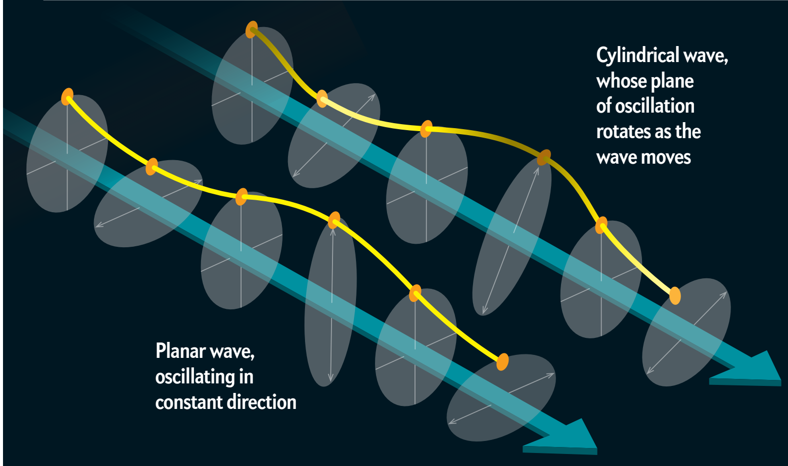
When Einstein published his 1936 paper on gravitational lensing—bending of light by gravity—he mistakenly concluded that the phenomenon would be unobservable. He thought only about lensing of stars by other stars, not the more pronounced lensing of galaxies by other galaxies, which is why he did not publish his results earlier. It is a good thing, too: The first time Einstein calculated the lensing effect, in 1912, he used an early form of his theory, and his estimate of the bending was too small. Had he published the erroneous prediction, it might have affected the ultimate acceptance of general relativity—and that would have been a *big* mistake.



Lensing angle from a galaxy is far greater; measuring how the light is bent can reveal the mass and structure of the intervening galaxy

Lensing angle from a single star is very small

## Gravitational Waves



Cylindrical wave, whose plane of oscillation rotates as the wave moves

Planar wave, oscillating in constant direction

General relativity implied the existence of gravitational waves, ripples in spacetime, but Einstein initially rejected his own prediction. He was saved from publishing this faulty assertion by another mistake: regarding peer review as an insult. After withdrawing a paper in anger over a reviewer's critique, he realized his error: he had tried to find a solution for waves oscillating in a constant direction as they move. He subsequently derived the correct expression for waves whose direction of oscillation rotates as they move. Gravitational waves have since been well confirmed, albeit indirectly.

## Cosmological Constant

In 1917 Einstein added a term, called the cosmological constant, to the equations of general relativity as a mathematical way of keeping the universe static. When he learned that the universe is expanding, he discarded the constant. What he did not realize is that such a term is a natural part of the theory. Scientists now recognize that the cosmological constant corresponds to an energy within empty space; that energy may explain the accelerating expansion of the universe.

Einstein's Field Equation

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

**R** and **g** describe the structure of spacetime

**Λ** (lambda), the cosmological constant, is a term that can describe a repulsive force throughout space

**G** is the gravitational constant

**c** is the speed of light

**T** represents the energy density of matter and radiation

*Illustrations by Jen Christiansen*

In a 1917 paper, "Cosmological Considerations in the General Theory of Relativity," Einstein therefore introduced an additional, constant term in his equations for general relativity to ensure a static universe. The cosmological term would provide a counteracting gravitational repulsion throughout all of space, "holding back gravity" as Einstein hoped. There was no physical justification for this term, other than staving off collapse.

Within a decade after the introduction of the cosmological constant, evidence began to mount that the universe wasn't static after all. At first, Einstein was resistant. Belgian physicist and Catholic priest Georges Lemaître developed a model of an expanding universe, complete with a kind of big bang, in 1927, which was two years before Edwin Hubble published his landmark paper documenting the recession of galaxies. Lemaître later recalled being admonished by Einstein, "Your calculations are correct, but your physics is abominable!"

Eventually Einstein came around. He went to visit Hubble and looked through his telescope at Mount Wilson Observatory near Pasadena, Calif., and in 1933 Einstein reportedly praised Lemaître's cosmological theory: "This is the most beautiful and satisfactory explanation of creation to which I have ever listened."

It was not lost on Einstein that in an expanding universe there was no longer any need for a cosmological constant to keep things static. Even in 1919 he wrote that the constant was "gravely detrimental to the formal beauty of the theory." And in an oft-quoted reference in George Gamow's book, *My World Line: An Informal Autobiography,* Gamow related the following anecdote: "Much later, when I was discussing cosmological problems with Einstein, he remarked that the introduction of the cosmological term was the biggest blunder he ever made in his life."

In retrospect, Einstein was completely mistaken in thinking that the cosmological constant was worthless, but his introduction of it was a blunder, for two reasons. Had he had the courage of his convictions, he would have recognized that general relativity's inconsistency with a static universe was a *prediction*. At a time when no one expected that the universe was dynamic on large scales, Einstein could have predicted cosmic expansion instead of having to grudgingly accept it later.

The introduction of the cosmological constant was also a blunder in a more fundamental way. Simply put, the constant could not work the way he intended: it would not allow the kind of static universe that he was trying to match. That error arose in part because once again Einstein used the wrong coordinate frame for his calculations. But his conception was wrong from a physical perspective as well. Although it is possible to briefly balance the gravitational attraction of matter with the repulsion from a cosmological constant, the smallest perturbation will produce runaway expansion or collapse. With or without the cosmological constant, the universe must be dynamic.

The cosmological constant ultimately proved far more durable than the limited astronomical knowledge that inspired it. Although the constant was an ad hoc addition to his equations, physicists now understand that when viewed through the lens of quantum theory, it corresponds to a possible energy residing in empty space. In fact, quantum physics requires the presence of such a cosmological term. Moreover, the energy content of empty space is not just a theoretical concept. In one of the most astonishing measurements in recent history, two groups in 1998 observed that the expansion of the universe is accelerating, driven outward by something that seems to act just like a cosmological constant. In this instance, one might say that Einstein actually blundered twice: by introducing the cosmological constant for the wrong reason and again by throwing it out instead of exploring its implications.

## THE ERROR HE NEVER ADMITTED

EINSTEIN'S ERRORS WERE INTELLECTUALLY FERTILE because they were all rooted in grand, provocative ideas about how physics works. That is true even of what is generally regarded as his greatest error of all: his refusal to accept quantum mechanics as a fundamental theory of nature.

Although Einstein had created the basis for quantum mechanics with his theory of the photoelectric effect (for which he later won the Nobel Prize), he never completely shed the mindset of classical physics. The idea that the location of a particle is a matter of probability or that one particle can instantaneously influence another one from a great distance struck him as absurd, although his views on the quandaries of quantum theory were more nuanced than he is usually given credit for [see "Is the Cosmos Random?" by George Musser, on page 88]. He spent most of his later years attempting to merge the equations of gravity and electromagnetism within a classical framework, into a so-called unified field theory.

As part of that effort, Einstein became fascinated by a speculation introduced by German mathematician Theodor Kaluza in 1921 and later elaborated on by Swedish physicist Oskar Klein. They suggested that if the universe contains five dimensions—three of familiar space, one of time and a fifth dimension curled up so as to be invisible—it would be possible to create a single, combined description of electromagnetism and gravity. For Einstein, one of the attractive facets of the theory was that it was purely classical. Klein had shown that, in the model, the apparent quantization of electrical charge could be a consequence of electromagnetism reflecting the geometry of the closed, circular shape of the fifth dimension.

Einstein's effort to construct a unified field theory ultimately went nowhere, but his flawed ideas once again led to important breakthroughs. In calling attention to the extra dimensions of Kaluza and Klein, Einstein may have helped inspire the higher-dimensional mathematics of modern string theory, a currently popular proposal for incorporating general relativity into quantum mechanics. Einstein probably would have been repelled by the idea of having general relativity arise out of a quantum landscape rather than the other way around. But as we have seen, he was anything but infallible. SA

### MORE TO EXPLORE

**The Origin of Gravitational Lensing: A Postscript to Einstein's 1936 *Science* Paper.** Jürgen Renn, Tilman Sauer and John Stachel in *Science,* Vol. 275, pages 184–186; January 10, 1997.

**Einstein versus the *Physical Review.*** Daniel Kennefick in *Physics Today,* Vol. 58, No. 9, pages 43–48; September 2005.

### FROM OUR ARCHIVES

**A Cosmic Conundrum.** Lawrence M. Krauss and Michael S. Turner; September 2004.

**The Right Way to Get It Wrong.** David Kaiser and Angela N. H. Creager; June 2012.

scientificamerican.com/magazine/sa

A LEGACY IN NUMBERS

# RELATIVITY'S REACH

## A visualization of recent physics terms affirms the enduring influence of Einstein's 100-year-old masterpiece

**The outer limits** of 21st-century physics involve arcane pursuits with strange and wonderful names like "M-theory" and "de Sitter universes." Many of these endeavors rely heavily on Albert Einstein's explanation of how gravity emerges from the bending of space and time.

With the assistance of the Office for Creative Research (OCR), a New York City data-visualization firm, Scientific American decided to look for some measure of how often recent scientific papers in relevant areas of physics still lean on Einstein's 100-year-old achievement.

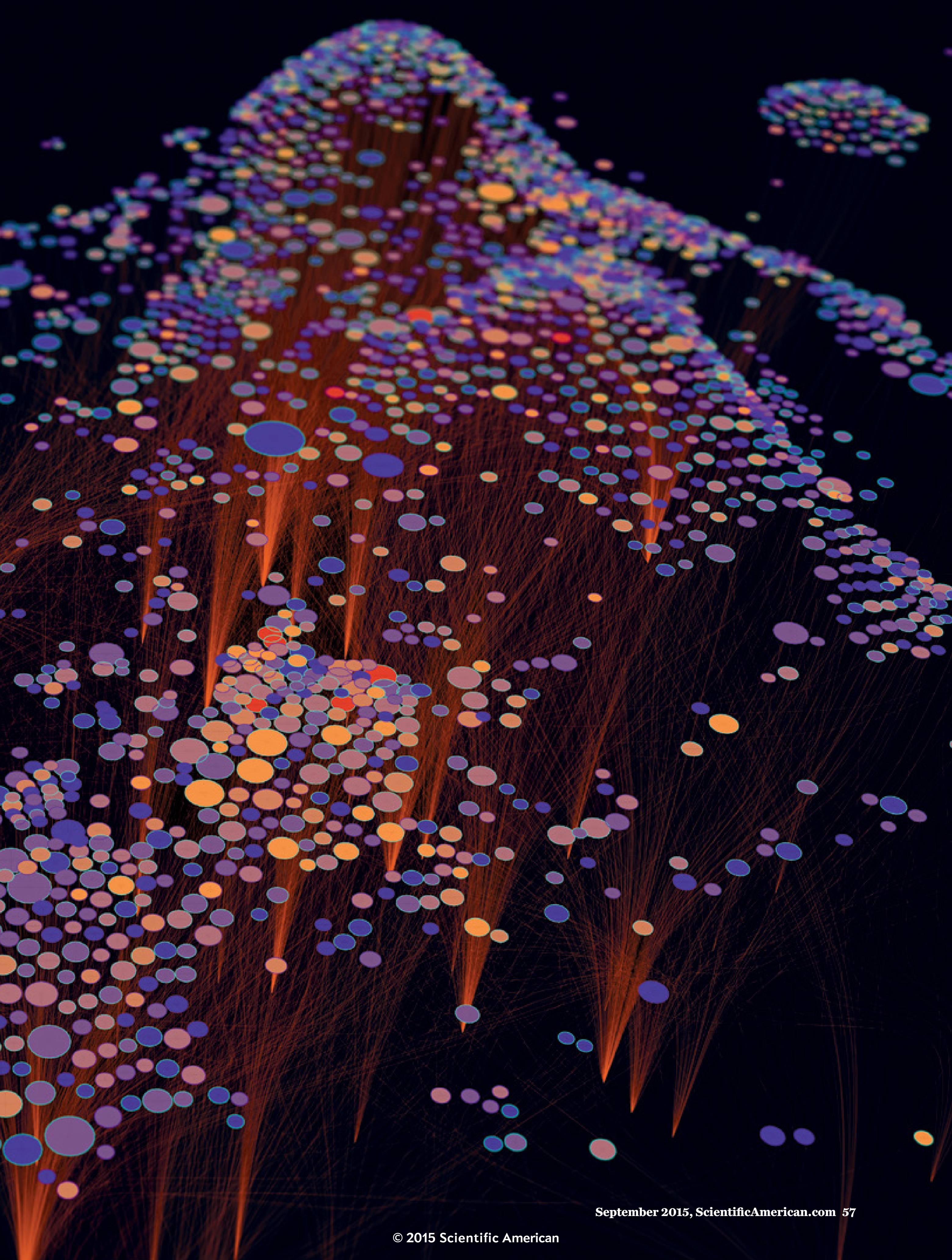
OCR examined a year's worth of the physics literature for references to general relativity or its conceptual offshoots. Specifically, OCR processed 2,435 abstracts of 2014 physics papers from the arXiv.org repository through a powerful text-analysis program incorporated into IBM's Watson AI system. The software extracted keywords that turned up repeatedly in abstracts from a section of arXiv on general relativity and quantum cosmology. We then edited this list down to 61 keywords, each of which represents a research topic that has grown out of general relativity. The arXiv's relativity section was scanned to discover which of the 61 words were turning up most often in the research reports.

The data visualization here is the result. Each incandescent colored dot stands for a paper that touches on at least one element of general relativity or its spin-offs [*see following three pages for details on how to interpret the visualization*]. For an interactive version, go to www.ScientificAmerican.com/sep2015/relativity-infographic.

It is apparent at a glance that Einstein's ideas are still going strong. Thousands of papers published every year make reference to his progeny. General relativity seems certain to continue to be a cornerstone of physics in decades to come. When we redo this data visualization 100 years from now, we are betting that it will yield the same pointillist explosion of color. —*The Editors*

BOUQUETS OF LIGHT: In this view of the three-dimensional visualization, clusters of colored dots represent groupings of research papers that cite particular keywords related to new areas of physics that have emerged from Einstein's theory. To the right, for example, one cluster corresponds to the keywords "black hole" and "event horizon."

*Graphics by the Office for Creative Research*



## Top View

Each dot equals one article from arXiv's 2014 general relativity and quantum cosmology database (2,435 total, some are obscured).

Article dots are positioned near keywords (*diamonds*). If the text has multiple keywords, the dot is placed between terms, such as the article with special relativity and Noether's theorem. Some keywords are linked with red lines.

The size of the dot is based on how often the 2014 article has been cited since publication through the middle of this year.

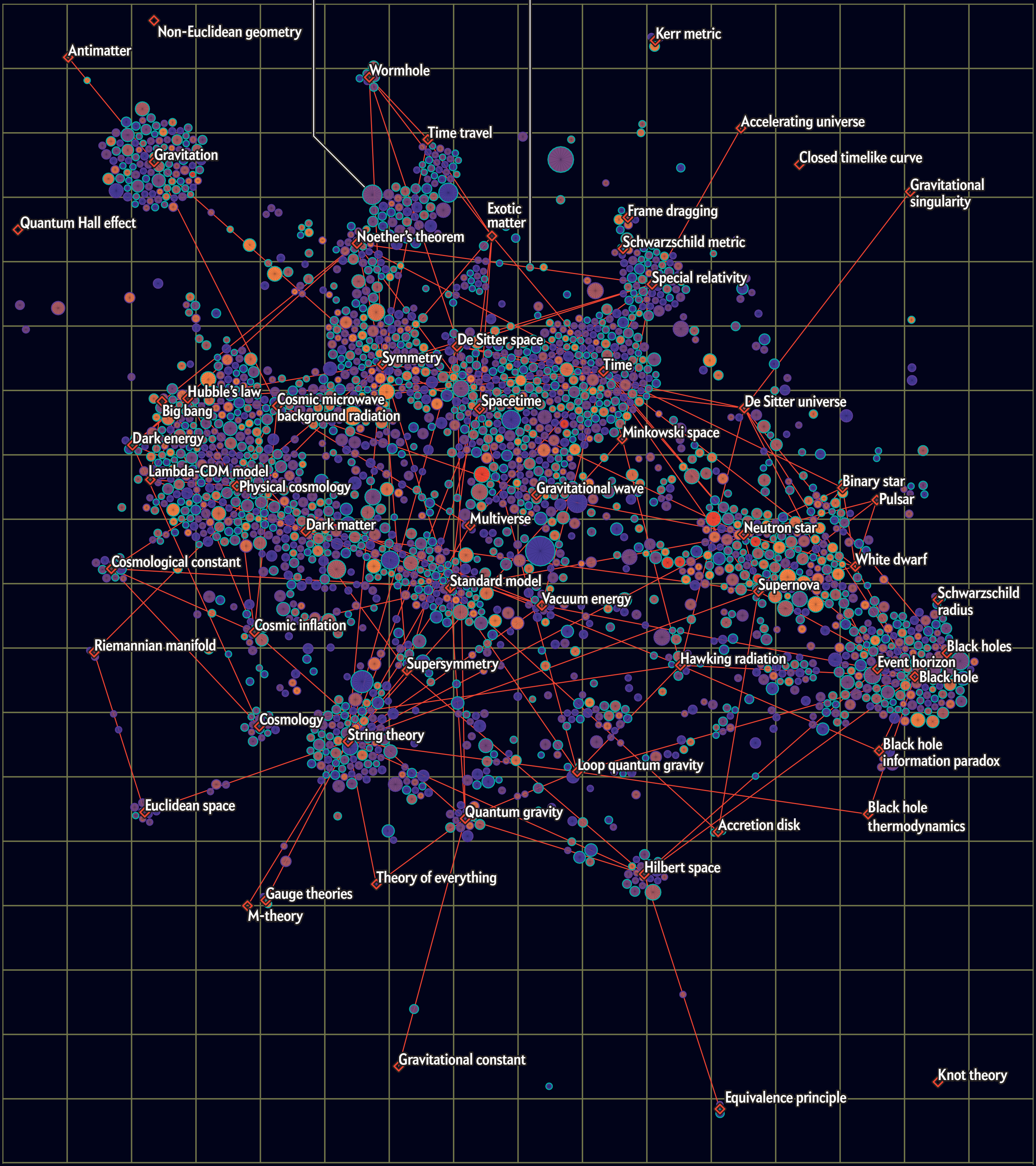
- ● No citations
- ⬤ 85 citations

The color of the dot indicates number of authors.

- ● 1 author
- ● 2 authors
- ● 3 authors
- ● 4 authors
- ● 5–849 authors
- ● 850+ authors

The dot outline indicates publication status. Many physicists put their papers in arXiv before they are published.

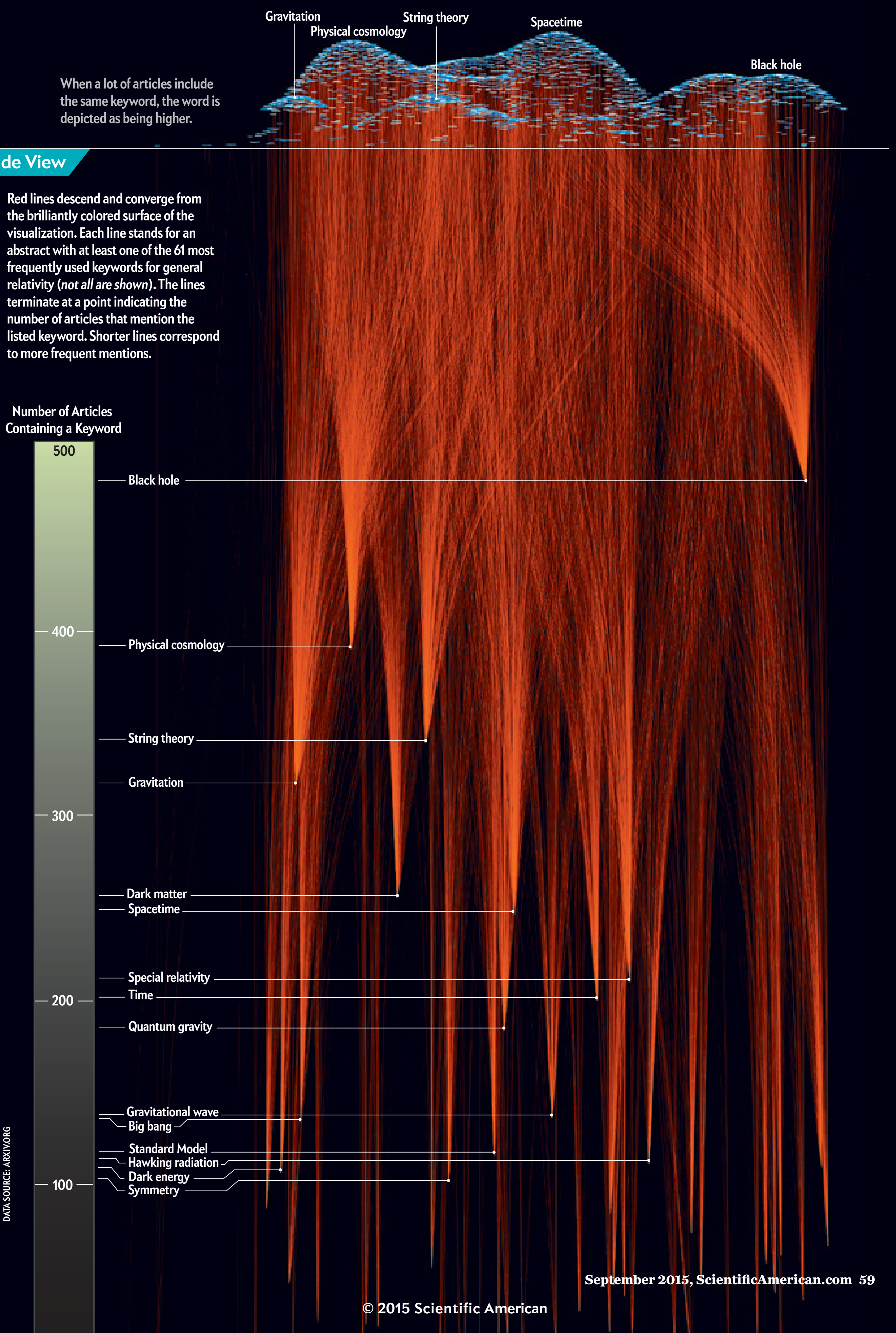
- ○ Currently published
- ○ Awaiting peer review/publication



When a lot of articles include the same keyword, the word is depicted as being higher.

## Side View

Red lines descend and converge from the brilliantly colored surface of the visualization. Each line stands for an abstract with at least one of the 61 most frequently used keywords for general relativity (*not all are shown*). The lines terminate at a point indicating the number of articles that mention the listed keyword. Shorter lines correspond to more frequent mentions.



DATA SOURCE: ARXIV.ORG

FUNDAMENTAL PHYSICS

# CLEANING UP AFTER EINSTEIN

## A new generation of physicists hope to succeed where Einstein failed

*By Corey S. Powell*

**Leslie Rosenberg's attempt** to understand the universe resembles a makeshift home hot-water heater tank, capped with some wires and shoved into a large, underground refrigerator. The experiment, housed in a laboratory adjacent to his office at the University of Washington, is a supercooled, magnetized vacuum chamber equipped with a sensitive detector that listens for the microwave "ping" of passing particles called axions. These particles are invisible and, so far, entirely hypothetical.

Rosenberg has been on the trail of this particle ever since he was a postdoctoral researcher at the University of Chicago in the early 1990s. In that time he has performed experiment after experiment, achieving ever greater precision and yet always the same old empty results, hoping for the positive detection that could rescue Albert Einstein's biggest—and most star-crossed—idea.

Physicists call it the unified field theory, but it is more popularly and evocatively known as the theory of everything. The idea has been to devise a single formulation that sums up the behavior of all the known forces of physics. Einstein started this quest nine decades ago. It bothered the great theorist that the two fundamental forces guiding the behavior of the universe—gravity and electromagnetism—appeared to play by different rules. He wanted to demonstrate that all types of matter and energy are governed by the same logic.

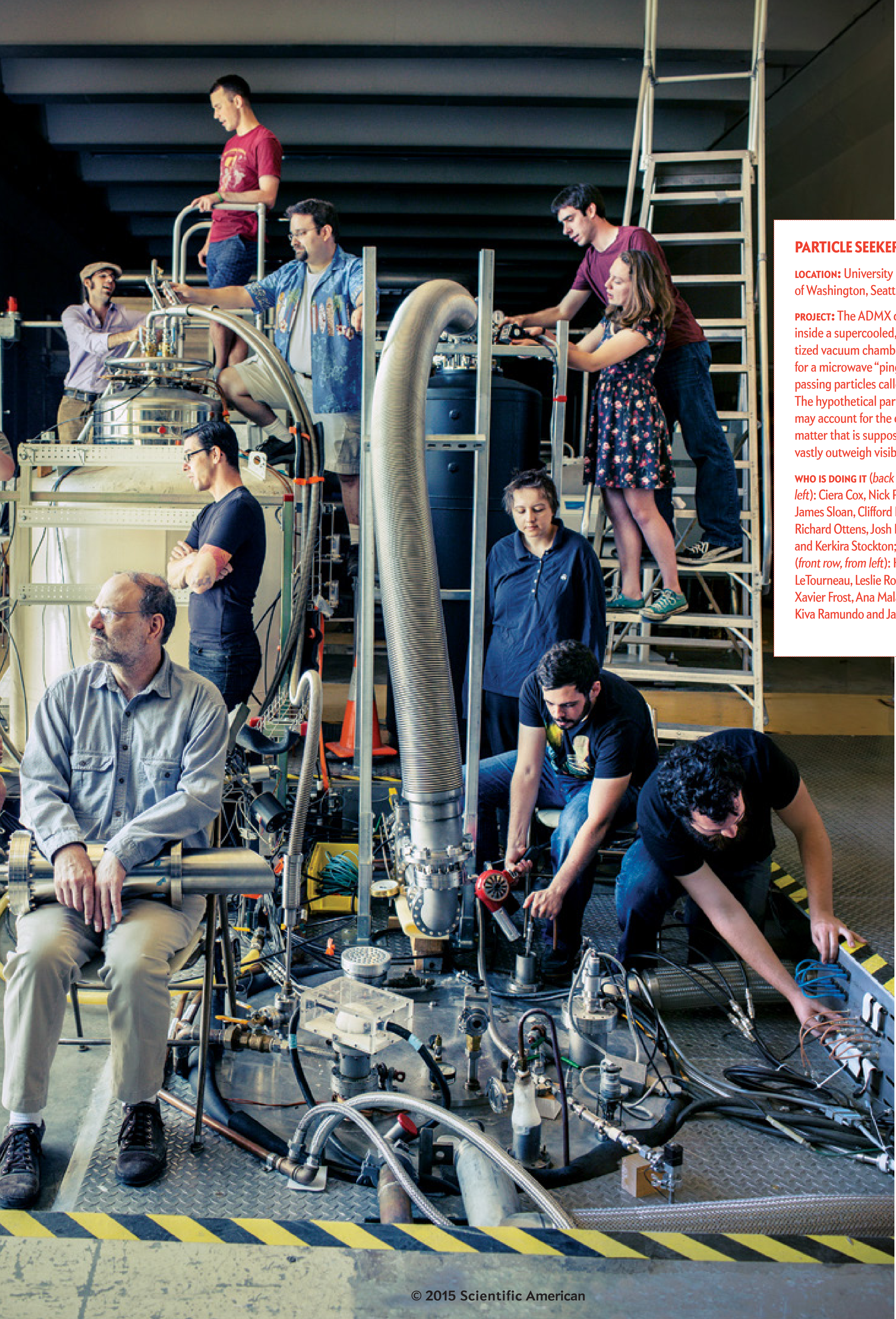
IN BRIEF

**At the end** of his life, Einstein tried to create a theory of everything, governing all forces in the cosmos.

**He failed,** in part because two of those forces, the weak and strong, had yet to be discovered.

**Physicists are making** the attempt again, starting with data on new types of particles and fields.

*Photograph by Timothy Archibald*



### PARTICLE SEEKERS

**LOCATION:** University of Washington, Seattle

**PROJECT:** The ADMX detector, inside a supercooled, magnetized vacuum chamber, listens for a microwave "ping" of passing particles called axions. The hypothetical particles may account for the dark matter that is supposed to vastly outweigh visible matter.

**WHO IS DOING IT** (*back row, from left*): Ciera Cox, Nick Posey, James Sloan, Clifford Plesha, Richard Ottens, Josh Povick and Kerkira Stockton; (*front row, from left*): Hannah LeTourneau, Leslie Rosenberg, Xavier Frost, Ana Malagon, Kiva Ramundo and Jacob Herr

Rolling up the universe into a single formula was a formidable ambition, even for Einstein. “I want to know how God created this world,” he wrote in an oft-cited 1920 letter to a German physics student. “I am not interested in this or that phenomenon, in the spectrum of this or that element. I want to know his thoughts. The rest are details.”

But as the Yiddish proverb goes, “Man plans and God laughs.” Einstein pursued God’s thoughts for three decades to no avail, running down one blind alley after another. When he died, in 1955, he left behind a set of unsolved unified field equations scrawled on his blackboard.

The task of unification has fallen to subsequent generations of physicists, who have broken the problem into myriad parts. What started as the grand vision of a singular genius has morphed into slow, grinding labor carried out by different teams of physicists, each trying to solve a small piece of a vast cosmic puzzle. Rosenberg, for instance, does not obsess over an all-encompassing theory of everything. He is focused on his one vexing and specific problem: the axion. It has theoretical properties that could wipe away the need to modify Einstein’s equations of gravity. “We’ll see what the data say,” Rosenberg notes. “I don’t want to look into the mind of God.”

Despite their narrow focus, Rosenberg and his compatriots have not taken their eyes off the prize. They are engaged in a broader effort to hammer out flaws in the theoretical edifice that Einstein created and to build a more complete model of particle physics from the ground up, rather than from the top down. They seek to push the science forward by finding out how nature really behaves, not how scientists think it should (an approach that Rosenberg dismisses as “navel gazing”). Other researchers are designing experiments to reveal a hidden aspect of physics called dark energy or to detect two-dimensional quantum units that could be building blocks of our apparently three-dimensional existence. Their hard data may be just what today’s physicists need to succeed where Einstein failed.

“We could actually test some of these crazy ideas about the evolution of the universe,” says physicist Joshua Frieman of the University of Chicago. Almost certainly, he believes, physicists will not get to a theory of everything without them.

### DARK SIDE OF THE UNIVERSE

A LOOK at Rosenberg’s Axion Dark Matter eXperiment (ADMX) reveals the power of the small-is-beautiful approach. In its seemingly modest search for just one particle and one new set of physics rules, ADMX could also refute concerns about general relativity and solve a major cosmology puzzle in the process.

That puzzle dates back to the 1930s, when astronomers began to realize that the universe appeared to be full of some unseen component that makes its presence known only by its gravitational pull on the visible stars. The discovery turned even stranger in the 1980s, when new models of the big bang showed that the invisible (or “dark”) stuff—whatever it is—could not consist of ordinary atoms. That left two unsettling possibilities. Perhaps gravity does not work the way Einstein thought it did at large scales, or perhaps the universe contains an unknown class of particles that are invisible to all our telescopes.

Possibility number one is shunned by the vast majority of physicists because it is ad hoc, and it is also difficult to reconcile with measurements of how galaxies move. The scientific mainstream has therefore lined up behind possibility number two, instigating dozens of crafty efforts to unmask the unseen dark particles. Which is where ADMX comes in.

Axions nicely match the inferred properties of dark matter, so

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Photograph by Sandy Nicholson

if Rosenberg and his ADMX team detect them, they would provide a more complete picture of how galaxies have formed and evolved. They would also do away with the need to make ugly modifications to some of Einstein's gravity equations. Above all, axions would force a revision of the Standard Model of particle physics. That model is a comprehensive, yet clearly incomplete, theory of fundamental particles and fields. Finding the axion would validate a much debated elaboration of the Standard Model, bringing physicists one step closer to a true theory of everything.

Until recently, axions were considered a long shot in the search for dark matter. Most of Rosenberg's colleagues were focusing their attention on another class of particles called WIMPs (weakly interacting massive particles), which were considered more theoretically attractive. "I was always a little odd duck out," Rosenberg admits cheerily. Then the various WIMP detectors kept getting better and better, without finding anything. The watershed moment came last year, when an ultrasensitive WIMP finder called Large Underground Xenon (LUX), beneath the hills of South Dakota, switched on. So far it, too, has come up empty.

Now is the make-or-break moment for Rosenberg to prove that axions are the answer and to shore up general relativity—Einstein's idea that gravity comes from a curvature of spacetime—in the process. The concept behind ADMX is deliciously straightforward. If dark matter really consists of particles, there must be a continuous wind of them blowing through the earth and everything on it (including you) all the time. And if those particles are axions, theoretically they will very occasionally decay. The particles themselves are invisible, but in

### HOLOGRAM HUNTERS

**LOCATION:** Fermi National Accelerator Laboratory (Fermilab), Batavia, Ill.

**PROJECT:** The Holometer experiment will look for tiny changes in a laser beam sent down two perpendicular pathways that suggest space and time are made of fundamental quantum units—a theory known as the holographic principle.

**WHO IS DOING IT** (*from left*): Sam Waldman, Ohkyung Kwon, Robert Lanza, Aaron Chou, Craig Hogan, Ray Tomlin, Stephen Meyer, Brittany Kamai, Lee McCuller, Jonathan Richardson, Chris Stoughton, Rainier Weiss and Richard Gustafson

**STRING THEORISTS**

**LOCATION:** Stanford University, Stanford, Calif.

**PROJECT:** String theorists attempt to unify all of nature's forces into a single framework by thinking of both particles and forces as vibrations of loops of string. Some versions of the theory make predictions about the beginning of the universe that might manifest in imprints in the radiation we can observe from the far reaches of the cosmos.

**WHO IS DOING IT** (*from left*): Andrei Linde, Renata Kallosh, Ahmed Almheiri, Leonard Susskind, Shamit Kachru, Patrick Hayden and Lampros Lamprou

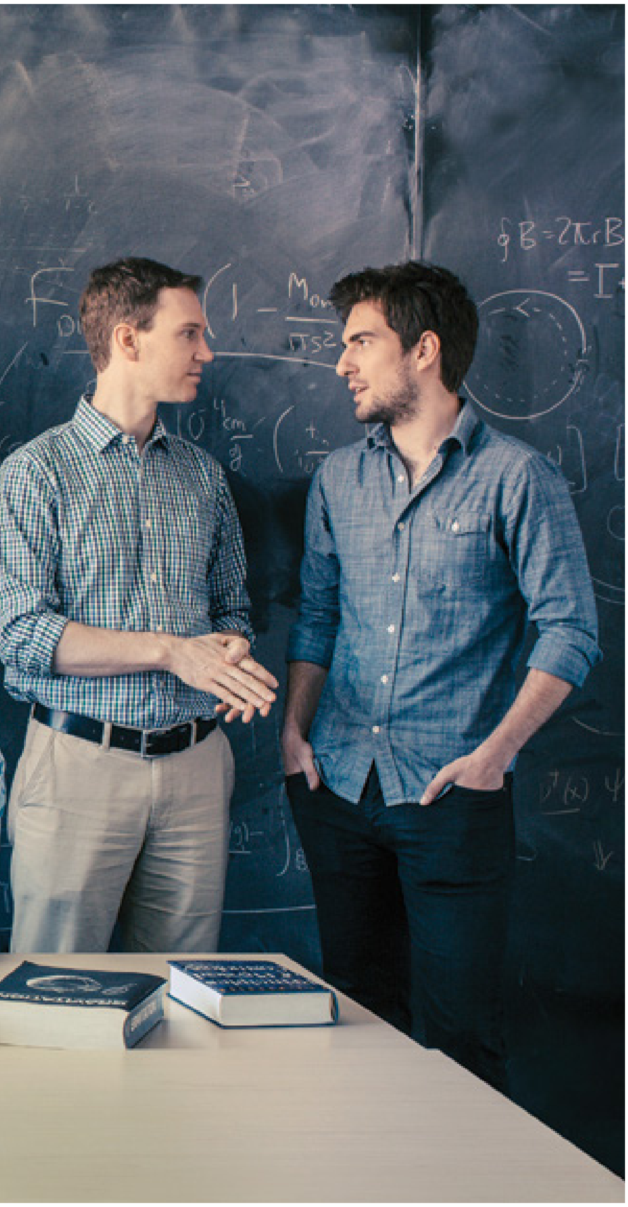
*Photograph by Timothy Archibald*

that rare decay process, they should turn into microwaves, which would produce a weak but detectable signal. Straightforward, yes, but difficult to execute in practice.

"We have a cavity the size of an oil drum," Rosenberg says, "and it's cooled to 100 millikelvins," which is 0.1 degree above absolute zero. The extremely low temperature ensures that the detector itself produces almost no microwave noise. Next the cavity is magnetized to stimulate the decay of axions. Then a small, pencil-shaped probe listens in for some microwaves that should not be there. Adding to the challenge, nobody knows exactly what kind of microwaves to listen for; the frequency of the signal depends on the mass of the axion, which is of course unknown.

The only way around this problem is to hop through the microwave band frequency by frequency; the entire ADMX endeavor is essentially a process of flipping channels on a CB radio. Rosenberg lights up when I offer that analogy: "I've always had this interest in radio electronics. I played with the radio as a kid, bouncing signals off the moon. Now we're looking at signals using receivers so sensitive they could get four bars of cell-phone reception on Mars!" He is also proud that ADMX, unlike Einstein's endless explorations of the unified field theory, is guaranteed to yield a concrete answer.

"By 2018 we will have completely covered the definitive search region for the axion," Rosenberg says. "At that point, it's either there, or it isn't." In other words, we will have either a big



new clue about how to build a theory of everything or one more idea to scratch off the list.

## ENERGY OF EMPTY SPACE

WHILE ROSENBERG WHITTLES AWAY at the problem of dark matter, other researchers are working toward a complete picture of physics by going after the other major unseen aspect of the universe: dark *energy*. It is the opposite of dark matter in its effect, producing a repulsive force rather than a gravitational attraction. Because dark energy counters the action of gravity, it has direct implications for how to interpret the equations of general relativity. More profoundly, dark energy cannot be explained within the current model of particle physics. It therefore provides a critical test for any would-be theory of everything.

One such test is being run by Chicago's Frieman. It uses a custom-built camera strapped to the Blanco four-meter telescope atop Cerro Tololo, a towering peak in Chile rising more than two kilometers above sea level. The idea is to gather a vast number of pictures of distant galaxies. Each image from the camera contains 570 megapixels, a huge amount of data, and it will collect about 400 images a night, 105 nights a year, over five years total. The project is called—not surprisingly—the Dark Energy Survey, and when it is complete in February 2018, the survey will have examined 300 million galaxies and about 4,000 supernova explosions. (For comparison, a state-of-the-art automated supernova search conducted at the University of California, Berkeley, from 1998 to 2000 turned up a grand total of 96.)

Like Rosenberg, Frieman used to work as a theorist but got pulled over to the observational side by the idea of designing actual tests. Now he has to confront the realities of the task. "Taking the data is hard," he says. "Processing the data is hard."

Frieman and his team pick apart observations from the survey four different ways, each one designed to capture a specific aspect of how dark energy behaves. One analysis zeroes in on a class of exploding stars called type Ia supernovae, which act as mile markers in space. Their brightness indicates their distance, and their color indicates how quickly they are moving away from us. Put together a bunch of those mile markers, and you get a sense of how the expansion of the universe has been changing over time. The other three kinds of analyses explore various patterns of how galaxies cluster. Gravity tends to pull everything together, and dark energy tends to push everything apart. Mapping how galaxy clusters change over cosmic time therefore reveals the intensity of the dark energy effect.

**Weird as they are, dark matter and dark energy can be thought of as garnishes atop a reality that Einstein would have recognized. But what if that reality needs adjustment to make progress?**

In the simplest models of dark energy, it is an unchanging and ubiquitous feature of empty space. It turns out that the standard theories of particle physics can account for the existence of such an energy; they just predict a value $10^{120}$ times too large. (It is sometimes called the worst prediction in all of physics.) Accounting for the real, drastically smaller value of dark energy is one of the most important tests for a prospective theory of everything. Astronomers also do not know yet whether dark energy is truly constant. If Frieman finds that it changes over time, that is another thing that a theory of everything must explain.

Before we reach that point, though, there is a more basic issue to settle. "Our assumption is that dark energy is what's driving the accelerated expansion, but we don't know that for sure. It could be that on the largest scales, general relativity just isn't the correct theory," Frieman says. A modified version of relativity could potentially mimic the dark energy effect, something that he will be investigating closely. One way or another, there must be a theory that goes beyond Einstein's, and the Dark Energy Survey will help find it.

## IS LIFE A HOLOGRAM?

WEIRD AS THEY ARE, dark matter and dark energy can still be thought of as garnishes on the universe as we know it: an icing of additional particles or fields atop the kind of reality that Einstein would have readily recognized. But what if that reality needs adjustment to make progress toward a more sweeping theory? What if spacetime itself has new, undetected properties that are not described by general relativity?

Craig Hogan, director of the Center for Particle Astrophysics at Fermi National Accelerator Laboratory, is exploring that head-scratcher with an experiment he calls the Holometer. His quest is to find out whether space and time are constructed out of fundamental units: a universe inherently built around ticks of time and marks on the ruler. In this alternative view, our sense of living in a three-dimensional universe is an illusion. If you could magnify space sufficiently—down to 10 trillion trillion times as small as an atom—you would see two-dimensional pixels that look three-dimensional only when viewed from a large-scale perspective, like the dots on a television screen.

Each of those units would follow quantum rules, such as having an amount of built-in uncertainty about its location. At large scales, space would appear continuous, as Einstein believed, but it would have an underlying quantum structure. In this way, a pixelated universe would force quantum mechanics into relativity, removing a key obstacle to creating a unified theory of physics.

The idea of the apparent 3-D universe emerging from a 2-D reality is known as the holographic principle, hence the name of Hogan's experiment. "Holometer" is also something of a pun, riffing on the name of a 16th-century precision surveying device. Hogan's instrument, now collecting data at Fermilab, is similarly designed to measure the lay of the land with unprecedented accuracy. It consists of a laser beam that is split in two, sent down different tunnels, bounced off a mirror and then recombined. If space has a quantum structure, the uncertainty of the location associated with each pixel should create a jitter within the device; that jitter would shift the two halves of the beam and knock them out of sync. In principle, the Holometer can measure movements at the attometer scale: $10^{-18}$ meter!

That may not be small enough, however. Any underlying quantum structure of space could be even more minuscule, far too subtle to detect experimentally, some of Hogan's colleagues have warned him. He took their skepticism as a dare. As we talk, he seems especially tickled by how acutely his experiment irks Leonard Susskind of Stanford University, one of the primary developers of the holographic universe concept. "Lenny has an idea of how the holographic principle works, and this isn't it. He's pretty sure that we're not going to see anything. We were at a conference last year, and he said that he would slit his throat if we saw this effect, " Hogan recalls.

Their dispute should be settled soon. After collecting one hour of data, the Holometer is approaching Planck sensitivity, the scale at which Hogan thinks the graininess of space might show up. A full answer could come within a year,, he predicts, and then something will happen—he is just not sure what: "If we don't see something, or we do see something, either way it's going to constrain people's ideas. Nobody knows what the hell to expect."

## EINSTEIN'S DREAM, CONTINUED

AFTER HOGAN'S COMMENTS, I was eager to speak with Susskind to hear his take. Contrary to the stereotype of the pensive, math-obsessed theorist, Susskind quickly launches into a discussion about testable concepts. "People bitch about theoretical physicists' being frivolous with their ideas because they don't face the issues of falsifiability. That's nonsense. We all are very concerned about falsifiability," he says. But if there is a laboratory test, he contends, the Holometer is not how to do it.

A better bet, Susskind says, is to look to the edge of the observable universe for behavior that supports string theory. In this theory, all particles and forces are different modes of vibrations in wiggling strings of energy, which makes it a unified explanation for all of them. (These strings are different from cosmic strings, which may be defects in spacetime.) It also makes predictions about physical conditions at the time of the big bang. More remarkable, some versions—the ones Susskind works on—make predictions about conditions at an even earlier stage, before our universe was born. Susskind believes astronomers might be able to identify evidence of that prior existence imprinted on radiation from the far reaches of our universe.

More likely, though, he believes the next strides toward the unification of physics will come not from experiment or observation but from intense mathematical explorations of black holes and space and time. "Important things are going to happen over the next five to 10 years," Susskind predicts. "I don't say we're going to have a complete theory of everything; we're not even close. But there are going to be major insights into the connection between gravity and quantum mechanics."

When that connection is revealed, Susskind—like most of today's theorists—expects that quantum mechanics will come out on top, with gravity and general relativity forced to live within its framework. But because Einstein was the one who started us down this path, it seems only fair to give the final word to one of today's leading Einsteinians, physicist Lee Smolin of the Perimeter Institute for Theoretical Physics in Ontario.

**COSMIC CRUSADERS**

**LOCATION:** Perimeter Institute for Theoretical Physics, Waterloo, Ontario

**PROJECT:** Theorists are exploring other ways to understand the whole universe within a single framework. One idea is that Einstein's relativity of time can be replaced by a relativity of size, leading to a reformulation of general relativity in which time and shape are meaningful but size is not.

**WHO IS DOING IT** (*back row, from right*): Daniel Carrasco Guariento, Gabriel Herczeg, Flavio Mercati, Sean Gryb and Hamish Forbes; (*front row, from right*): Niall Ó Murchadha, Henrique Gomes, Andrea Napoletano, Julian Barbour and Lee Smolin

Smolin is convinced that many of his quantum-obsessed colleagues are literally thinking too small in their pursuit of an ultimate theory. “Quantum mechanics is only sensible as a theory of a subsystem,” he says, “but general relativity is not a description of subsystems. It is a description of the universe as a closed system.” If you want to understand the universe as a whole, then you have to think of it as Einstein did, in relativistic terms.

That approach has led Smolin to the startling hypothesis that the laws of physics may evolve over time and that the universe has a memory of its own history—what he calls the principle of precedence. In this way, he envisions moving beyond specific, unexplained details of quantum mechanics (the strength of this particular field or the mass of that particular particle) and regarding them all as developmental aspects of the single, closed-system universe. He even has a notion of how to test his idea.

“If we could evolve a system that is large and complex but still described by a pure quantum state, we would force nature to invent some novel systematics. We could imagine doing that with quantum devices,” Smolin says. After creating the same system over and over in the lab, nature might start to develop a preference for a certain quantum state. “It would be hard to distinguish from the noises of experimental practice. But not impossible.”

Smolin does not intend to sound mystical, but in some way he seems to be talking not about the physical universe but about the spirit of Einstein. One century ago a single man revealed a novel way to think about the universe. Sixty years ago that life was snuffed out, as all human lives are sooner or later. But the mind of Einstein still leaves a distinct imprint on today’s researchers. They run new experiments in the service of an old ideal. The impulse seems unstoppable, as they keep recapitulating his search for a deeper truth, a higher enlightenment.

### MORE TO EXPLORE

**Search for Hidden Sector Photons with ADMX Detector.** A. Wagner et al. in *Physical Review Letters,* Vol. 105, No. 17, Article No. 171801; October 19, 2010.

**Time Reborn: From the Crisis in Physics to the Future of the Universe.** Lee Smolin. Houghton Mifflin Harcourt, 2013.

**Mass and Galaxy Distributions of Four Massive Galaxy Clusters from Dark Energy Survey Science Verification Data.** P. Melchior et al. in *Monthly Notices of the Royal Astronomical Society,* Vol. 449, No. 3, pages 2219–2238; May 21, 2015.

### FROM OUR ARCHIVES

**On the Generalized Theory of Gravitation.** Albert Einstein; April 1950.

scientificamerican.com/magazine/sa

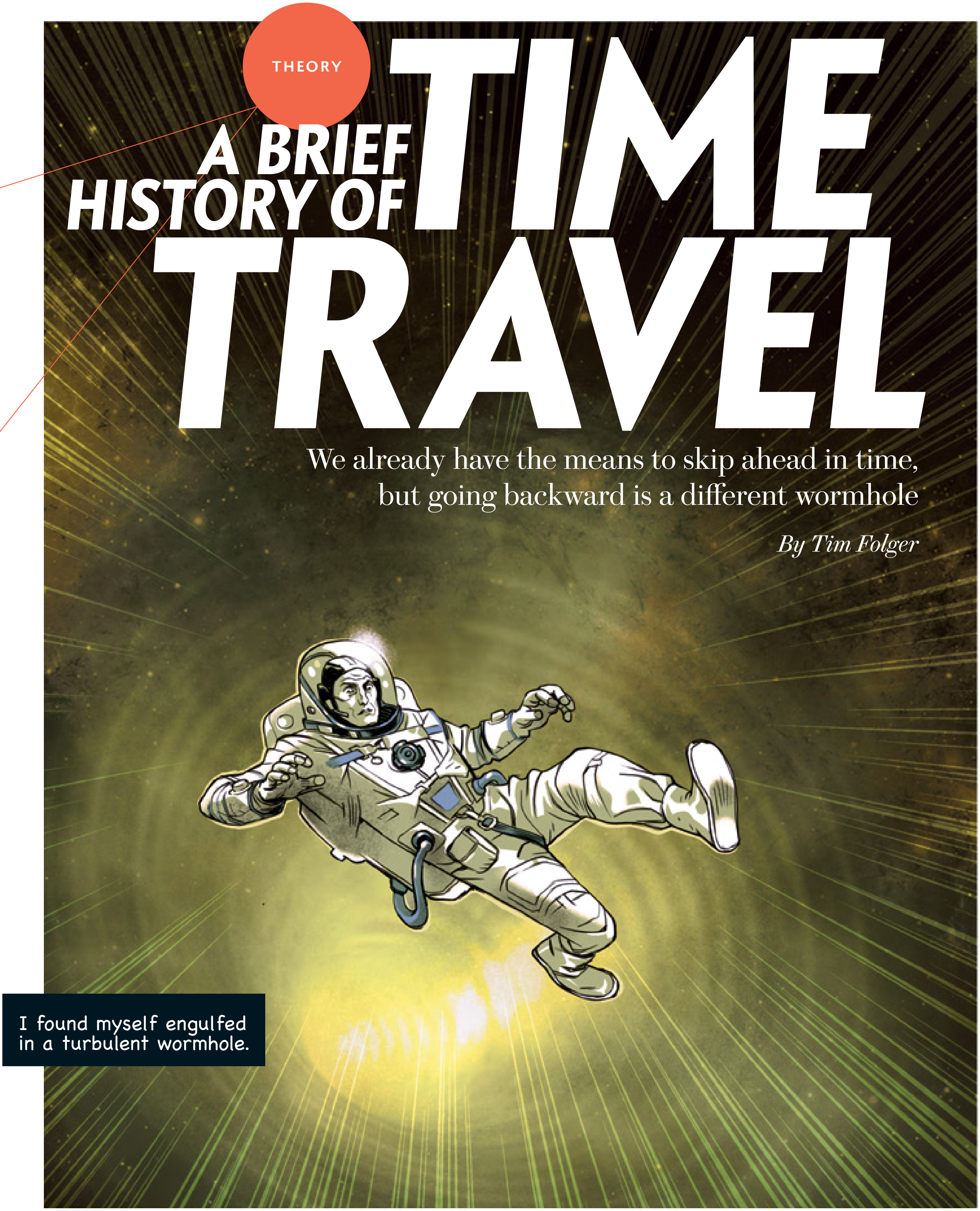
*Photograph by Sandy Nicholson*

THEORY

# A BRIEF HISTORY OF TIME TRAVEL

We already have the means to skip ahead in time, but going backward is a different wormhole

*By Tim Folger*



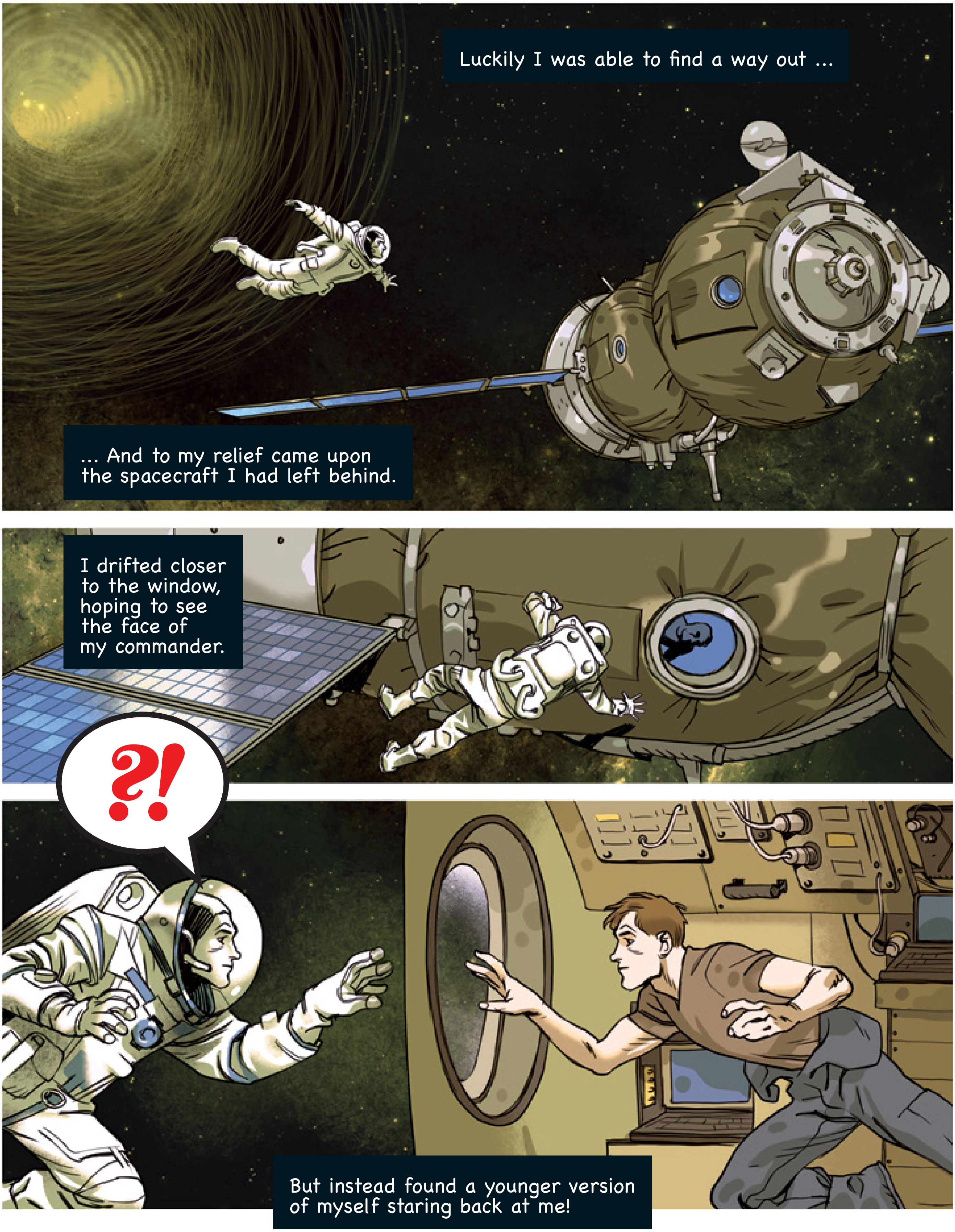


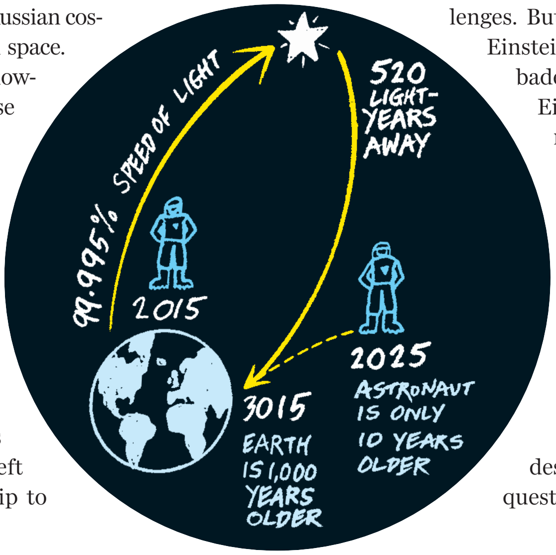
*Illustration by Asaf Hanuka*

**Tim Folger** writes for *National Geographic, Discover* and other national publications. He is also the series editor for *The Best American Science and Nature Writing,* an annual anthology published by Houghton Mifflin Harcourt.

**H. G. Wells published** his first novel, *The Time Machine,* in 1895, just a few years before Queen Victoria's six-decade reign over the U.K. ended. An even more durable dynasty was also drawing to a close: the 200-year-old Newtonian era of physics. In 1905 Albert Einstein published his special theory of relativity, which upset Isaac Newton's applecart and, to Wells's presumed delight, allowed something that had been impossible under Newton's laws: time travel into the future. In Newton's universe, time was steady everywhere and everywhen; it never sped up or slowed down. But for Einstein, time was relative.

Time travel is not only possible, it has already happened, though not exactly as Wells imagined. The biggest time traveler to date is Sergei K. Krikalev, according to J. Richard Gott, an astrophysicist at Princeton University. Over the course of his long career, which began in 1985, the Russian cosmonaut spent a little over 803 days in space. As Einstein proved, time passes more slowly for objects in motion than for those at rest, so as Krikalev hurtled along at 17,000 miles an hour onboard the *Mir* space station, time did not flow at the same rate for him as it did on Earth. While Krikalev was in orbit, he aged 1⁄48 of a second less than his fellow earthlings. From another perspective, he traveled 1⁄48 of a second into the future.

The time-travel effect is much easier to see with longer distances and higher speeds. If Krikalev left Earth in 2015 and made a round-trip to Betelgeuse—a star that is about 520 light-years from Earth—at 99.995 percent the speed of light, by the time he returned to Earth he would be only 10 years older. Sadly, everyone he knew would be long dead because 1,000 years would have passed on Earth; it would be the year 3015. "Time travel to the future, we know we can do," Gott says. "It's just a matter of money and engineering!"



Jumping a few nanoseconds—or centuries—into the future is relatively straightforward, despite practical challenges. But going *backward* in time is harder. Einstein's special theory of relativity forbade it. After another decade of work, Einstein unveiled his general theory of relativity, which finally lifted that restriction. How someone would actually travel back in time, however, is a vexing problem because the equations of general relativity have many solutions. Different solutions assign different qualities to the universe—and only *some* of the solutions create conditions that permit time travel into the past.

Whether any of those solutions describes our own universe is an open question, which raises even more pro-

## IN BRIEF

**Traveling very fast** allows you to go forward in time. Traveling backward in time is much harder, but mathematics says it is possible through geometric structures called closed timelike curves.

**A wormhole is one** such curve. You would enter it through a spherical opening. Once inside, everything you observed in space would be normal and so would the passage of time.

**Closed timelike curves** are useful for testing theories about the cosmos. For example, if one were present at the start of our universe, it could have allowed the universe to create itself.

**Quantum mechanics—**and indeed, the nature of the universe itself—might forbid wormholes and therefore prevent backward time travel. Physicists just do not know yet if this is the case.

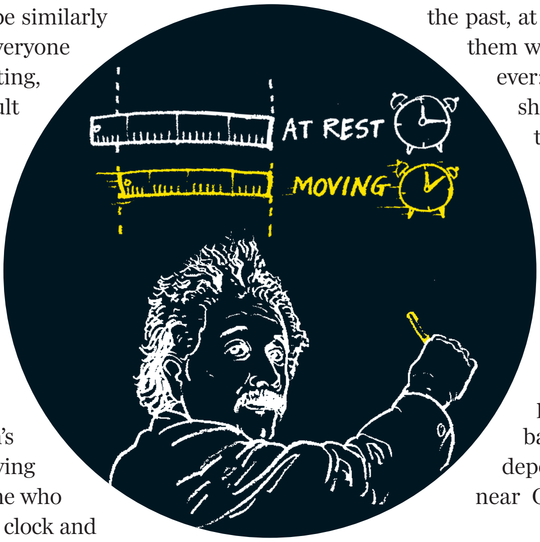
*Illustrations by Nigel Holmes*

found investigations: Just how much tweaking of fundamental physics would it take to allow backward time travel? Does the universe itself somehow prevent such journeys even if Einstein's equations do not rule them out? Physicists continue to speculate, not because they imagine time travel will ever be practical but because thinking about the possibility has led to some surprising insights about the nature of the universe we inhabit, including, perhaps, how it came to be in the first place.

### A NEW WAY OF LOOKING AT TIME

WITH HIS SPECIAL THEORY of relativity, Einstein made time malleable in a way that must have pleased Wells, who presciently believed that we inhabit a universe in which three-dimensional space and time are knit together into a four-dimensional whole. Einstein arrived at his revolutionary results by exploring the implications of two fundamental ideas. First, he argued that even though all motion is relative, the laws of physics must look the same for everyone anywhere in the universe. Second, he realized that the speed of light must be similarly unchanging from all perspectives: if everyone sees the same laws of physics operating, they must also arrive at the same result when measuring the speed of light.

To make light a universal speed limit, Einstein had to jettison two commonsense notions: that all observers would agree on the measurement of a given length and that they would also agree on the duration of time's passage. He showed that a clock in motion, whizzing past someone at rest, would tick more slowly than a stationary clock at the person's side. And the length of a ruler moving swiftly by would shorten. Yet for anyone who was traveling at the same speed as the clock and ruler, the passage of time and the length of the ruler would appear normal.



At ordinary speeds, the time-and-space-distorting effects of special relativity are negligible. But for anything moving at a hefty fraction of the speed of light, they are very real. For example, many experiments have confirmed that the decay rate of unstable particles called muons slows by an order of magnitude when they are traveling at close to the speed of light. The speeding muons, in effect, are minuscule time travelers—subatomic Krikalevs—hopping a few nanoseconds into the future.

### GÖDEL'S STRANGE UNIVERSE

THOSE SPEEDY CLOCKS and rulers and muons are all racing forward in time. Can they be thrown into reverse? The first person to use general relativity to describe a universe that permits time travel into the past was Kurt Gödel, the famed creator of the incompleteness theorems, which set limits on the scope of what mathematics can and cannot prove. He was one of the towering mathematicians of the 20th century—and one of the oddest. His many foibles included a diet of baby food and laxatives.

Gödel presented this model universe as a gift to Einstein on his 70th birthday. The universe Gödel described to his skeptical friend had two unique properties: It rotated, which provided centrifugal force that prevented gravity from crunching together all the matter in the cosmos, creating the stability Einstein demanded of any cosmic model. But it also allowed for time travel into the past, which made Einstein deeply uneasy. In Gödel's cosmos, space travelers could set out and eventually reach a point in their own past, as if the travelers had completed a circuit around the surface of a giant cylinder. Physicists call these trajectories in spacetime "closed timelike curves."

A closed timelike curve is any path through spacetime that loops back on itself. In Gödel's rotating cosmos, such a curve would circle around the entire universe, like a latitude line on Earth's surface. Physicists have concocted a number of different types of closed timelike curves, all of which allow travel to the past, at least in theory. A journey along any of them would be disappointingly ordinary, however: Through the portholes of your spaceship, you would see stars and planets—all the usual sights of deep space. More important, time—as measured by your own clocks—would tick forward in the usual way; the hands of a clock would not start spinning backward even though you would be traveling to a location in spacetime that existed in your past.

"Einstein was already aware of the possibility of closed timelike curves back in 1914," says Julian Barbour, an independent theoretical physicist who lives near Oxford, England. As Barbour recalls,

**TIME FOR LUNCH:** **After more than 803 days hurtling through space, Sergei K. Krikalev (*left*) had traveled $\frac{1}{48}$ of a second into the future.**

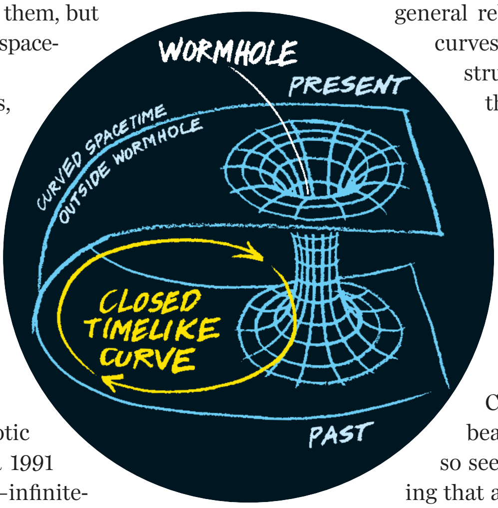
GETTY IMAGES

Einstein said, “My intuition strives most vehemently against this.” The curves’ existence would create all kinds of problems with causality—how can the past be changed if it has already happened? And there is the hoary grandfather paradox: What happens to a time traveler who kills his or her grandfather before the grandfather meets the grandmother? Would the demented traveler ever be born?

Fortunately for fans of causality, astronomers have found no evidence that the universe is rotating. Gödel himself apparently pored over catalogs of galaxies, looking for clues that his theory might be true. Gödel might not have devised a realistic model of the universe, but he did prove that closed timelike curves are completely consistent with the equations of general relativity. The laws of physics do not rule out traveling to the past.

## AN ANNOYING POSSIBILITY

OVER THE PAST FEW DECADES cosmologists have used Einstein’s equations to construct a variety of closed timelike curves. Gödel conjured an entire universe that allowed them, but more recent enthusiasts have warped spacetime only within parts of our universe.



In general relativity, planets, stars, galaxies and other massive bodies warp spacetime. Warped spacetime, in turn, guides the motions of those massive bodies. As the late physicist John Wheeler put it, “Spacetime tells matter how to move; matter tells spacetime how to curve.” In extreme cases, spacetime might bend enough to create a path from the present back to the past.

Physicists have proposed some exotic mechanisms to create such paths. In a 1991 paper, Gott showed how cosmic strings—infinitely long structures thinner than an atom that may have formed in the early universe—would allow closed timelike curves where two strings intersected. In 1983 Kip S. Thorne, a physicist at the California Institute of Technology, began to explore the possibility that a type of closed timelike curve called a wormhole—a kind of tunnel joining two different locations in spacetime—might allow for time travel into the past. “In general relativity, if you connect two different regions of space, you’re also connecting two different regions of time,” says Sean M. Carroll, a colleague of Thorne’s at Caltech.

The entrance into a wormhole would be spherical—a three-dimensional entrance into a four-dimensional tunnel in spacetime. As is the case with all closed timelike curves, a trip through a wormhole would be “like any other journey,” Carroll says. “It’s not that you disappear and are reassembled at some other moment of time. There is no respectable theory where that kind of science-fiction time travel is possible.” For all travelers, he adds, “no matter what they do, time flows forward at one second per second. It’s just that your local version of ‘forward’ might be globally out of sync with the rest of the universe.”

Although physicists can write equations that describe wormholes and other closed timelike curves, all the models have serious problems. “Just to get a wormhole in the first place, you need negative energy,” Carroll says. Negative energy is when the energy in a volume of space spontaneously fluctuates to less than zero. Without negative energy, a wormhole’s spherical entrance and four-dimensional tunnel would instantaneously implode. But a wormhole held open by negative energy “seems to be hard, probably impossible,” Carroll says. “Negative energies seem to be a bad thing in physics.”

Even if negative energy kept a wormhole open, just when you would be on the verge of turning that into a time machine, “particles would be moving through the wormhole, and every particle would loop back around an infinite number of times,” Carroll says. “That leads to an infinite amount of energy.” Because energy deforms spacetime, the entire thing would collapse into a black hole—an infinitely dense point in spacetime. “We’re not 100 percent sure that that happens,” Carroll says. “But it seems to be a reasonable possibility that the universe is actually preventing you from making a time machine by making a black hole instead.”

Unlike black holes, which are a natural consequence of general relativity, wormholes and closed timelike curves in general are completely artificial constructs—a way of testing the bounds of the theory. “Black holes are hard to avoid,” Carroll says. “Closed timelike curves are very hard to make.”

Even if wormholes are physically implausible, it is significant that they fit in with the general theory of relativity. “It’s very curious that we can come so close to ruling out the possibility of time travel, yet we just can’t do it. I also think that it’s annoying,” Carroll says, exasperated that Einstein’s beautiful theory might allow for something so seemingly implausible. But by contemplating that annoying possibility, physicists may gain a better understanding of the kind of universe we live in. And it may be that if the universe did not permit backward time travel, it never would have come into existence.

## DID THE UNIVERSE CREATE ITSELF?

GENERAL RELATIVITY describes the universe on the largest scales. But quantum mechanics provides the operating manual for the atomic scale, and it offers another possible venue for closed timelike curves—one that gets at the origin of the universe.

“On a very small scale—$10^{-30}$ centimeter—you might expect the topology of spacetime to fluctuate, and random fluctuations might give you closed timelike curves if nothing fundamental prevents them,” says John Friedman, a physicist at the University of Wisconsin–Milwaukee. Could those quantum fluctuations somehow be magnified and harnessed as time machines? “There’s certainly no formal proof that you *can’t* have macroscopic closed timelike curves,” Friedman says. “But the community of people who have looked at these general questions would bet pretty heavily against it.”

There is no doubt that the creation of a loop in spacetime on either a quantum scale or a cosmic one would require some very extreme physics. And the most likely place to expect extreme physics, Gott says, is at the very beginning of the universe.

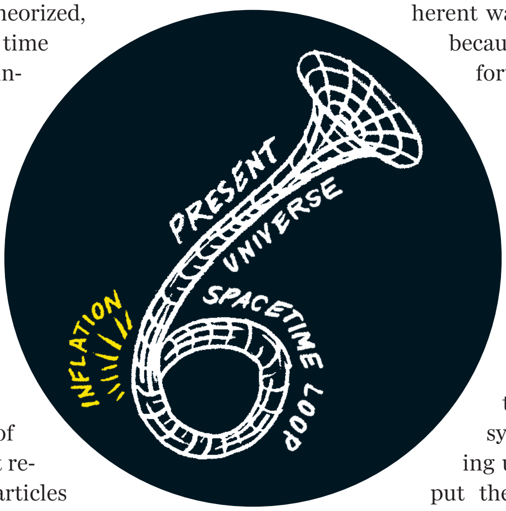
In 1998 Gott and Li-Xin Li, an astrophysicist now at Peking

University in China, published a paper in which they argued that closed timelike curves were not merely possible but essential to explain the origin of the universe. "We investigated the possibility of whether the universe could be its own mother—whether a time loop at the beginning of the universe would allow the universe to create itself," Gott says.

Gott and Li's universe "starts" with a bout of inflation—just as in standard big bang cosmology, where an all-pervasive energy field drove the universe's initial expansion. Many cosmologists now believe that inflation gave rise to countless other universes besides our own. "Inflation is very hard to stop once it gets started," Gott says. "It makes an infinitely branching tree. We're one of the branches. But you have to ask yourself, Where did the trunk come from? Li-Xin Li and I said it could be that one of the branches just loops around and grows up to be the trunk."

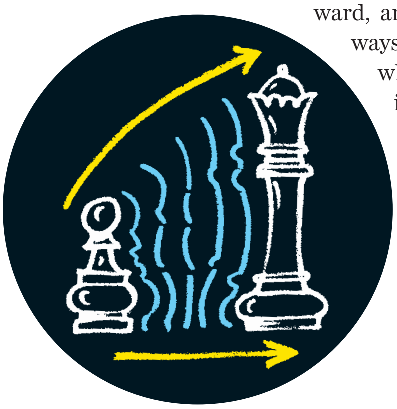
A simple two-dimensional sketch of Gott and Li's self-starting universe looks like the number "6," with the spacetime loop at the bottom and our present-era universe as the top stem. A burst of inflation, Gott and Li theorized, allowed the universe to escape from the time loop and expand into the cosmos we inhabit today.

It is difficult to contemplate the model, but its main appeal, Gott says, is that it eliminates the need for creating a universe out of nothing. Yet Alexander Vilenkin of Tufts University, Stephen Hawking of the University of Cambridge and James Hartle of the University of California, Santa Barbara, have proposed models in which the universe does indeed arise out of nothing. According to the laws of quantum mechanics, empty space is not really empty but is filled with "virtual" particles that spontaneously pop into and out of existence. Hawking and his colleagues theorized that the universe burst into being from the same quantum-vacuum stew. But in Gott's view, the universe is not made out of nothing; it is made out of something—itself.



### A COSMIC CHESS GAME

For now, there is no way to test whether any of those theories might actually explain the origin of the universe. The famed physicist Richard Feynman compared the universe to a great chess game being played by the gods. Scientists, he said, are trying to understand the game without knowing the rules. We watch as the gods move a pawn one space forward, and we learn a rule: pawns always move one space forward. But what if we never saw the opening of a game, when a pawn can move two spaces forward? We might also assume, mistakenly, that pawns always remain pawns—that they never change their identity—until we see a pawn transformed into a queen. "You would say that's against the rules," Gott says. "You can't change your pawn into a queen. Well, yes, you can! You just never saw a game that extreme before. Time-travel research is like that. We're testing the laws of physics by looking at extreme conditions. There's nothing logically impossible about time travel to the past; it's just not the universe we're used to." Turning a pawn into a queen could be part of the rules of relativity.



Such wildly speculative ideas may be closer to philosophy than to physics. But for now, quantum mechanics and general relativity—powerful, counterintuitive theories—are all we have to figure out the universe. "As soon as people start trying to bring quantum theory and general relativity into this, the first thing to say is that they really have no idea what they're doing," says Tim Maudlin, a philosopher of science at New York University. "It's not really rigorous mathematics. It's one piece of mathematics that sort of looks like general relativity and another little piece of mathematics that sort of looks like quantum theory, mixed together in some not entirely coherent way. But this is what people have to do because they honestly don't know how to go forward in a way that makes sense."

Will some future theory eliminate the possibility of time travel into the past? Or will the universe again turn out to be far stranger than we imagine? Physics has advanced tremendously since Einstein redefined our understanding of time. Time travel, which existed only in the realm of fiction for Wells, is now a proved reality, at least in one direction. Is it too hard to believe that some kind of symmetry exists in the universe, allowing us to travel backward in time? When I put the question to Gott, he replies with an anecdote:

"There's a story where Einstein was talking to a guy. The guy pulled a notebook out and scribbled something down. Einstein says, 'What's that?' The guy says, 'A notebook. Whenever I have a good idea, I write it down.' Einstein says, 'I've never had any need for a notebook; I've only had three good ideas.' "

Gott concludes: "I think we're waiting for a new good idea."

**MORE TO EXPLORE**

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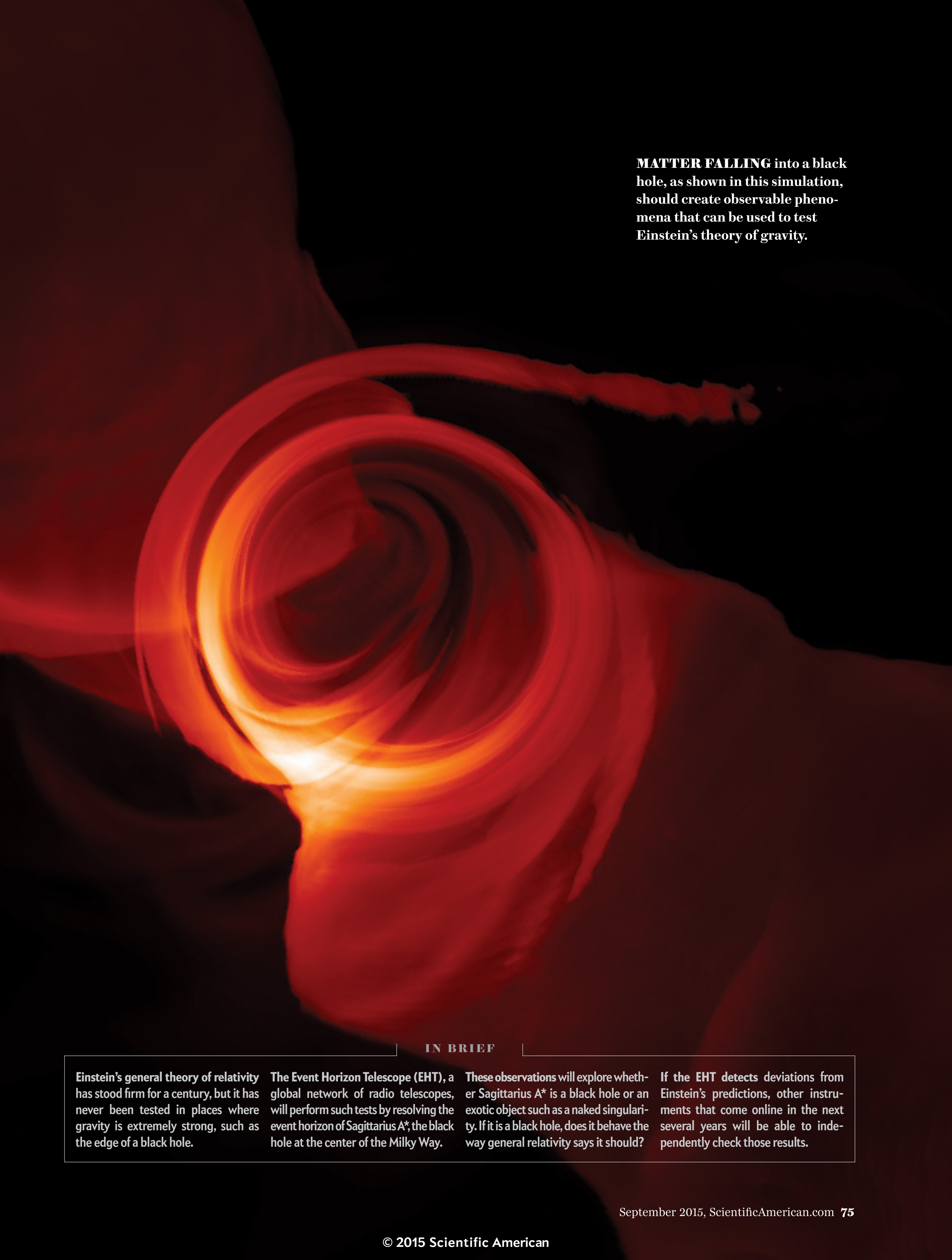
scientificamerican.com/magazine/sa

ASTRONOMY

# THE BLACK HOLE TEST

**General relativity has never been tested in places where the effects of gravity become truly extreme—for example, at the edge of a black hole. That will soon change**

*By Dimitrios Psaltis and Sheperd S. Doeleman*



**MATTER FALLING** into a black hole, as shown in this simulation, should create observable phenomena that can be used to test Einstein's theory of gravity.

IN BRIEF

Einstein's general theory of relativity has stood firm for a century, but it has never been tested in places where gravity is extremely strong, such as the edge of a black hole.

The Event Horizon Telescope (EHT), a global network of radio telescopes, will perform such tests by resolving the event horizon of Sagittarius A*, the black hole at the center of the Milky Way.

These observations will explore whether Sagittarius A* is a black hole or an exotic object such as a naked singularity. If it is a black hole, does it behave the way general relativity says it should?

If the EHT detects deviations from Einstein's predictions, other instruments that come online in the next several years will be able to independently check those results.

**Scientists have been trying** unsuccessfully to poke holes in Albert Einstein's general theory of relativity for a full century. So far, however, Einstein's theory has had it easy. Every assessment to date has been conducted in rather weak gravitational fields. To put general relativity to its greatest test, we need to see whether it holds up where gravity is extremely strong. And nowhere in the universe today is gravity stronger than at the edge of a black hole—at the event horizon, the boundary beyond which gravity is so overwhelming that light and matter that pass through can never escape.

**Dimitrios Psaltis** is a professor of astronomy and physics at the University of Arizona. He has pioneered the development of tests of Einstein's general theory of relativity in strong gravitational fields using observations of black holes and neutron stars in the electromagnetic spectrum.

**Sheperd S. Doeleman** is an astronomer at the Massachusetts Institute of Technology and the Harvard-Smithsonian Center for Astrophysics, where he leads teams that make ultrahigh-resolution observations of black holes. He coordinates the Event Horizon Telescope project.

The interior of a black hole is unobservable, but the gravitational field surrounding these objects causes matter close to the horizon to produce huge amounts of electromagnetic radiation that telescopes can detect. Near the black hole, the crushing force of gravity compresses inflowing matter, known as the accretion flow, into ever smaller volumes. This causes the infalling matter to reach temperatures of billions of degrees—which, ironically, makes the vicinity immediately surrounding a black hole one of the brightest spots in the cosmos.

If we could observe a black hole with a telescope with enough magnifying power to resolve the event horizon, we could follow matter as it spirals down toward the point of no return and see whether it behaves as general relativity says it should. There is, of course, a catch: developing a telescope that can resolve a black hole horizon poses several challenges. Notably we have to contend with the black hole's tiny size when viewed from Earth. Even the supermassive black holes now thought to inhabit the centers of most galaxies, which weigh in at millions or billions of our sun's mass and in some cases have diameters larger than our solar system, are so far away from Earth that they subtend incredibly tiny angles on the sky. The nearest example is Sagittarius A*, the four-million-solar-mass black hole at the center of the Milky Way; its event horizon would appear to be only 50 microarcseconds across, or roughly the size of a DVD seen on the moon. To resolve an object so small, a telescope must have an angular resolution more than 2,000 times finer than that achieved by the Hubble Space Telescope.

What is more, such black holes are obscured from our view in two ways. First, they occur at the very centers of galaxies, deep within dense clouds of gas and dust that block most of the electromagnetic spectrum. Second, even material that emits the light we want to detect—that glowing whirlpool of crushed matter spiraling in toward the horizon—is itself opaque to most wavelengths of light. Consequently, there are only a few wavelengths of light that can escape from the black hole's edge to be observed by us on Earth.

The Event Horizon Telescope (EHT) project is an international effort to overcome these hurdles and perform detailed observations of a black hole. To achieve the highest angular resolutions possible from the surface of Earth, the EHT exploits a technique known as very long baseline interferometry (VLBI), in which astronomers at radio dishes across the globe observe the same target simultaneously, record the data they collect on hard drives, and then later combine all those data using a supercomputer to form a single image. By doing so, many telescopes located on different continents can form one virtual Earth-sized telescope. The resolving power of a telescope is given by the ratio of the wavelength of light it observes to its size, and so VLBI routinely makes images of the radio sky with detail that far surpasses the magnifying power of any optical telescope.

By advancing the technologies used in VLBI so that observations can be made at the shortest radio wavelengths, the EHT will soon be able to meet all the challenges of black hole imaging. At these wavelengths (close to one millimeter in size), the Milky Way is largely transparent, enabling the EHT to observe Sagittarius A* with a minimum of blurring from the intervening gas. These same wavelengths are also able to pierce the matter falling toward the black hole, allowing access to the innermost regions surrounding Sagittarius A*'s event horizon. And in a true Goldilocks coincidence, the magnifying power of a globe-spanning VLBI array at millimeter wavelengths is well suited to resolving the event horizons of the nearest supermassive black holes.

In a parallel development, theoretical astrophysicists have developed mathematical models and computer simulations to explore a wide range of possible outcomes of these observations and to develop tools to interpret them. Using novel supercomputer algorithms, they have simulated the churn of matter just outside the black hole's event horizon, and in all simulations they have found that the black hole casts a "shadow" on the light coming off the accretion flow.

University of Washington physicist James Bardeen predicted the existence of a black hole shadow in 1973. By definition, any light that crosses the event horizon can never return. Bardeen identified the point *outside* the horizon where a photon will orbit the black hole. If a light ray crosses this orbit heading inward, it is caught forever and spirals inward to the event horizon. Light rays originating between the event horizon and this orbit *can* escape, but they have to be pointed almost radially outward, or they, too, risk being caught by the black hole's gravity and having their trajectories bent backward toward the event horizon. We call this boundary the photon orbit.

As far as light is concerned, the black hole acts like an opaque

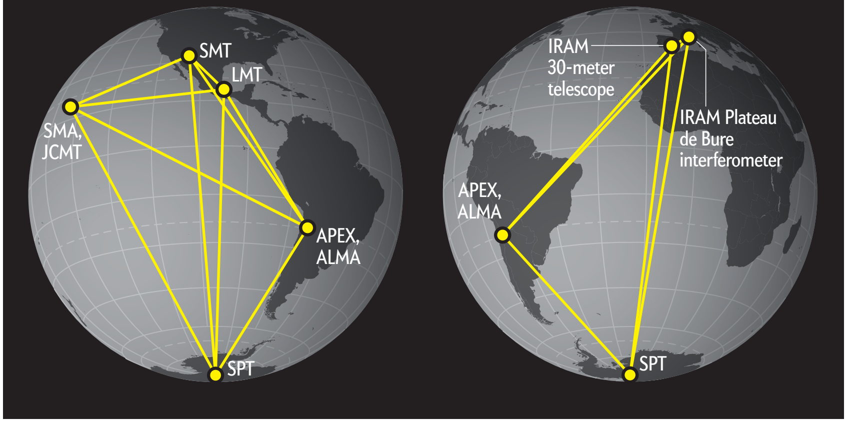
PRECEDING PAGES: COURTESY OF CHI-KWAN CHAN *University of Arizona*

object, with the photon orbit defining its boundary. The contrast between the bright ring of the photon orbit and the dimmer interior is what is known as the shadow. The apparent size of this shadow as seen by observers on Earth is actually predicted to be quite a bit larger than the photon orbit. This occurs because the intense gravitational field surrounding the black hole "magnifies" the shadow through gravitational lensing. [For more on gravitational lensing, see box in "What Einstein Got Wrong," by Lawrence M. Krauss, on page 54.]

BASICS

## A Telescope the Size of Earth

**At least nine radio telescopes** and arrays around the globe will together form the Event Horizon Telescope (EHT). Every telescope is located at high altitude to minimize the absorption of the signals in Earth's atmosphere. By spanning the globe and operating at millimeter wavelengths, the array will achieve an effective angular resolution that is comparable to a few millionths of an arc second—good enough to spot a DVD on the moon.



The EHT is now poised to observe this shadow and other features of black holes. In 2007 and 2009 observations verified that the technological approach was sound—and that the ultimate science goal was within reach—by targeting Sagittarius A* and another supermassive black hole at the heart of the galaxy Virgo A (also known as M87). These early observations linked together sites in Hawaii, Arizona and California to successfully measure the extent of radio emission at a 1.3-millimeter wavelength from both sources. In both cases, the measurements matched the expected size of the black hole shadow.

Observations planned with the full, planet-spanning web of dishes will yield enough data to allow us to construct complete images of these black holes. An additional, equally important set of observations will use VLBI data to search for and trace the trajectories of localized active regions ("hotspots") as they circle the black hole. Because general relativity predicts both what these black holes should look like and how matter should orbit them, these observations will allow us to perform a series of tests of Einstein's theory of relativity in the place where its most extreme predictions become manifest.

### CHECKING COSMIC CENSORSHIP

THE EHT WILL ENABLE US to answer a basic question: Is Sagittarius A* a black hole? All available evidence suggests that the answer is yes, but no one has ever directly observed a black hole, and other possibilities are consistent with general relativity. For example, Sagittarius A* could be something called a naked singularity.

A singularity in physics is a place where the solution to an equation is undefined and where the laws of nature as we understand them no longer operate. General relativity predicts that the universe began in a singularity—an initial moment when all the contents of the cosmos were concentrated into a single point of infinite density. The theory also tells us that a singularity, where gravity becomes infinite and matter is compressed to infinite density, lies at the center of every black hole.

In a black hole, the event horizon hides the singularity from our universe. General relativity does not require all singularities to be "clothed" by a horizon, however. There are an infinite number of solutions to Einstein's equations in which the singularities are "naked." Some of these solutions describe normal black holes spinning so fast that their horizons have "opened up" to reveal the singularity within; others describe black holes that have no event horizon.

Naked singularities, unlike black holes, remain highly theoretical: nobody has come up with a real-world recipe that would lead to their formation. Every astrophysically plausible computer simulation of the gravitational collapse of a star leads to the formation of a black hole with a horizon. Indeed, in 1969 Roger Penrose introduced the cosmic censorship hypothesis: the idea that physics somehow censors the nakedness of singularities by always enshrouding them with a horizon.

In September 1991 California Institute of Technology physicists John Preskill and Kip Thorne made a bet with University of Cambridge physicist Stephen Hawking that the cosmic censorship hypothesis is false and that naked singularities do exist. Two and a half decades later the bet is still standing, begging for an experiment that will settle it. Proving that Sagittarius A* has an event horizon would not conclusively disprove the existence of naked singularities elsewhere. Yet determining that the black hole in the center of our Milky Way is a naked singularity would allow us to directly observe phenomena at conditions where modern physics breaks down.

### LOOKING FOR HAIR

DISCREDITING COSMIC CENSORSHIP would not be a death blow to general relativity; after all, its equations allow for naked singularities. Yet we also expect the EHT to test a long-standing idea about black holes called the no-hair theorem. And if the no-hair theorem is false, general relativity will, at minimum, have to be modified; the mathematical proof of this theorem leaves no wiggle room.

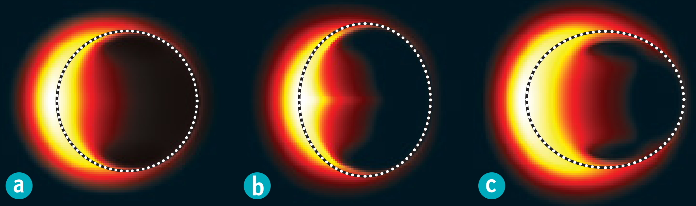
The theorem says that any black hole that is surrounded by an event horizon can be completely described using just three properties: mass, spin and electrical charge. In other words, any two

*Maps by Terra Carta*

# Testing Einstein with Black Holes

**Astrophysicists** have created sophisticated models based on Einstein's general theory of relativity that predict how matter should behave in the vicinity of a black hole. Soon, Event Horizon Telescope observations of the black hole in the center of the Milky Way will tell us whether reality matches those predictions. If it does not, Einstein's theory may need to be modified.

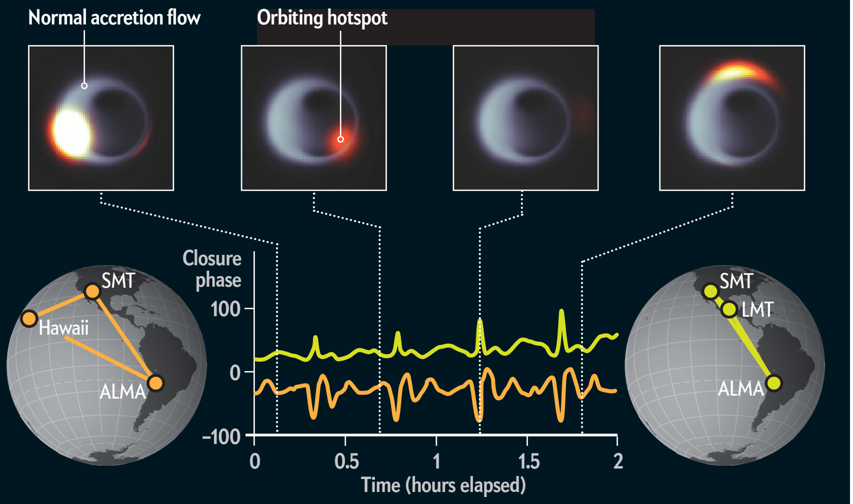
## The Shape of the Shadow



A black hole casts a shadow on the emission from the hot matter surrounding it. The shape and size of the shadow depend, in principle, on how fast the black hole is spinning, on the amount that light rays are gravitationally bent in its vicinity, and on the orientation of the observer. Because of a lucky coincidence, all three effects conspire to make the shadow nearly circular for all black holes and observers ⓐ. This coincidence, however, occurs only if Einstein's theory is correct and the no-hair theorem—which states that a black hole can be completely described by its mass, spin and charge—is satisfied. If observations reveal an elliptical shadow, as shown in images ⓑ and ⓒ, then Einstein's theory will not pass this test.

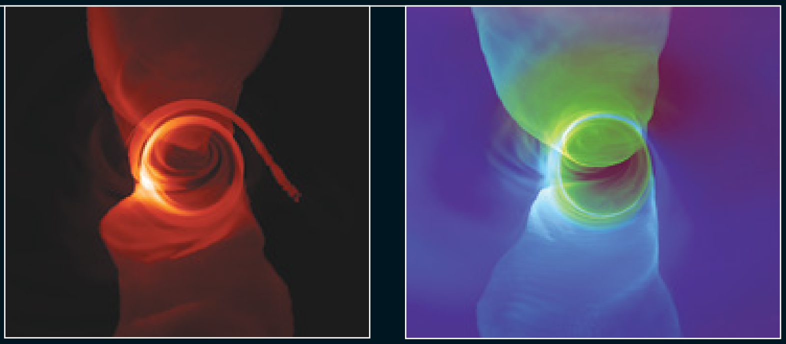
## Tracking Closure Phase

Black holes sometimes flare up, and one explanation is that the normal steady accretion flow may be disrupted by "hotspots," regions of increased temperature that orbit the black hole before dissipating. The EHT will use trios of telescopes to measure the difference in time of arrival of light emitted by hotspots; with these data, it is possible to triangulate the position of hotspots. The simulation at the right shows such a signal (called closure phase) based on data from two different triangles. The orbit of the hotspot creates a "heartbeat" pattern—a time signature in closure phase. Measuring these signals will make it possible to map the spacetime of the black hole and test the predictions of Einstein's theory.



## Simulating a Complex Reality

Scientists affiliated with the EHT are using supercomputers to perform elaborate numerical simulations of accreting black holes that exhibit the expected complexities of astrophysical objects. The right image depicts a black hole in a fairly quiet state of emission; on the left is a magnetically active region during a flare. With these simulations, scientists have developed algorithms that will allow them to extract the properties of black hole shadows from real-world observational data.



COURTESY OF AVERY E. BRODERICK *University of Waterloo and Perimeter Institute for Theoretical Physics (a, b, c* and *top four images in Tracking Closure Phase)*; COURTESY OF CHI-KWAN CHAN *University of Arizona (bottom two images)*; TERRA CARTA *(globes)*

black holes with the same mass, spin and electrical charge are entirely identical, just as any two electrons are indistinguishable. Black holes, the theorem states, have no "hair"—no geometric irregularities or distinguishing characteristics.

When we first started to think about imaging black holes using VLBI, we thought we could use the shapes and sizes of black hole shadows to learn the spins and orientations of the black holes that produced them. But our simulations presented us with an unexpected and, ultimately, very pleasant surprise. No matter how fast we let the black holes spin in our simulations, and no matter where we placed our mock observers, the black hole shadows always appeared nearly circular with an apparent size equal to about five times the radius of the event horizon. Because of some lucky coincidence—and if there is a deep physical reason for this, we still have not uncovered it—no matter how we alter the parameters in our models, the size and shape of the black hole shadow remain practically unchanged. This coincidence is excellent news if our goal is to test Einstein's theory because it happens only if the general theory of relativity holds up [*see box on opposite page*]. If Sagittarius A* has an event horizon, and if the size or the shape of its shadow deviates from our predictions, that would constitute a violation of the no-hair theorem—and, thus, of general relativity.

## TRACING ORBITS AND MORE

EHT OBSERVATIONS will generate a great deal more data than are used to make images. The antennas will record the full polarization of the radiation emitted by the black hole, which will enable us to create maps of the magnetic fields near the event horizon. Such maps could help us understand the physics behind the powerful "jets" emanating from the centers of galaxies such as M87—beams of extraordinarily energetic matter traveling near the speed of light for up to thousands of light-years. Astrophysicists believe that magnetic fields near the event horizon of supermassive black holes power these jets; mapping the magnetic fields could help us test that hypothesis.

We can learn other things by watching the motion of matter around a black hole. The accretion flows around the black holes are expected to be highly turbulent and variable. Computer simulations often show the presence of localized, short-lived, magnetically active regions in them—"hotspots" similar to magnetic eruptions on the surface of the sun. These hotspots, which may explain the brightness variations that are often seen in Sagittarius A*, would circle the black hole at nearly the speed of light, along with the underlying accretion flow, completing full orbits in less than half an hour. In some cases, they become gravitationally lensed as they move behind the black hole and generate nearly complete Einstein rings—bright, gravitationally warped circles of light just like those the Hubble Space Telescope has detected from distant quasars. In other cases, they orbit around the black hole a few times before they lose their energy and dissipate.

Hotspots could complicate the process of making an image because the VLBI technique uses telescopes much like a time-lapse camera, leaving the virtual shutter open for the full duration of the observation and using the natural rotation of Earth to get as many different angles on the black hole as possible. If a bright spot in the accretion flow orbits the black hole, its appearance will be smeared, just as a photograph of a sprinter will be blurry if the camera shutter is left open too long.

Yet hotspots could also enable us to perform an entirely different test of general relativity. The EHT can trace the orbits of hotspots using a technique that goes by the fancy name of closure phase variability tracking. The method involves measuring the delays between the time of arrival of light from the hotspot at three telescopes and then using basic triangulation to infer the position of the hotspot in the sky. Orbiting hotspots will produce distinctive signatures in the raw data collected by the telescopes. And in much the same way that Einstein's equations predict the size and shape of the black hole shadow, they also disclose everything we need to know about the orbits that hotspots should trace. This hotspot model is somewhat schematic, and reality may be more complex. Nevertheless, at full sensitivity the EHT will be able to monitor structure in the accretion flow as it orbits the black hole, and that could provide yet another way of checking to see whether the predictions of general relativity hold up near the edge of a black hole.

## EXTRAORDINARY EVIDENCE

WHAT HAPPENS if our observations appear to disagree with Einstein's theory? To use an expression popularized by Carl Sagan, extraordinary claims require extraordinary evidence. In the natural sciences, extraordinary evidence often means one or more verifications of any claim by independent methods. In the coming years, powerful optical and radio telescopes, as well as space-based gravitational-wave detectors, may provide such verification by monitoring the orbits of stars, neutron stars—tiny, incredibly dense objects produced by the gravitational collapse of massive stars—and other objects around supermassive black holes.

The optical interferometer GRAVITY, which is being built for use on the European Southern Observatory's Very Large Telescope (VLT) in Chile, as well as next-generation 30-meter-class optical telescopes, will track the orbits of stars in our galaxy that lie fairly close to Sagittarius A*'s event horizon—at a distance only a few hundred times the radius of the black hole. Once completed, the Square Kilometer Array (SKA), a radio interferometer under construction in South Africa and in Australia, will begin monitoring the orbits of rapidly spinning neutron stars, called pulsars, around the same black hole. And the evolved Laser Interferometer Space Antenna (eLISA) will detect gravitational waves emitted as small compact objects orbit around supermassive black holes in nearby galaxies.

Because of the very strong gravitational fields of the black holes, the elliptical orbits of these objects will shift (precess) rapidly; this effect is so pronounced that the points of maximum distance from the black holes should trace a complete circle in only a few orbits. At the same time, the black holes will drag spacetime around with them, causing the orbital planes of objects within those spacetimes to precess as well. Measuring the rates of orbital precession for objects at different distances from a black hole will lead to a complete three-dimensional reconstruction of spacetime around a black hole, providing many tests of general relativity in the presence of extremely strong gravity.

Together all these instruments will help decide whether Einstein's general theory of relativity—in particular, its predictions about black holes—will survive intact for another century or be sacrificed on the altar of scientific progress. SA

### MORE TO EXPLORE

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**Testing the No-Hair Theorem with Observations in the Electromagnetic Spectrum. II. Black Hole Images.** Tim Johannsen and Dimitrios Psaltis in *Astrophysical Journal,* Vol. 718, No. 1, pages 446–454; July 20, 2010.

**Jet-Launching Structure Resolved Near the Supermassive Black Hole in M87.** Sheperd S. Doeleman et al. in *Science,* Vol. 338, pages 355–358; October 19, 2012.

**The Power of Imaging: Constraining the Plasma Properties of GRMHD Simulations using EHT Observations of Sgr A*.** Chi-Kwan Chan et al. in *Astrophysical Journal,* Vol. 799, No. 1, Article No. 1; January 20, 2015.

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A STUDY IN CONTRASTS

# WHO WAS EINSTEIN, REALLY?

Sure, he was pretty good at science. But science isn't everything

## WORLD CITIZEN

*Einstein was an outspoken progressive whose views sometimes provoked a backlash.*

## CURMUDGEON

*He may have been the greatest scientist of them all, but Einstein was also socially inept (by his own admission) and, at times, boorish, particularly to the women in his life.*

**ANTIFEMINIST**
In a written contract to his estranged wife, he suggested that they could continue to live together if she met certain conditions, among them:

① That my clothes and laundry are kept in good order.

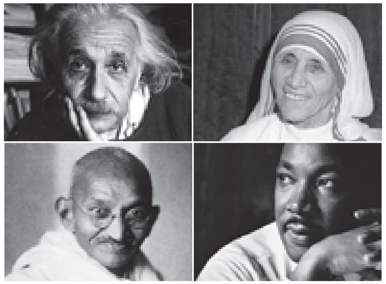
② That I will receive my three meals regularly in my room.

③ That my bedroom and study are kept neat, and especially that my desk is left for my use only.

## ROCK STAR

*A celebrity in his own lifetime, Einstein was arguably the first theoretical physicist to have groupies. On a visit to New York City in the 1920s, he drew large crowds.*

**HERO OF HEROES**
The physicist, according to one survey, is considered the greatest hero of all time, ahead of Mother Teresa, Gandhi and Martin Luther King.



## REBEL

*Einstein often rejected the public's urge to place him on a pedestal. He bucked the status quo and was viewed as an enemy by the Nazis, not least because he was a Jew.*

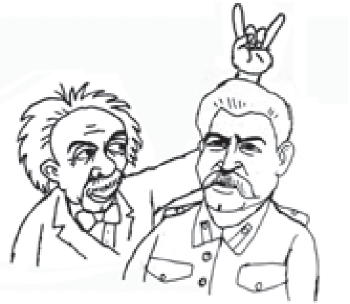
**ICONOCLAST**
"To punish me for my contempt of authority, fate has made me an authority myself," in a message to a friend, 1930.

**SCIENCE OF THE JEWS**
The Nazis championed the notion that Einstein's relativity was a "Jewish theory," mired in foggy thinking. Two German Nobel Prize winners promulgated the idea of "Aryan physics," which, unlike Einstein's theory, did not attempt to destroy the "world view of German man."

*Illustrations by Scott Menchin*

**ARDENT PACIFIST**
Had he known that the Germans were not close to getting the A-bomb, he said, he would never have made his influential personal appeal to F.D.R. to move ahead with the Manhattan Project.

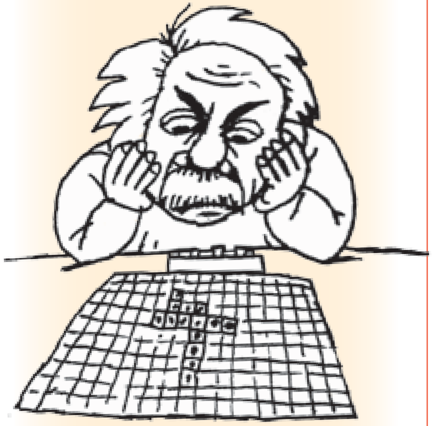
**RIGHT-WING TARGET**
A reactionary women's organization sent a letter to the State Department in 1932 recommending that Einstein be denied a visa because "not even Stalin himself is affiliated with so many anarcho-Communist international groups."



**CHAMPION OF WORLD GOVERNMENT**
"At present we are far from possessing any supranational organization competent to render verdicts of incontestable authority and enforce absolute submission to the execution of its verdicts."

**CIVIL-RIGHTS ADVOCATE**
He was friends with Marian Anderson and Paul Robeson and called racism "a disease of white people."

**PUTTING THE MIND ON HOLD**
He disliked games and anything recreational that required mental agility. "When I get through with work, I don't want anything that requires the working of the mind."

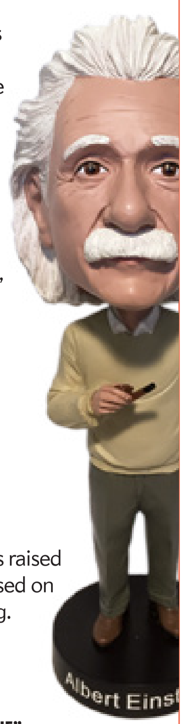


**BAD DAD**
His second son had schizophrenia. Although he helped pay for his care, Einstein never saw him after 1933.

**SOCIAL INEPTITUDE**
In rejecting the offer of the presidency of Israel, he said that he lacked "the natural aptitude and the experience to deal properly with people."

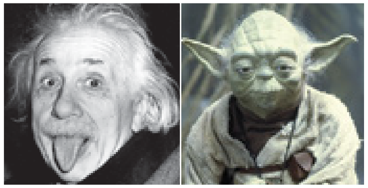
**NOT A TREKKIE**
Einstein derided science fiction.

**EINSTEIN THE BRAND**
He didn't have to build his own personal brand. It created itself. Rights to use Einstein's likeness in bobbleheads and other knickknacks must be procured from the same company (Corbis Entertainment) that manages rights for Steve McQueen, Muhammad Ali, Charlie Chaplin, Thomas Edison, Johnny Cash, the Wright brothers and Martin Luther King.



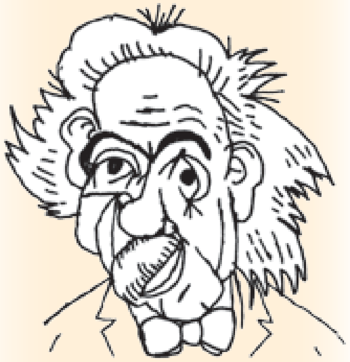
**IN THE BEGINNING WAS THE WORD**
A Kickstarter campaign has raised money to create a font based on Einstein's handwriting.

**"RECKLESS IS HE"**
Artist Stuart Freeborn took Einstein as inspiration for the character Yoda in *Star Wars.*

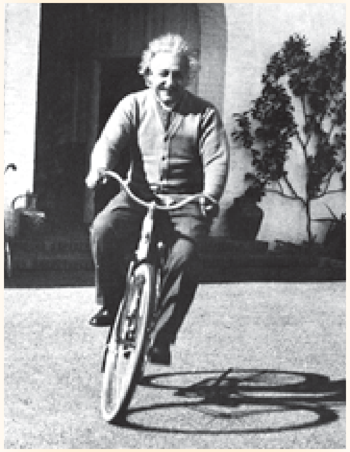


**DO YOU BELIEVE IN ALBERT?**
A 2002 book by science writer and editor Corey S. Powell—*God in the Equation*—suggested that Einstein might be a prophet of sorts.

**"I'M NOT A CUBIST"**
He rejected numerous attempts to equate his ideas about space, time and gravity with the zeitgeist of the 20th century—the upheavals taking place in art, music and philosophy. The theory of relativity had nothing to do, he said, with the growing subjectivity—relativism—evident in the arts and philosophy.



**EVERYMAN**
"I have no special talent, I'm only passionately curious," in a note to his biographer in 1952.



CORBIS (*Martin Luther King, Jr., and Marian Anderson*); GETTY IMAGES (*Paul Robeson, Einstein leaning on hand, Mother Teresa, Gandhi and Einstein sticking out tongue*); BEN MEYER *Caltech Archives* (*Einstein on bike*); SCIENTIFIC AMERICAN (*Einstein bobblehead*); THE PICTURE DESK (*Yoda*)

**EINSTEIN'S BRAIN** was meticulously mapped by pathologist Thomas Harvey, who also supervised the dissection of the specimen. In defiance of hospital protocol, Harvey took the tissues into his own possession and controlled access to them for decades.

NEUROSCIENCE

# GENIUS IN A JAR

## The bizarre journey of Einstein's brain illustrates the pitfalls in science's search for the origins of brilliance

*By Brian D. Burrell*

**On April 18, 1955,** Albert Einstein died at Princeton Hospital of a ruptured aortic aneurysm. Within hours the pathologist on call, Thomas Harvey, acting on his own initiative, removed the famed physicist's brain without the family's permission. He then preserved the organ, counter to Einstein's stated wish to be cremated. Harvey managed to secure a retroactive blessing from Einstein's son Hans Albert, with the stipulation that the brain would be used only for scientific purposes. But Harvey himself lacked the expertise needed to analyze the organ, so he began to seek out specialists to help him. It would take him 30 years to find one. The quest changed the course of Harvey's life and consigned his precious specimen to a fate that is at once strange, sad and fraught with ethical complications.

### IN BRIEF

**Scientists have long** sought the anatomical roots of genius in the brains of renowned thinkers.

**When Einstein died,** pathologist Thomas Harvey removed his brain without permission and took possession of it for decades while he sought out experts to conduct all manner of analyses on it.

**None of the studies** of Einstein's brain or any of the other "elite" brains have been able to conclusively pinpoint the source of mental greatness.

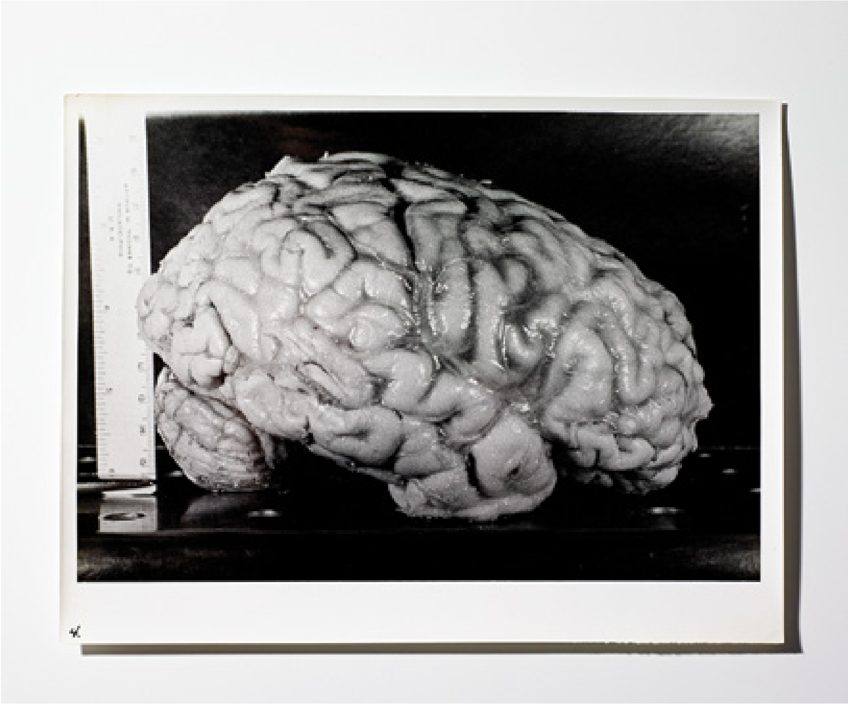
**Researchers have yet** to demonstrate that extraordinary intellectual achievement stems purely from nature rather than nurture.

*Photographs by Plamen Petkov*

**Brian D. Burrell** is a lecturer in mathematics at the University of Massachusetts Amherst. He explored the neuroscience tradition of studying brains of famous intellectuals in *Postcards from the Brain Museum* (Broadway, 2005). His latest book, with Harvard University neurologist Allan H. Ropper, is *Reaching Down the Rabbit Hole* (St. Martin's Press, 2014).

Einstein was not the first renowned thinker to have his brain scrutinized in the name of science. The past is littered with similar examples. I found myself drawn into the curious history of these so-called elite brain studies around 15 years ago, when I heard my frustrated calculus students complaining that the Einsteins of the world have a neuroanatomical advantage over mere mortals such as themselves. I found this idea dismaying—most people's brains are fully equipped to learn college-level calculus—but it prompted me to investigate the scientific literature to see exactly what, if anything, brain research has revealed about the source of mathematical ability in particular and exceptional intellect in general. In so doing, I found that, despite enthusiastic efforts over the past two centuries to discern the anatomy of talent or genius, scientists are not much closer to finding it now than they were in the 1800s.

The case of Einstein's brain is perhaps the most prominent example of how profound this failure has been. As of this writing, half a dozen reports on his brain, each highlighting a different anatomical feature as the possible fount of his brilliance, have come forth—all to great media fanfare. None has revealed a credible anatomical basis for the man's aptitude. Instead they simply add to the pile of flawed brain studies that have collectively spawned what one critic has ruefully termed a "neuromythology" of genius.



**HARVEY'S PHOTOGRAPHS** show the right lateral view (*left*) and frontal view (*right*) of Einstein's brain prior to dissection.

SCIENTIFIC AMERICAN AND ST. MARTIN'S PRESS ARE AFFILIATES

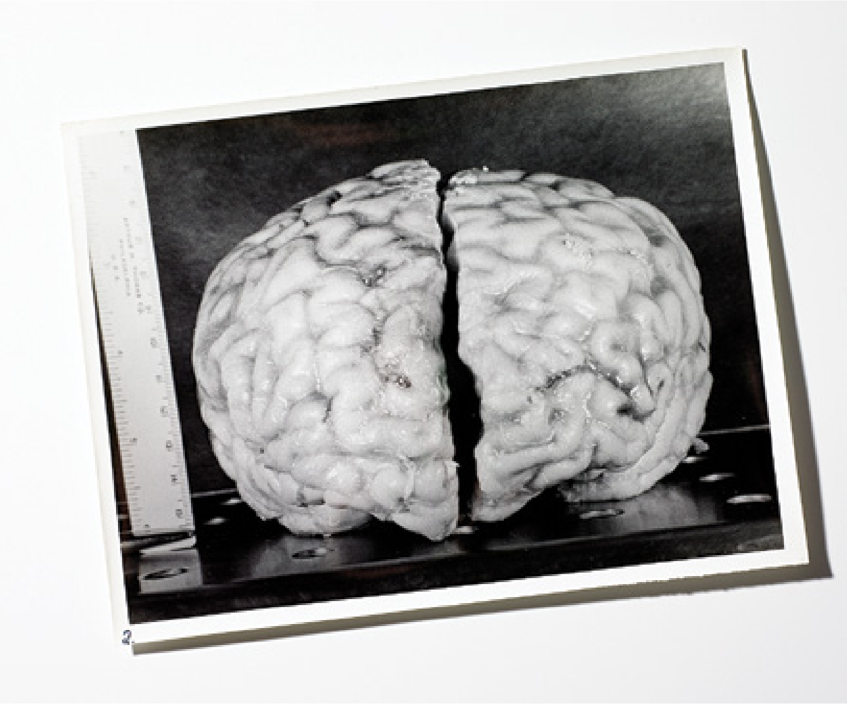
### BRAIN EQUALS MIND?

THE LONG AND CHECKERED TRADITION of studying the brains of gifted people began 100 years before Einstein's death with the passing in 1855 of German mathematician Carl Friedrich Gauss, the Einstein of his day. Gauss's University of Göttingen colleagues presided over his autopsy and removed his brain. One of them, an anatomist named Rudolph Wagner, then preserved the whole brain in an alcohol solution and later convinced Gauss's son to allow him to keep it for research. Wagner obtained the organ to bolster his firmly held belief in René Descartes's philosophy of dualism: the idea of the mind as something more than the sum of the brain's physical functions. Are human beings merely sophisticated machines, or are they endowed by God with a soul substance? This question was the hot-button issue of the era. Either brain equals mind, or it doesn't. For Wagner, the very existence of God hung on the answer.

Acquiring the brain of a celebrated genius opened the door to more acquisitions, and within seven years Wagner published two detailed studies of the comparative anatomy of primate brains. His data set included measurements of 964 brains from people of all walks of life—English poet Lord Byron and French naturalist Georges Cuvier, among them. Wagner found nothing to dispel his dualistic view of the mind. Neither brain weight nor surface convolution patterns seemed to correspond with intellectual prowess. Cuvier's brain was huge, but so was the brain of a manual laborer. Gauss's brain had an intricate pattern of grooves, or sulci, in the cerebral surface, but so did a washerwoman's. Thus, the crucial difference between a genius and an average Joe, it seemed, had to lie below the surface or even beyond brain anatomy altogether. Perhaps it derived, as Wagner hoped, from the divine element, the ghost in the machine.

Scientific materialists of that era, unhappy with Wagner's findings, took the audacious step of founding brain-donation societies in hopes of identifying the physical underpinnings of exceptional talent. Membership hinged on the promise to bequeath one's brain to one's fellows. By the end of the 19th century, as science began to usurp the role of religion, bestowing one's brain became a positively fashionable thing to do. Enthusiasm peaked at the founding of the brain societies, however, and quickly waned in the absence of any substantiated findings. By the dawn of the 20th century the specimens had piled up, but most went unstudied or were lost to neglect.

Exactly what fueled Harvey's obsession with Einstein's brain is unknown. He was aware of the historical precedents, of the many collections of celebrated brains. He may have simply been overcome by curiosity. But the political atmosphere of the 1950s may have motivated him, too. Harvey knew that in the 1920s, the search for the anatomy of genius had moved on to the cellular level. Soviet scientists, having amassed a pantheon of celebrated brains, including those of Vladimir Lenin and Joseph Stalin, established a secretive research program to map the cortical layers of the brain's hemispheres based on neuronal patterns, a specialty known as cytoarchitectonics. Outsiders were denied access to the specimens, and the Soviets always seemed poised to announce a great discovery, although they never did. It was in this atmosphere of cold war competitiveness and paranoia that Harvey decided to appropriate Einstein's brain.



## SLICED AND DICED

BY ALL ACCOUNTS, Harvey was an eccentric man but scrupulous. Once he acquired his hallowed relic, he approached it as methodically as any crime scene investigator. He photographed the cortical surface from every angle, inserting a scale bar so that measurements could be made from the images. He then took the specimen to the pathology laboratory at the University of Pennsylvania and entrusted it to a gifted technician, Marta Keller. Under Harvey's exacting instructions, while using the best practices at the time for neurological tissue preparation, Keller spent the next eight months dissecting portions of the cortex, embedding 240 numbered chunks of it in blocks of a clear plastic material called celloidin and mounting 12 sets of microscope slides with stained tissue slices. Harvey sent slide sets to several of his peers. None of them found anything unusual in the slides, but they did find something strange about Harvey's obsessive control over the brain.

Pathologists generally have the latitude of removing, preserving and studying organs, explains Umberto De Girolami, a neuropathologist at Boston's Brigham and Women's Hospital. But "all tissues removed, as authorized to be retained by written permission, are under the custody of the hospital and are never considered the personal property of the attending pathologist." In defiance of protocol and his employer's demands, Harvey refused to relinquish his precious specimen and was eventually fired in 1960. He packed his belongings and left for the Midwest, bringing with him two jars. One contained the sugar-cube-size, celloidin-embedded chunks Keller had so carefully prepared; the other held the undissected portions of Einstein's brain. He stowed the jars in a beer cooler along with the remaining sets of slides and the calibrated photographs.

Harvey suffered several downward turns after the hospital terminated him. His marriage fell apart, and he lost his medical license. He then took a job in a plastics-extrusion factory. He moved frequently, at one point becoming a neighbor and drinking companion of writer William S. Burroughs. But he never lost interest in the brain, and eventually, three decades after he removed it from Einstein's corpse, Harvey found a neuroscientist to study it. Or rather she found him.

In 1985 Marian C. Diamond of the University of California, Berkeley, requested four of Harvey's tissue blocks. She was interested in studying Einstein's glial cells. Glial cells act as a support system for neurons. In Diamond's previous work with mice, she found that exposure to a sensory-enriched environment produces a higher ratio of glial cells to neurons than does a nonstimulating environment. She suspected that Einstein might have possessed a high ratio of glial cells to neurons in portions of his cortex associated with higher neural functions such as mental imagery, memory and attention.

When Diamond examined the material Harvey sent, she found what she was looking for in one of the four tissue blocks and concluded that the higher proportion of glial cells she observed resulted from Einstein's enhanced use of this tissue. In the ensuing media frenzy around her study, however, journalists gave the impression that this surfeit was not the product of his deep thinking but the cause of it.

It was not long before scientists themselves began to search for anatomical explanations for Einstein's intellectual prowess. Studies in the 1990s by Britt Anderson, then at the University of Alabama at Birmingham, and psychologist Sandra Witelson of McMaster University in Ontario attributed it to other distinctive aspects of his brain. Anderson called attention to the high density of cells in his prefrontal cortex. For her part, Witelson focused on the atypical absence of the so-called parietal operculum, part of a fissure that divides the parietal lobe. As a result, she claimed, Einstein had an expanded cortical region associated with visuospatial and mathematical abilities.

The ensuing decade saw the publication of many interesting studies on anatomical anomalies in the brains of professional musicians and London taxi drivers but nothing on Einstein. Then, in 2007, just around the time of Harvey's death, neuro-ophthalmologist Frederick E. Lepore of what is now the Rutgers

**DESPITE HARVEY'S CONSIDERABLE EFFORTS** to prepare Einstein's brain for study, the source of the physicist's genius remains unknown. Today his brain is scattered in several locations. Harvey's personal collection of drawings, photographs and tissue slides (*above*) is housed at the National Museum of Health and Medicine in Silver Spring, Md.

Robert Wood Johnson Medical School discovered a previously unreported cache of Harvey's calibrated photographs of Einstein's brain. He shared these with Dean Falk, a paleoanthropologist at Florida State University who works primarily on brain evolution. Falk noticed some odd features in the topography of the brain, including a knob on the cortex known as the Omega sign that had previously been linked to musical talent. "It is interesting to contemplate," she wrote, "that [Einstein's] extraordinary abilities may, to some degree, have been associated with the unusual gross anatomy of his cerebral cortex."

In the most recent of the Einstein brain studies, published online in 2013, Falk and Weiwei Men of East China Normal University in Shanghai claimed to find another anatomical explanation for the physicist's prodigious powers of thought: in addition to his unique cortical structure and cytoarchitectonics, Einstein had "enhanced communication routes between at least some parts of his two cerebral hemispheres," they claimed. They based their conjecture on measurements of the cross-sectional area of the corpus callosum, the fiber bundle connecting the left and right hemispheres, of Einstein's brain as compared with a control group.

> **When you begin with the assumption that geniuses are different from everyone else, the culprit would logically be any anatomical anomaly you happen to come across.**

As compelling as these proposed explanations for Einstein's achievements are at first glance, they all suffer from similar methodological defects. Terence Hines, a psychologist at Pace University, has been their most persistent critic. Hines observes that, among other scientific sins, the architects of these studies have tended to favor findings that support their preconceptions, downplaying aspects of Einstein's brain that are either within normal limits or even deficient. Poorly chosen comparative samples have further confused matters. Anderson, for instance, measured Einstein's brain against only five other brains in her study—hardly enough to capture the range of human variation and generate statistically significant conclusions.

Perhaps most troubling of all is the post hoc fallacy that haunts almost every claim to have pinpointed the anatomical substrate of genius: when you begin with the assumption that geniuses are different from everyone else, the culprit would logically be any anatomical anomaly that you happen to come across. And if you make enough measurements of anyone's brain, you will find something that sets it apart.

### NATURE VS. NURTURE

TODAY, SOME 60 YEARS AFTER Harvey's fateful decision, Einstein's brain is scattered in several locations. Harvey returned the bulk of it—170 of the original 240 pieces embedded in celloidin, along with the cerebellum and brain stem—to Princeton Hospital (since replaced with the University Medical Center of Princeton at Plainsboro) shortly before his death a decade ago. That material is now in the care of pathologist Elliot Krauss of the Princeton medical center, who holds Harvey's old job and who guards the material closely. Harvey's personal collection of some 500 slides, as well as his calibrated photographs, went to the National Museum of Health and Medicine in Silver Spring, Md. Other slides and bits and pieces are distributed among a dozen museums and university researchers. And speculation about the source of Einstein's brilliance continues.

Would science, and neuroscience in particular, be better off if Einstein's brain had been cremated with his body? The point is now moot, but the question deserves some consideration. In 1906, more than a century before Men and Falk did their research, American anatomist Edward Anthony Spitzka thought he had found the key to mental acuity in the cross-sectional area of the corpus callosum. In his report he suggested that men of genius "were capable of their great efforts of the intellect … as it were, 'without taking pains.'" Authors of subsequent elite brain studies, including those focused on Einstein, have echoed his suggestion that mental greatness is purely a trick of nature. Yet none has shown it to be true.

To my mind, this failure is ultimately a good thing because the discovery of substrates of talent—or lack thereof—in the brain would have troubling practical and ethical implications. If medical imaging could reveal anatomical correlates of talent, would parents then start screening children and directing them to training regimens that accord with their neuroanatomy? Would they deny physics club or music lessons to a kid who lacks the Omega sign?

To a student who laments not being born with a math brain, I would point out that Einstein might not have been either. We don't know, and it doesn't matter. Behind the great achievements of a Gauss or an Einstein is in all cases a life devoted to contemplation, curiosity, collaboration and, perhaps most of all, hard work.

#### MORE TO EXPLORE

**On the Brain of a Scientist: Albert Einstein.** Marian C. Diamond et al. in *Experimental Neurology,* Vol. 88, No. 1, pages 198–204; April 1985.

**Alterations in Cortical Thickness and Neuronal Density in the Frontal Cortex of Albert Einstein.** Britt Anderson and Thomas Harvey in *Neuroscience Letters,* Vol. 210, No. 3, pages 161–164; June 7, 1996.

**The Exceptional Brain of Albert Einstein.** Sandra F. Witelson et al. in *Lancet,* Vol. 353, No. 9170, pages 2149–2153; June 19, 1999.

**The Corpus Callosum of Albert Einstein's Brain: Another Clue to His High Intelligence?** Weiwei Men et al. in *Brain.* Published online September 24, 2013.

**The Cerebral Cortex of Albert Einstein: A Description and Preliminary Analysis of Unpublished Photographs.** Dean Falk, Frederick E. Lepore and Adrianne Noe in *Brain,* Vol. 136, No. 4, pages 1304–1327; April 1, 2013.

#### FROM OUR ARCHIVES

**High-Aptitude Minds.** Christian Hoppe and Jelena Stojanovic; *Scientific American Mind,* August/September 2008.

scientificamerican.com/magazine/sa

# IS THE COSMOS RANDOM?

QUANTUM PHYSICS

## Einstein's assertion that God does not play dice with the universe has been misinterpreted

*By George Musser*

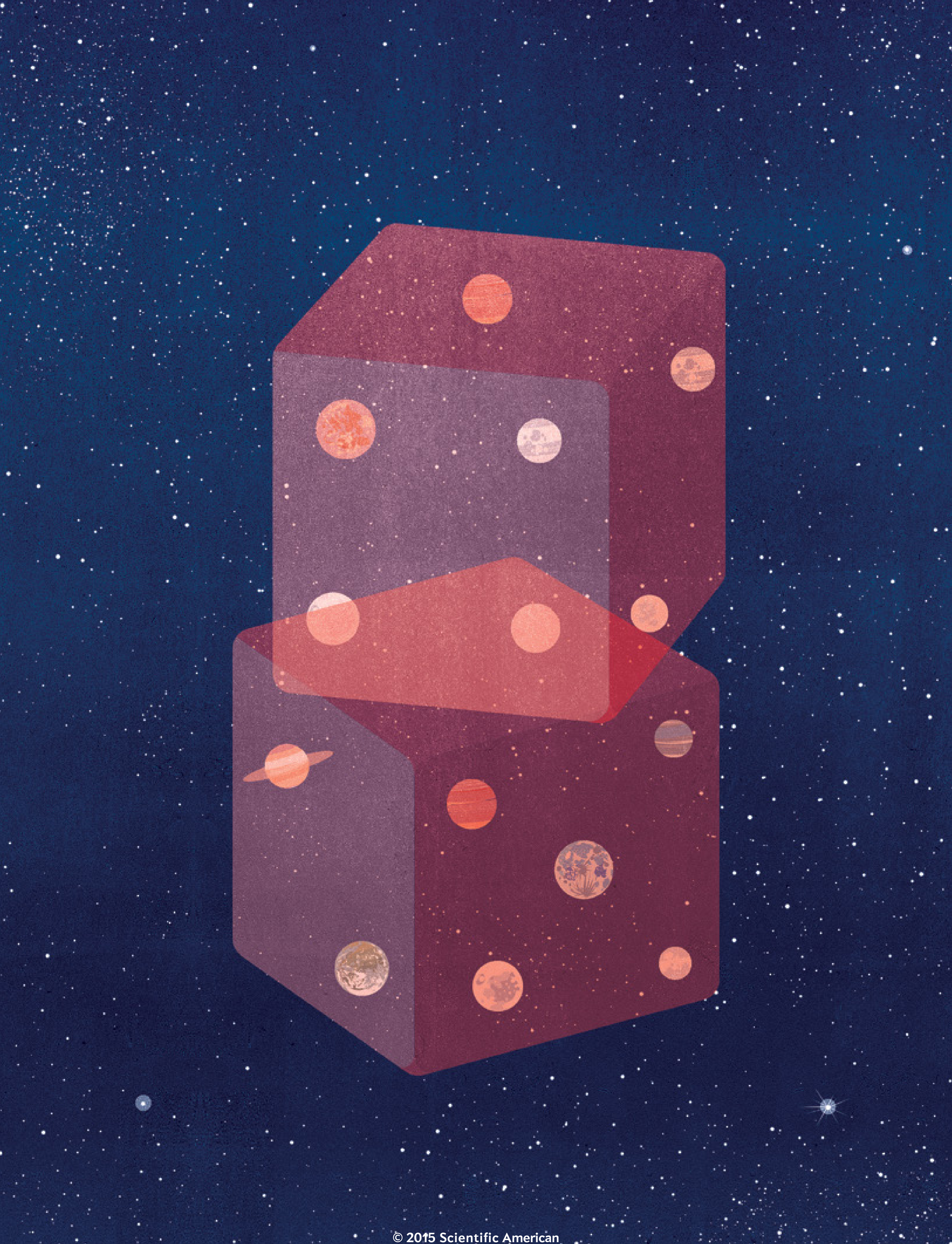
**Few of Albert Einstein's sayings** have been as widely quoted as his remark that God does not play dice with the universe. People have naturally taken his quip as proof that he was dogmatically opposed to quantum mechanics, which views randomness as a built-in feature of the physical world. When a radioactive nucleus decays, it does so spontaneously; no rule will tell you when or why. When a particle of light strikes a half-silvered mirror, it either reflects off it or passes through; the outcome is open until the moment it occurs. You do not need to visit a laboratory to see these processes: lots of Web sites display streams of random digits generated by Geiger counters or quantum optics. Being unpredictable even in principle, such numbers are ideal for cryptography, statistics and online poker.

Einstein, so the standard tale goes, refused to accept that some things are indeterministic—they just happen, and there is not a darned thing anyone can do to figure out why. Almost alone among his peers, he clung to the clockwork universe of classical physics, ticking mechanistically, each moment dictating the next. The dice-playing line became emblematic of the B side of his life: the tragedy of a revolutionary turned reactionary who upended physics with relativity theory but was, as Niels Bohr put it, "out to lunch" on quantum theory.

Over the years, though, many historians, philosophers and physicists have challenged this story line. Diving into what Einstein actually said, they have found that his thinking about indeterminism was far more radical and nuanced than is commonly portrayed. "It becomes a kind of a mission to get the story right," says Don A. Howard, a historian at the University of Notre Dame. "It's amazing when you dig into the archives and see the disparity from the common narrative." As he and others have shown, Einstein accepted that quantum mechanics was indeterministic—as well he might, because he was the one who had *discovered* its indeterminism. What he did not accept was that this indeterminism was fundamental to nature. It gave every indication of arising from a deeper level of reality that the theory was failing to capture. His critique was not mystical but focused on specific scientific problems that remain unsolved to this day.

The question of whether the universe is a clockwork or a craps table strikes at the heart of what we suppose physics to be: a search for simple rules that underlie the wondrous diversity of nature. If some things happen for no reason, they mark the limits of rational inquiry. "Fundamental indeterminism would mean an end to science," worries Andrew S. Friedman, a cosmologist at the Massachusetts Institute of Technology. And yet philosophers throughout history have supposed that indeterminism is a prerequisite for human free will. Either we are all gears in the clock-

*Illustration by Shout*



**George Musser** is a contributing editor at *Scientific American* and author of the book *Spooky Action at a Distance,* to be published by Scientific American/Farrar, Straus and Giroux in November.

work, so that everything we do is preordained, or we are the agents of our own destiny, in which case the universe must not be deterministic after all. This dichotomy has had very real consequences for how society holds people responsible for their actions. Assumptions about free will suffuse our legal system; to be culpable, an offender must have acted with intent. The courts continually wrestle with whether people are innocent by reason of insanity, adolescent impulsiveness or rotten social background.

Whenever people talk about a dichotomy, though, they usually aim to expose it as false. Indeed, many philosophers think it is meaningless to say whether the universe is deterministic or indeterministic. It can be either, depending on how big or complex your object of study is: particles, atoms, molecules, cells, organisms, minds, communities. “The distinction between determinism and indeterminism is a level-specific distinction,” says Christian List, a philosopher at the London School of Economics and Political Science. “If you have determinism at one particular level, it is fully compatible with indeterminism, both at higher levels and at lower levels.” The atoms in our brain can behave in a completely deterministic way while still giving us freedom of action because atoms and agency operate on different levels. Likewise, Einstein sought a deterministic subquantum level without denying that the quantum level was probabilistic.

## WHAT EINSTEIN OBJECTED TO

HOW EINSTEIN EVER GOT TAGGED as antiquantum is almost as big a mystery as quantum mechanics itself. The very notion of quanta—of discrete units of energy—was his brainchild in 1905, and for a decade and a half he stood practically alone in its defense. Einstein came up with most of what physicists now recognize as the essential features of quantum physics, such as light’s peculiar ability to act as both particle and wave, and it was his thinking about wave physics that Erwin Schrödinger built on to develop the most widely used formulation of quantum theory in the 1920s. Nor was Einstein antirandomness. In 1916 he showed that when atoms emit photons, the timing and direction of emission are random. “This goes against the popular image of Einstein as an adversary to probability,” says philosopher Jan von Plato of the University of Helsinki.

But Einstein and his contemporaries faced a serious problem. Quantum phenomena are random, but quantum *theory* is not. The Schrödinger equation is 100 percent deterministic. It describes a particle or system of particles using a so-called wave function, which expresses particles’ wave nature and accounts for the undulating patterns that collections of particles can form. The equation predicts what happens to the wave function at every moment with complete certainty. In many ways, the equation is *more* deterministic than Newton’s laws of motion: it does not lead to muddles such as singularities (where quantities become infinite and thus indescribable) or chaos (where motion becomes unpredictable).

The tricky part is that determinism of the Schrödinger equation is the determinism *of the wave function,* and the wave function is not directly observable, as the positions and velocities of particles are. Instead the wave function specifies the quantities that can be observed and the likelihood of each eventuality. The theory leaves open what exactly the wave function is and whether it should be taken literally as a real wave out there in the world. Thus, it also leaves open whether observed randomness is instrinsic to nature or just a facade. “People say that quantum mechanics is indeterministic, but that’s too quick,” says philosopher Christian Wüthrich of the University of Geneva in Switzerland.

Werner Heisenberg, another early pioneer of quantum theory, envisioned the wave function as a haze of potential existence. If it fails to pinpoint unequivocally where a particle is located, that is because the particle is not, in fact, located anywhere. Only when you observe the particle does it materialize somewhere. The wave function might have been spread out over a huge region of space, but at the instant the observation is made, it abruptly collapses to a narrow spike at a single position, and the particle pops up there. When you so much as look at a particle—bam!—it stops behaving deterministically and leaps to an end result like a kid grabbing a seat in musical chairs. No law governs collapse. There is no equation for it. It just happens.

Collapse became a core ingredient of the Copenhagen interpretation, the view of quantum mechanics named for the city where Bohr had his institute and Heisenberg did much of his early work. (Ironically, Bohr himself never accepted wave function collapse.) Copenhagen takes the observed randomness of quantum physics at face value, incapable of further explanation. Most physicists accepted it, if only because of a psychological anchoring effect: it was a good enough story, and it was the first.

Although Einstein was not antiquantum, he was definitely anti–Copenhagen interpretation. He recoiled from the idea that the act of measurement should cause a break in the continuous evolution of a physical system, and that was the con-

### IN BRIEF

**“I, at any rate,** am convinced that He is not playing at dice,” Albert Einstein wrote to a colleague in 1926. Repeated over the years, his sound bite became the quintessential put-down of quantum mechanics and its embrace of randomness.

**Closer examination,** though, reveals that Einstein did not reject quantum mechanics or its indeterminism, although he did think—for solid scientific reasons—that the randomness could not be a fundamental feature of nature.

**Today many philosophers** argue that physics is *both* indeterministic and deterministic, depending on the level of reality being considered.

**This view dissolves** the much debated dilemma between determinism and free will. Even if everything that particles do is preordained, the choices we make can be completely open because the low-level laws governing particles are not the same as the high-level laws governing human consciousness.

*SCIENTIFIC AMERICAN AND FARRAR, STRAUS AND GIROUX ARE AFFILIATES*

text in which he began to complain about divine dice rolling. "It's that, specifically, that Einstein is lamenting in 1926 and not a blanket metaphysical assertion of determinism as an absolutely necessary condition," Howard says. "He's specifically in the thick of these arguments about whether or not wave function collapse introduces discontinuities."

Collapse could not be a real process, Einstein reasoned. It would require instantaneous action at a distance—a mysterious mechanism ensuring that, say, the left side and right side of a wave function both collapse to the same narrow spike even when no force is coordinating them. Not just Einstein but every physicist of his day thought such a process impossible; it would operate faster than light, in apparent violation of relativity theory. In effect, quantum mechanics does not just give you dice to play with. It gives you pairs of dice that always come up doubles, even if you roll one in Vegas and the other on Vega. For Einstein, it seemed obvious that the dice must be loaded—possessing hidden attributes that fix their outcome in advance. But Copenhagen denied any such thing, implying the dice really do affect each other instantly across the vastness of space.

Einstein was further troubled by the power that Copenhagen accorded to measurement. What is a measurement, anyway? Is it something that only conscious beings or tenured professors can do? Heisenberg and other Copenhagenists failed to elaborate. Some suggested that we create reality in the act of observing it—an idea that sounds poetic, perhaps a little too poetic. Einstein also thought it took a lot of chutzpah for Copenhagenists to claim that quantum mechanics was complete, a final theory never to be superseded. He regarded all theories, including his own, as stepping-stones to something greater.

In fact, Howard argues that Einstein would have been happy to entertain indeterminism as long as his concerns were addressed—if, for example, someone could spell out what a measurement was and how particles could stay in sync without acting at a distance. As a sign that Einstein considered indeterminism a secondary concern, he made the same demands of deterministic alternatives to Copenhagen and rejected them, too. Another historian, Arthur Fine of the University of Washington, thinks Howard overstates Einstein's receptiveness to indeterminism but agrees that the man's thinking was more solidly grounded than the dice-playing sound bite has led generations of physicists to assume.

## RANDOM THOUGHTS

IF YOU TUG ON COPENHAGEN'S LOOSE ENDS, Einstein thought, you should find that quantum randomness is like every other type of randomness in physics: the product of deeper goings-on. The dancing of a dust mote in a shaft of sunlight betrays the complex motions of unseen air molecules, and the emission of a photon or radioactive decay of a nucleus is analogous, Einstein figured. In his estimation, quantum mechanics is a broad-brush theory that expresses the overall behavior of nature's building blocks but lacks the resolution to capture individual cases. A deeper, more complete theory would explain the motion in full without any mysterious jumps.

In this view, the wave function is a collective description, like saying that a fair die, repeatedly tossed, will land roughly the same number of times on each side. Wave function collapse is not a physical process but the acquisition of knowledge. If you roll a six-sided die and it lands on, say, four, the range of one to six "collapses" to the actual outcome of four. A godlike demon, able to track all the atomic details affecting the die—the exact way your hand sends the cube tumbling across the table—would never speak of collapse.

**Einstein was trying to explain randomness, not explain it away.**

Einstein's intuitions were backed up by his early work on the collective effects of molecular motion—studied by the branch of physics known as statistical mechanics—in which he had demonstrated that physics could be probabilistic even when the underlying reality was deterministic. In 1935 Einstein wrote to philosopher Karl Popper, "I do not believe that you are right in your thesis that it is impossible to derive statistical conclusions from a deterministic theory. Only think of classical statistical mechanics (gas theory, or the theory of Brownian movement)."

The probabilities in Einstein's way of thinking were just as objective as those in the Copenhagen interpretation. Although they did not appear in the fundamental laws of motion, they expressed other features of the world; they were not merely artifacts of human ignorance. Einstein gave Popper the example of a particle that moves around a circle at steady speed; the chance of finding the particle in a given arc of the circle reflects the symmetry of its path. Similarly, a die has a one-sixth chance of landing on a given side because it has six equal sides. "He did understand better than most at that time that there was significant physical content in the details of statistical-mechanical probabilities," Howard says.

Another lesson of statistical mechanics was that the quantities we observe do not necessarily exist on a deeper level. For instance, a gas has a temperature, but a single gas molecule does not. By analogy, Einstein came to believe that a subquantum theory needed to mark a radical break from quantum mechanics. In 1936 he wrote, "There is no doubt that quantum mechanics has seized hold of a beautiful element of truth.... However, I do not believe that quantum mechanics will be the *starting point* in the search for this basis, just as, vice versa, one could not go from thermodynamics (resp. statistical mechanics) to the foundations of mechanics." To fill in that deeper level, Einstein sought a unified field theory, in which particles derive from structures that look nothing like particles. In short, conventional wisdom is wrong that Einstein repudiated the randomness of quantum physics. He was trying to explain the randomness, not to explain it away.

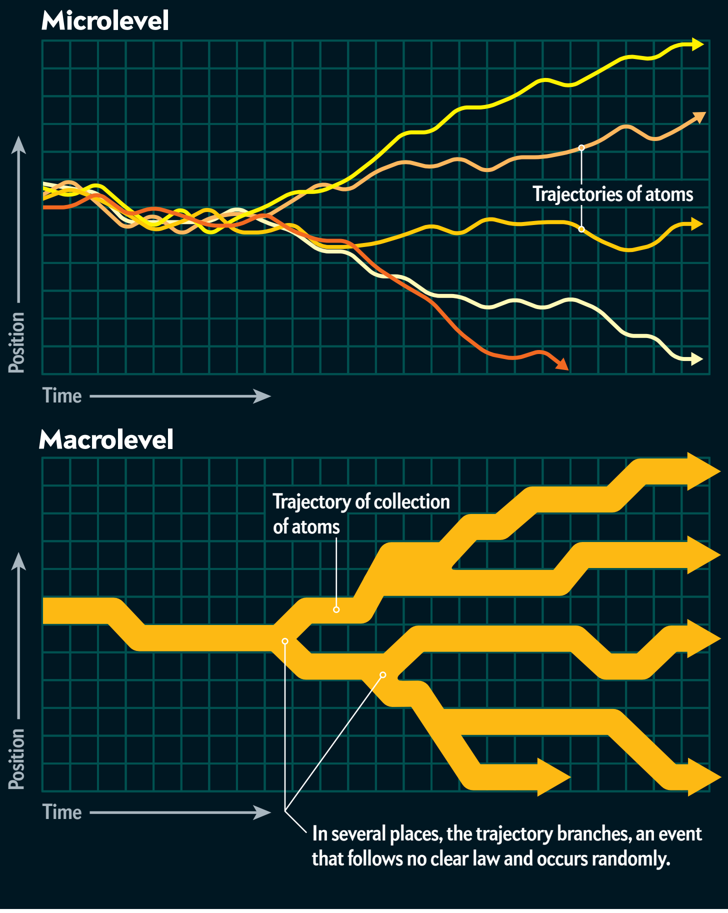
## DO YOUR LEVEL BEST

ALTHOUGH EINSTEIN'S OVERALL PROJECT FAILED, his basic intuition about randomness still holds: indeterminism can emerge from determinism. The quantum and subquantum levels—or any other pair of levels in the hierarchy of nature—consist of dis-

KEY CONCEPT

# Reality’s Many Realms

**Is the world deterministic or indeterministic?** The answer depends not only on the basic laws of motion but also on the level at which a system is described. Consider five atoms in a gas moving deterministically (*top plot*). They start at nearly the same location and gradually spread out. On a macroscopic level (*bottom plot*), though, one would not see individual atoms but an amorphous puff of gas. After a time, the gas might split at random into multiple puffs. This macrolevel randomness is not an artifact of an observer’s ignorance about the microlevel; it is an objective feature of nature, reflecting how atoms agglomerate. Analogously, Einstein suspected that a deterministic subrealm of the universe leads to the randomness of the quantum realm.



SOURCE: “EMERGENT CHANCE,” BY CHRISTIAN LIST AND MARCUS PIVATO, IN *THE PHILOSOPHICAL REVIEW*, VOL. 124, NO. 1; JANUARY 2015

tinct types of structures, so they abide by different types of laws. The laws governing one level can leave a genuine element of randomness even if the laws underneath it are completely regimented. “A deterministic microphysics does not induce a deterministic macrophysics,” says philosopher Jeremy Butterfield of the University of Cambridge.

Think of a die at the atomic level. It can be constructed from zillions of atomic configurations that look utterly indistinguishable to the eye. If you track any one of these configurations as the cube is rolled, it will lead to a specific outcome—deterministically. In some configurations, the die ends up showing one dot; in others, two; and so on. Therefore, a single macroscopic condition (being rolled) can lead to multiple possible macroscopic outcomes (showing one of six faces) [*see box at left*]. “If we describe the die at a macrolevel, we can think of it as a stochastic system, which admits objective chance,” says List, who has studied the meshing of levels with Marcus Pivato, a mathematician at the University of Cergy-Pontoise in France.

Although the higher level builds (in the jargon, “supervenes”) on the lower one, it is autonomous. To describe dice, you need to work at a level where dice exist, and when you do so, you cannot help but neglect atoms and their dynamics. If you cross one level with another, you commit the fallacy of a category mistake, which is like asking about the political affiliations of a tuna sandwich (to use an example from philosopher David Z Albert of Columbia University). “When we have phenomena that can be described at multiple levels, we have to be conceptually very careful in not mixing levels,” List says.

For this reason, the die roll is not merely apparently random, as people sometimes say. It is truly random. A godlike demon might brag that it knows exactly what will happen, but it knows only what will happen *to the atoms*. It does not even know what a die is because that is higher-level information. The demon never sees a forest, only trees. It is like the protagonist of Argentine writer Jorge Luis Borges’s short story “Funes, the Memorious,” a man who remembers everything and grasps nothing. “To think is to forget a difference, to generalize, to abstract,” Borges wrote. For the demon to know which side the die lands on, you have to tell it what to look for. “The demon would only be able to infer the higher-level history if the demon was given our specification of how we partition the physical level,” List says. Indeed, the demon might well come to envy our mortal perspective.

The level logic works the other way, too. Indeterministic microphysics can lead to deterministic macrophysics. A baseball can be made of particles behaving randomly, yet its flight is entirely predictable; the quantum randomness averages out. Likewise gases consist of molecules executing enormously complicated—and effectively indeterministic—movements, yet their temperature and other properties follow laws that are dead simple. More speculatively, some physicists such as Robert Laughlin of Stanford University suggest that the lower level is utterly

*Graphic by Jen Christiansen*

irrelevant. The building blocks could be anything and still produce the same collective behavior. After all, systems as diverse as water molecules, stars in a galaxy and cars on a highway obey the same laws of fluid flow.

## FREE AT LAST

WHEN YOU THINK IN TERMS OF LEVELS, the worry that indeterminism might mark the end of science evaporates. There is no big wall around us, cordoning off a law-abiding chunk of the universe from the anarchic and inexplicable beyond. Instead the world is a layer cake of determinism and indeterminism. The earth's climate, for example, supervenes on Newton's deterministic laws of motion, but weather reports are probabilistic, whereas seasonal and longer-term climate trends are again predictable. Biology, too, supervenes on deterministic physics, but organisms and ecosystems require different modes of description, such as Darwinian evolution. "Determinism doesn't explain everything," says Tufts University philosopher Daniel C. Dennett. "Why are there giraffes? Because it was 'determined' that there would be?"

Human beings are embedded within this layer cake. We have the powerful sense of free will. We often do the unpredictable, and in most of life's decisions, we feel we were capable of doing otherwise (and often wish we had). For millennia, so-called philosophical libertarians—not to be confused with the political kind—have argued that human freedom requires particle freedom. Something must break the deterministic flow of events, such as quantum randomness or the "swerves" that some ancient philosophers thought atoms can undergo.

The trouble with this line of thought is that it would free the particles but leave us enslaved. Whether your decision was preordained at the big bang or made by a mutinous particle, it is not your decision. To be free, we need indeterminism not at the particle level but at the human level. And that is possible because the human and particle levels are autonomous. Even if everything you do can be traced to earlier events, you can be the author of your actions because neither you nor the actions exist at the level of matter, only at the macrolevel of mind. "This macroindeterminism riding on microdeterminism may secure free will," Butterfield says. Macroindeterminism is not the cause of your decision. It *is* your decision.

Some might complain that you are still a puppet of the laws of nature, that your freedom is an illusion. But the word "illusion" itself conjures up desert mirages and ladies sawed in half: things that are unreal. Macroindeterminism is not like that. It is quite real, just not fundamental. It is comparable to life. Individual atoms are completely inanimate, yet enormous masses of them can live and breathe. "Anything to do with agents, their intentional states, their decisions and choices: none of this features in the conceptual repertoire of fundamental physics, but that doesn't mean those phenomena aren't real," List observes. "It just means that those are very much higher-level phenomena."

It would be a category mistake, not to mention completely unenlightening, to describe human decisions as the mechanics of atoms in your brain. Instead you need to use all the concepts of psychology: desire, possibility, intention. Why did I choose water over wine? Because I wanted to. My desire explains my action. Most of the times that we ask "Why?" we are seeking someone's motivations rather than the physics backstory. Psychological explanations presume the kind of indeterminism that List is talking about. For example, game theorists model human decisions by laying out the range of options and showing which one you will select if you are acting rationally. Your freedom to choose a certain option steers your choice even if you never plump for that option.

To be sure, List's arguments do not explain free will fully. The hierarchy of levels opens up space for free will by separating psychology from physics and giving us the opportunity to do the unexpected. But we have to seize the opportunity. If, for example, we made every decision on a coin toss, that would still count as macroindeterminism but would hardly qualify as free will in any meaningful sense. Some people's decision making may be so debilitated that they cannot be said to act freely.

This way of thinking about determinism also makes sense of an interpretation of quantum theory that was developed in the years after Einstein's death in 1955: the many-worlds interpretation. Advocates argue that quantum mechanics describes a collection of parallel universes—a multiverse—that behaves deterministically in the large but looks indeterministic to us because we are able to see only a single universe. For instance, an atom might emit a photon to the left or to the right; quantum theory leaves the outcome open. According to the many-worlds interpretation, that is because the same situation arises in a zillion parallel universes; in some, the photon goes deterministically left, and in others, it goes right. Not being able to tell which of those universes we reside in, we cannot predict what will happen, so the situation from the inside looks inexplicable. "There is no true randomness in the cosmos, but things can appear random in the eye of the beholder," says cosmologist Max Tegmark of the Massachusetts Institute of Technology, a prominent proponent of this view. "The randomness reflects your inability to self-locate."

That is very similar to saying that a die or brain could be constructed from any one of countless atomic configurations. The configurations might be individually deterministic, but because we cannot know which one corresponds to our die or our brain, we have to think of the outcome as indeterministic. Thus, parallel universes are not some exotic idea out there in the cosmos. Our body and brain are little multiverses, and it is the multiplicity of possibility that endows us with freedom. SA

### MORE TO EXPLORE

**Review Essay: The Shaky Game (by Arthur Fine).** Don Howard in *Synthese,* Vol. 86, No. 1, pages 123–141; January 1991.

**Freedom Evolves.** Daniel C. Dennett. Viking, 2003.

**Laws, Causation and Dynamics at Different Levels.** Jeremy Butterfield in *Interface Focus,* Vol. 2, No. 1, pages 101–114; February 2012.

**Free Will, Determinism, and the Possibility of Doing Otherwise.** Christian List in *Noûs,* Vol. 48, No. 1, pages 156–178; March 2014.

**Our Mathematical Universe: My Quest for the Ultimate Nature of Reality.** Max Tegmark. Knopf, 2014.

### FROM OUR ARCHIVES

**100 Years of Quantum Mysteries.** Max Tegmark and John Archibald Wheeler; February 2001.

**Was Einstein Right?** George Musser; September 2004.

**Finding Free Will.** Christof Koch; *Scientific American Mind,* May/June 2012.

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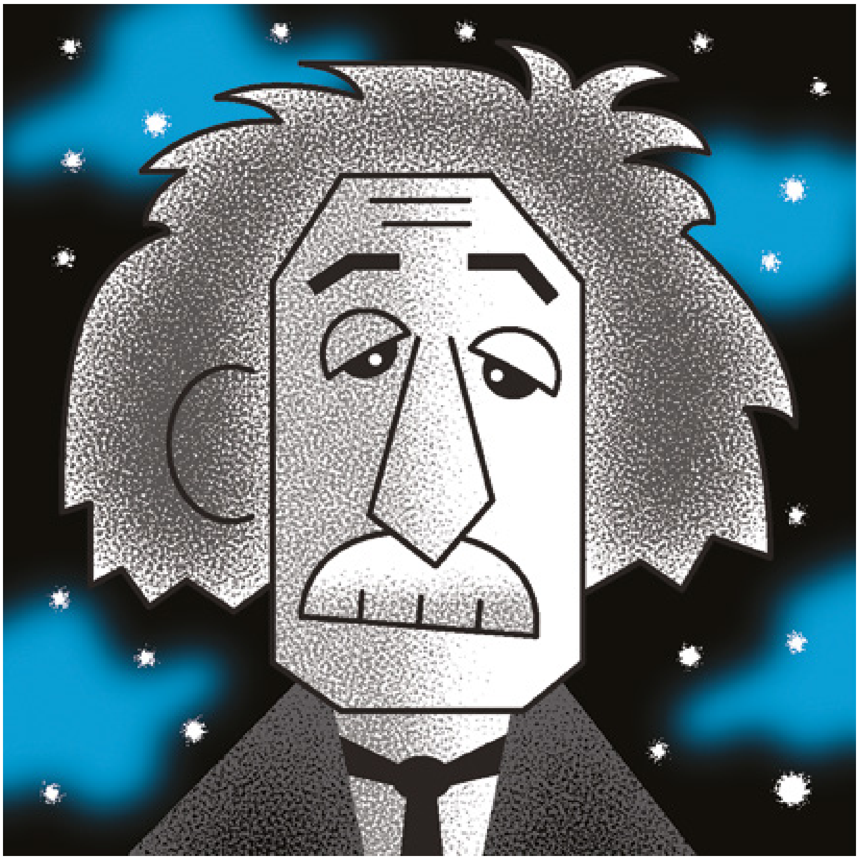
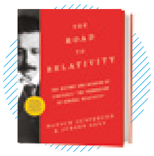


# New Takes on the Great Man

Four recent tomes explore the loyalties, inspirations and trials of Albert Einstein

## The Road to Relativity: The History and Meaning of Einstein's "The Foundation of General Relativity"

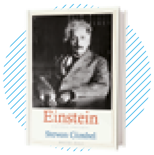
by Hanoch Gutfreund and Jürgen Renn.
Princeton University Press, 2015 ($35)



**Any devotee** of Einstein will relish the chance to parse this annotated facsimile of the physicist's original manuscript on general relativity. The authors provide a full English translation and painstakingly explain, page by page, Einstein's text and equations, which lay out his theory and the path he took to derive it. Their cogent descriptions and the accompanying illustrations and documents open a fascinating window onto Einstein's otherwise inaccessible opus.

## Einstein: His Space and Times

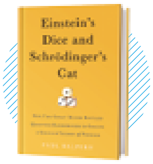
by Steven Gimbel.
Yale University Press, 2015 ($25)



**Einstein renounced** religion at the age of 12, when he decided his Jewish beliefs were incompatible with the analytical mind-set of his truer devotion, science. Yet the world never stopped seeing him as a Jew, and over time he became a champion for his oppressed people and a supporter of the Zionist cause. "Einstein had alienated himself from the larger Jewish community, but the times forced him to realize that his heritage was an inalienable part of who he was," writes philosophy professor Gimbel in this look at Einstein's relationship to Judaism and his political activism.

## Einstein's Dice and Schrödinger's Cat: How Two Great Minds Battled Quantum Randomness to Create a Unified Theory of Physics

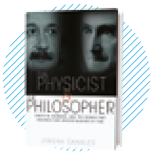
by Paul Halpern. Basic Books, 2015 ($27.99)



**Einstein notoriously** disliked the inherent randomness in quantum theory—which he described as God playing dice with the universe—and he was not alone. His lifelong friend and another giant of 20th-century physics, Erwin Schrödinger, was one of the architects of quantum mechanics and yet struggled with the mainstream interpretation of the theory, which he parodied in his famous "Schrödinger's cat" thought experiment. Physicist Halpern recounts the two men's quest to find an overarching theory that would resolve these issues and the occasions when vanity and rivalry threatened, but never destroyed, their friendship.

## The Physicist and the Philosopher: Einstein, Bergson, and the Debate That Changed Our Understanding of Time

by Jimena Canales.
Princeton University Press, 2015 ($35)



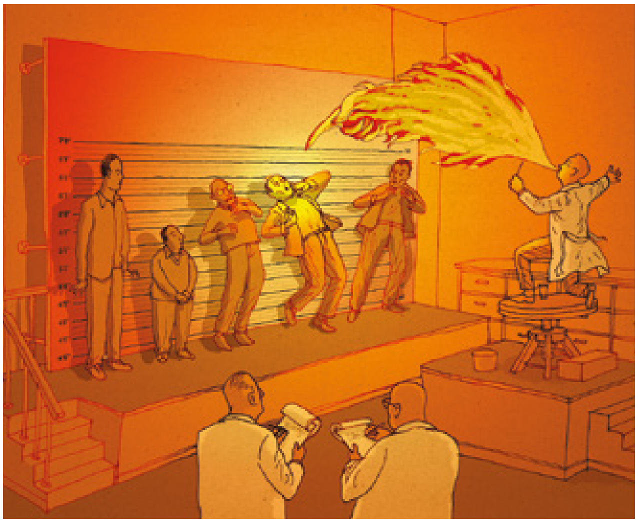
**On April 6, 1922,** Einstein clashed with the most famous philosopher of the day, Henri Bergson, about the nature of time. Einstein espoused the picture he formulated in general relativity of time as inseparable from space and lacking the absolute reality that humans tend to perceive in it. Bergson claimed that science alone cannot describe time, which he said was closely intertwined with the "vital impulse" of life and creative expression. Science historian Canales describes how their debate initiated a rift between physics and philosophy, "splitting the century into two cultures and pitting scientists against humanists, expert knowledge against lay wisdom."

Illustration by Stephen Savage

**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

# Forensic Pseudoscience

## How trustworthy are DNA and other crime scene tests?



**The criminal justice system** has a problem, and its name is forensics. This was the message I heard at the Forensic Science Research Evaluation Workshop held May 26–27 at the AAAS headquarters in Washington, D.C. I spoke about pseudoscience but then listened in dismay at how the many fields in the forensic sciences that I assumed were reliable (DNA, fingerprints, and so on) in fact employ unreliable or untested techniques and show inconsistencies between evaluators of evidence.

The conference was organized in response to a 2009 publication by the National Research Council entitled *Strengthening Forensic Science in the United States: A Path Forward,* which the U.S. Congress commissioned when it became clear that DNA was the only (barely) reliable forensic science. The report concluded that "the forensic science system, encompassing both research and practice, has serious problems that can only be addressed by a national commitment to overhaul the current structure that supports the forensic science community in this country." Among the areas determined to be flawed and in need of more research are: accuracy and error rates of forensic analyses, sources of potential bias and human error in interpretation by forensic experts, fingerprints, firearms examination, tool marks, bite marks, impressions (tires, footwear), bloodstain-pattern analysis, handwriting, hair, coatings (for example, paint), chemicals (including drugs), materials (including fibers), fluids, serology, and fire and explosive analysis.

Take fire analysis. According to John J. Lentini, author of the definitive book *Scientific Protocols for Fire Investigation* (CRC Press, second edition, 2012), the field is filled with junk science. "What does that pattern of burn marks over there mean?" he recalled asking a young investigator who joined him on one of his more than 2,000 fire investigations. "Absolutely nothing" was the correct answer. Most of the time fire investigators find nonexistent patterns, Lentini elaborated, or they think a certain mark means the fire burned "fast" or "slow," allegedly indicated by the "alligatoring" of wood: small, flat blisters mean the fire burned slow; large, shiny blisters mean it burned fast. Nonsense, he said. It may take a while for a fire to get going, but once a couch or bed burns and reaches a certain temperature, you are not going to be able to discern much about its cause.

Lentini debunked the myth of window "crazing" in which cracks indicate rapid heating supposedly caused by an accelerant (arson). In fact, the cracks are caused by rapid cooling, as when firefighters spray water on a burning building with windows. He also noted that burn marks on the floor are not the result of a liquid deliberately poured on it. When a fire consumes an entire room, the extreme heat burns even the floor, along with melting metal and leaving burn marks under a doorway threshold, which many investigators assume implies the use of an accelerant. "Most of the 'science' of fire and explosive analysis has been conducted by insurance companies looking to find evidence of arson so they don't have to pay off their policies," Lentini explained to me when I asked how his field became so fraught with pseudoscience.

Itiel Dror of the JDI Center for the Forensic Sciences at University College London spoke about his research on "cognitive forensics"—how cognitive biases affect forensic scientists. For example, the hindsight bias can lead one to work backward from a suspect to the evidence, and then the confirmation bias can direct one to find additional confirming evidence for that suspect even if none exists. Dror discussed studies that show "that the same expert examiner, evaluating the same prints but within different contexts, may reach different and contradictory decisions." Not just fingerprints. Even DNA analysis is subjective. "When 17 North American expert DNA examiners were asked for their interpretation of data from an adjudicated criminal case in that jurisdiction, they produced inconsistent interpretations," Dror and his co-author wrote in a 2011 paper in *Science and Justice.*

No one knows how many innocent people have been convicted based on junk forensic science, but the National Research Council report recommends substantial funding increases to enable labs to conduct experiments to improve the validity and reliability of the many forensic subfields. Along with a National Commission on Forensic Science, which was established in 2013, it's a start.

**SCIENTIFIC AMERICAN ONLINE**
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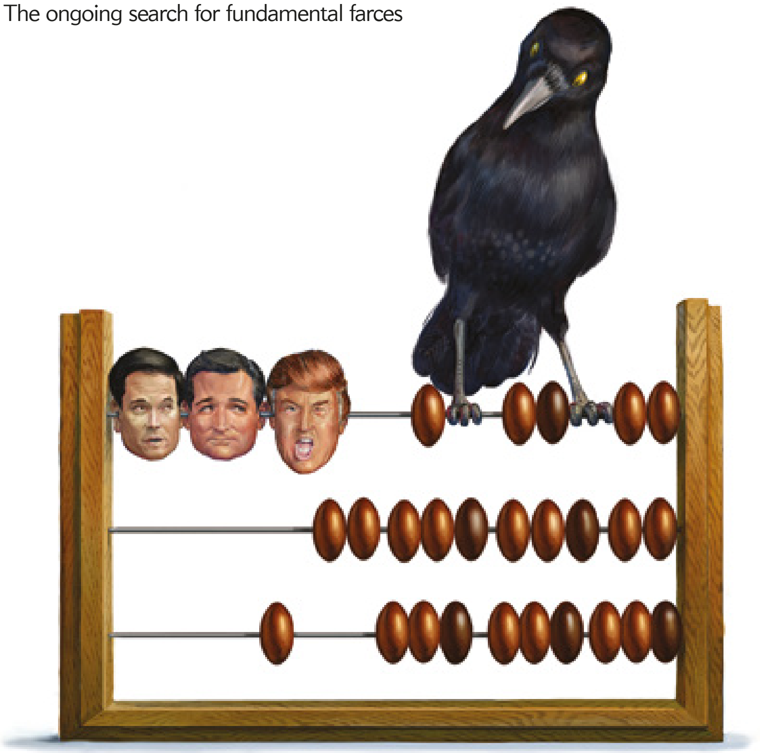
*Illustration by Izhar Cohen*

## Anti Gravity by Steve Mirsky

The ongoing search for fundamental farces

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



# Numbers Games

## Some animals can count; others can be counted on

**It's nice to know** that the great man we celebrate in this special issue had a warm sense of humor. For example, in 1943 Albert Einstein received a letter from a junior high school student who mentioned that her math class was challenging. He wrote back, "Do not worry about your difficulties in mathematics; I can assure you that mine are still greater."

Today we know that his sentiment could also have been directed at crows, which are better at math than those members of various congressional committees that deal with science who refuse to acknowledge that global temperatures keep getting higher. Studies show that crows can easily discriminate between a group of, say, three objects and another containing nine. They have more trouble telling apart groups that are almost the same size, but unlike the aforementioned committee members, at least they're trying.

A study in the *Proceedings of the National Academy of Sciences USA* finds that the brain of a crow has nerve cells that specialize in determining numbers—a method quite similar to what goes on in our primate brain. Human and crow brains are substantially different in size and organization, but convergent evolution seems to have decided that this kind of neuron-controlled numeracy is a good system. (Crows are probably unaware of evolution, which is excusable. Some members of various congressional committees that deal with science pad their reactionary résumés by not accepting evolution, which is astonishing.)

Crows are not the only avian types out there illustrating that "birdbrain" should really be a compliment. Mexican jays in Arizona (which to Donald Trump's probable dismay cross the border with impunity) know lots about legume load. That is, researchers report in the *Journal of Ornithology* that they observed the birds picking up peanuts in their beaks to gauge the samples' hefts. After literally weighing their options, the birds would fly off with the densest nut—but enough about various congressional committees that deal with science. And Donald Trump.

By the way, although the journal article refers to the Mexican jays as *Aphelocoma ultramarina,* in 2011 the American Ornithologists' Union decided that *A. ultramarina* should probably be considered a separate species called the transvolcanic jay. And that the birds still to be called Mexican jays, which include the subjects of the peanut study, should be referred to as *Aphelocoma wollweberi.* Mexican jays used to be called gray-breasted jays, for anyone keeping score at home. The thing to remember is that the birds don't care, and if you worry about these designations too much, you could wind up aphelocomatose.

Dogs may not have the talents, let alone the talons, of some birds, but their domesticated sophistication extends into realms that look suspiciously ethical or moral. The journal *Animal Behaviour* recently featured a study in which 54 dogs watched an unknown person either help the dog's owner with a task or refuse to help. And the dogs later turned their noses up at a snack offer from that good-for-nothing creep who would not give a hand to the most wonderful person in the world. Well, to be more accurate, the dogs were less likely to accept the snack from the rat punk than from somebody else, anyway. In a follow-up interview, one weak-willed dog allegedly described its choice to take the tasty morsel as "rough."

Finally, in invertebrate news, here's a quote from a late June story by the Australian Broadcasting Corporation about a finding published in the *Proceedings of the Royal Society B:* "A tiny worm which procreates by jabbing a needle-like penis into its own head has left biologists in Europe stunned." That's some jab.

Of course, the flatworm is hermaphroditic; its actions would otherwise be mere self-abuse. But during times when it can't find a discrete mate, the male end bends around to the head end to engage in what's technically called hypodermic insemination. The sperm then travels to the midbody, where fertilization occurs. So it looks like it injects where it does because that's the easiest place for the tail to wriggle around to reach. That is, it did the math and used its head.

**SCIENTIFIC AMERICAN ONLINE**
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*Illustration by Matt Collins*

# 50, 100 & 150 Years Ago

compiled by Daniel C. Schlenoff

Innovation and discovery as chronicled in *Scientific American*

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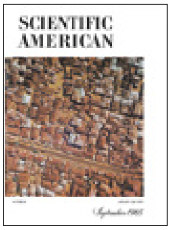


## September 1965

### Cities on the Rise

“Urbanized societies, in which a majority of the people live crowded together in towns and cities, represent a new and fundamental step in man’s social evolution. Although cities themselves first appeared some 5,500 years ago, they were small and surrounded by an overwhelming majority of rural people; moreover, they relapsed easily to village or small-town status. The urbanized societies of today, in contrast, not only have urban agglomerations of a size never before attained but also have a high proportion of their population concentrated in such agglomerations. Neither the recency nor the speed of this evolutionary development is widely appreciated. Before 1850 no society could be described as predominantly urbanized, and by 1900 only one—Great Britain—could be so regarded. Today, only 65 years later, all industrial nations are highly urbanized.”

## September 1915

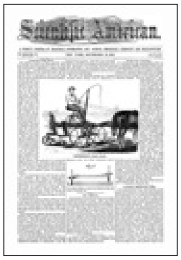
### War and Wildlife

“The war is having a great influence on the birds throughout Europe, especially on the birds of passage. These birds were observed in places where they were never seen before and were missed in the localities where battles were raging. In Luxembourg, where otherwise millions of birds congregate in the leafy forests, there are now scarcely any to be seen or heard. A nature lover there writes that ‘whole oat fields have sprung up along the roads and in the market squares of the little towns and villages where the horses have been fed as the cavalry passed through.’ This would never have been possible in other years, for then the birds would soon have pecked up every grain that fell to the ground.”

### Against the Sea

“Twice during the thirteen years since it was built has the great concrete wall along the waterfront of Galveston withstood the furious onslaughts of a raging sea lashed by a hurricane, and in each case the seawall has stood perfectly. In the latest storm the damage done to the city was chiefly in the business section, north of Broadway, where the plan of grade raising has never been carried out. The writer at the request of the County Commissioners Court of the County of Galveston inspected the work immediately after the two great storms of 1909 and 1915, and in neither case did he find the seawall damaged in the slightest degree, though heavy timbers and logs were driven over it and badly damaged the boulevard.—Brigadier-General Henry M. Robert”

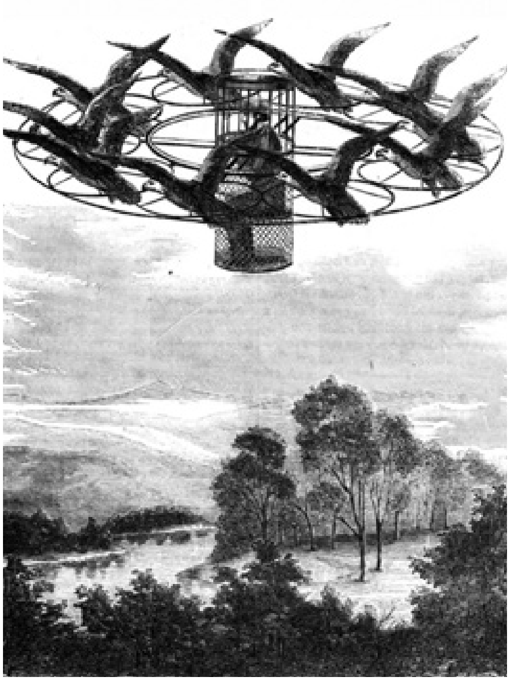
*The author also wrote* Robert’s Rules of Order, *originally published in 1876.*



## September 1865

### Nitroglycerin for Blasting

“Glycerine, as we all know, is the sweet principle of oil, and is extensively used for purposes of the toilet, but it has now received an application of rather an unexpected nature. In 1847 Ascanio Sobrero discovered that glycerine, when treated with nitric acid, was converted into a highly explosive substance, which he called nitro-glycerine. It is oily, heavier than water, soluble in alcohol and ether, and acts so powerfully on the nervous system that a single drop placed on the tip of the tongue will cause a violent headache that will last for several hours. This liquid seems to have been almost forgotten by chemists, and it is only now that Mr. Nable [*sic*—Alfred Nobel], a Swedish engineer, has succeeded in applying it to a very important branch of his art, viz., blasting.”



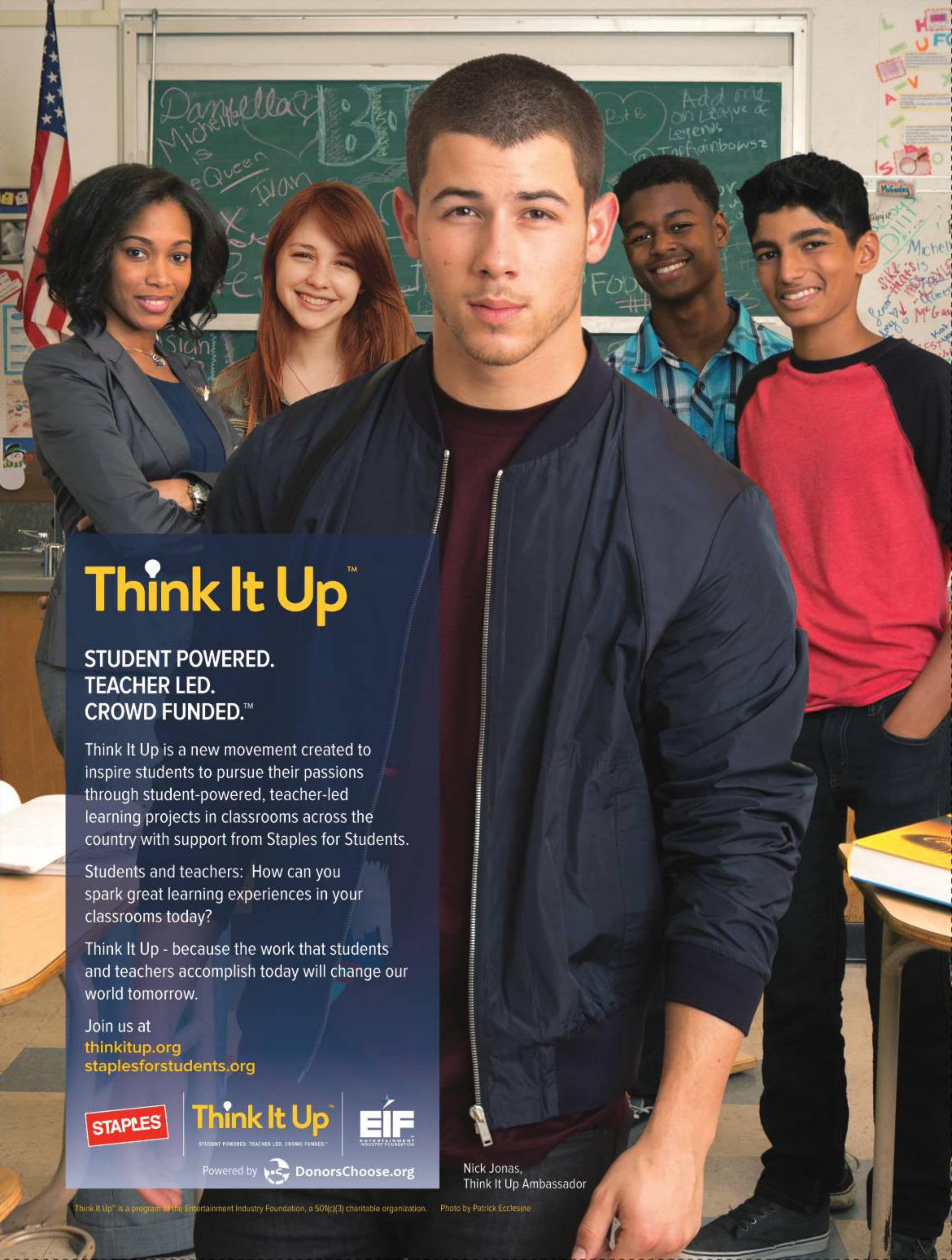
**DREAM OF FLIGHT:** A creative plan to slip the surly bonds of Earth, 1865

SCIENTIFIC AMERICAN, VOL. XIII, NO. 13 (NEW SERIES); SEPTEMBER 23, 1865

### Brilliant(-ish) Invention

“Messrs Editors—I venture to submit for publication a plan, to me apparently simple and feasible, but that I have never put to the test of experiment. It is to do what man has already done upon the earth—make use of the powers of the inferior animals given to him to be his servants to effect his purposes. There are many birds noted for strength of wing and endurance in flight. The brown eagle and the American swan particularly suggest themselves. I propose to obtain a number of such birds and attach them by jackets fitted around their bodies and cords to a frame work, which shall sustain a basket large enough to hold a man.”

*A slide show of other optimistic inventions from 1865 is at www.ScientificAmerican.com/sep2015/creative-inventions*



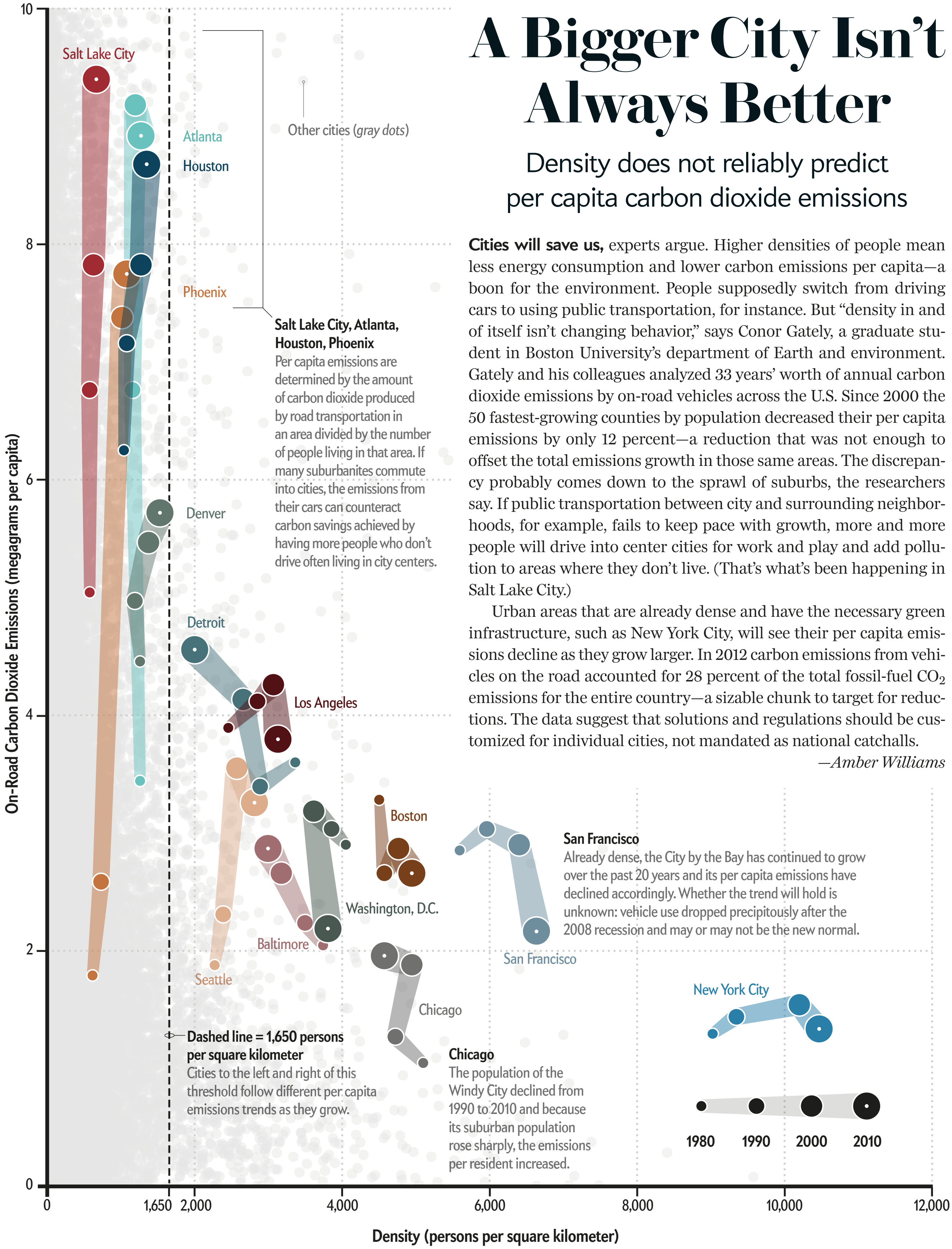
# A Bigger City Isn't Always Better

## Density does not reliably predict per capita carbon dioxide emissions

**Cities will save us,** experts argue. Higher densities of people mean less energy consumption and lower carbon emissions per capita—a boon for the environment. People supposedly switch from driving cars to using public transportation, for instance. But "density in and of itself isn't changing behavior," says Conor Gately, a graduate student in Boston University's department of Earth and environment. Gately and his colleagues analyzed 33 years' worth of annual carbon dioxide emissions by on-road vehicles across the U.S. Since 2000 the 50 fastest-growing counties by population decreased their per capita emissions by only 12 percent—a reduction that was not enough to offset the total emissions growth in those same areas. The discrepancy probably comes down to the sprawl of suburbs, the researchers say. If public transportation between city and surrounding neighborhoods, for example, fails to keep pace with growth, more and more people will drive into center cities for work and play and add pollution to areas where they don't live. (That's what's been happening in Salt Lake City.)

Urban areas that are already dense and have the necessary green infrastructure, such as New York City, will see their per capita emissions decline as they grow larger. In 2012 carbon emissions from vehicles on the road accounted for 28 percent of the total fossil-fuel $CO_2$ emissions for the entire country—a sizable chunk to target for reductions. The data suggest that solutions and regulations should be customized for individual cities, not mandated as national catchalls.

*—Amber Williams*



**Salt Lake City, Atlanta, Houston, Phoenix**
Per capita emissions are determined by the amount of carbon dioxide produced by road transportation in an area divided by the number of people living in that area. If many suburbanites commute into cities, the emissions from their cars can counteract carbon savings achieved by having more people who don't drive often living in city centers.

**San Francisco**
Already dense, the City by the Bay has continued to grow over the past 20 years and its per capita emissions have declined accordingly. Whether the trend will hold is unknown: vehicle use dropped precipitously after the 2008 recession and may or may not be the new normal.

**Dashed line = 1,650 persons per square kilometer**
Cities to the left and right of this threshold follow different per capita emissions trends as they grow.

**Chicago**
The population of the Windy City declined from 1990 to 2010 and because its suburban population rose sharply, the emissions per resident increased.

SOURCE: "CITIES, TRAFFIC, AND $CO_2$: A MULTIDECADAL ASSESSMENT OF TRENDS, DRIVERS, AND SCALING RELATIONSHIPS," BY CONOR K. GATELY, LUCY R. HUTYRA AND IAN SUE WING, IN *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES USA,* VOL. 112, NO. 16; APRIL 21, 2015

*Graphic by Tiffany Farrant-Gonzalez*