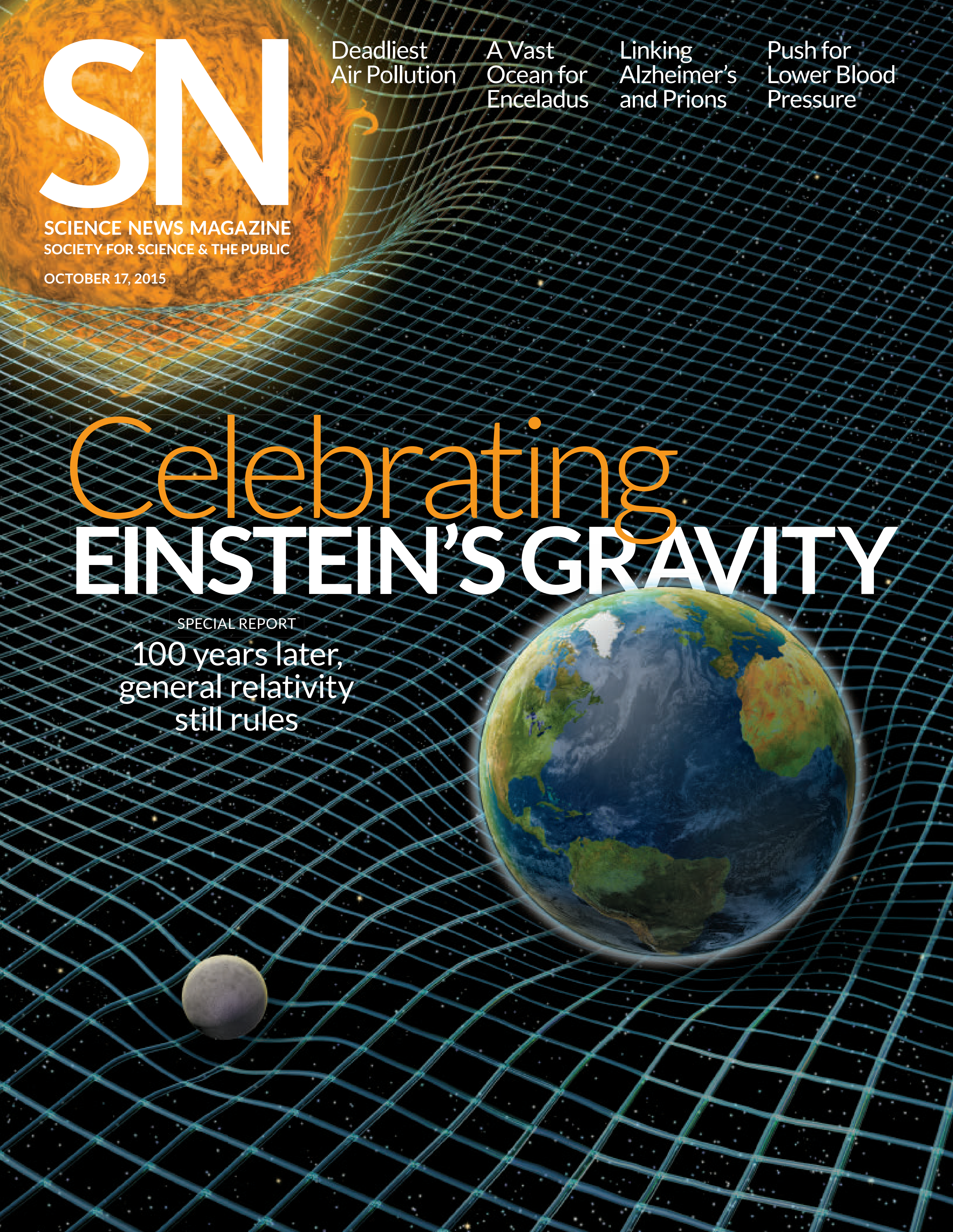

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SCIENCE NEWS MAGAZINE
SOCIETY FOR SCIENCE & THE PUBLIC
OCTOBER 17, 2015

Deadliest Air Pollution

A Vast Ocean for Enceladus

Linking Alzheimer's and Prions

Push for Lower Blood Pressure

Celebrating EINSTEIN'S GRAVITY

SPECIAL REPORT

100 years later, general relativity still rules

What's 500 Million Years Longer Than Forever?

Diamonds may be forever, but Stauer has found a stone that's been around a half a billion years longer.

I once asked a wise old lady to tell me the secret to age and beauty. "Travel to Ratanakiri," she whispered in my ear. "There you'll see that the oldest thing on earth can also be the most beautiful." Intrigued, I took a plane to literally the ends of the earth, took a car to the outskirts of town, then a motorbike deep into the jungle. Half a day's hike later, I discovered what she meant—the clearest and brightest blue hyacinth stones I'd ever laid eyes on.

Ancient deposits of hyacinth in Australia date back 4.4 billion years. Hyacinth is the oldest known substance on earth and is 500,000,000 years older than diamonds. Hyacinth has been found in rare jewelry pieces gong back to the Middle Ages. Today, a gorgeous 4 carat brilliant round cut hyacinth is housed in the Smithsonian National Museum of Natural History. In our opinion, the most beautiful variety of hyacinth are the spectacular blue stones. And, now I know that some of the rarest and most beautiful blue hyacinths are found in Ratanikiri. I'm excited to share them with you in the **Blue Hyacinth Pendant**—a stunning cluster of 7.50 total carats of blue hyacinth rounds to sparkle and catch the light.

Blue hyacinth is very dense, giving this pendant substantial heft, weighing in at an impressive 7.50 carats. It also packs a wallop on the Moh's scale, measuring the same hardness as an emerald. And, due to hyacinth's double refraction properties, you can see twice as many facets and twice as much fire.

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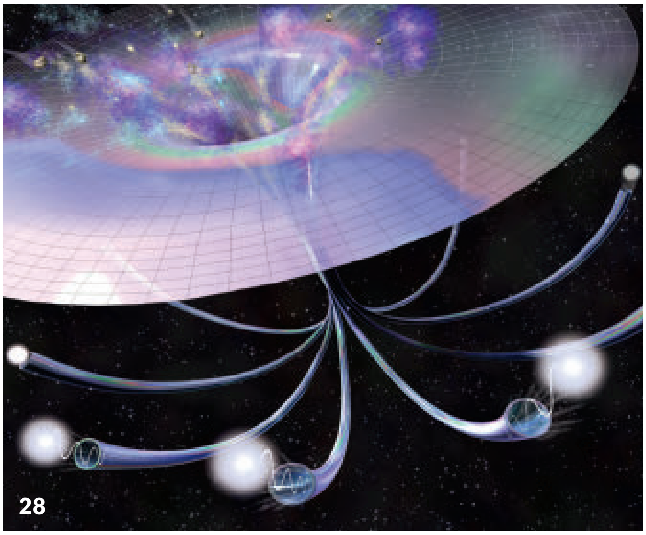
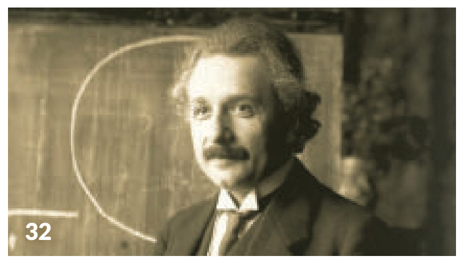


Special Report

GRAVITY'S CENTURY

News



Departments

SOCIETY UPDATE
SSP competition alumni gather for panel discussions, celebrations

COVER Einstein's general theory of relativity describes gravity as the warping of spacetime by masses such as the sun, Earth and moon. *Nicolle Rager Fuller*

FROM TOP: NICOLLE RAGER FULLER; FERDINAND SCHMUTZER/WIKIMEDIA COMMONS; JAMES HARVEY

General relativity centennial celebrates Einstein's genius

SANDY SCHAFFER

Einstein is shorthand for genius, and describing everything Albert Einstein did to inspire that synonym would take a book, or multiple books (see reviews of some on Page 32). But in this issue, *Science News* uses the opportunity of the 100th anniversary of the general theory of relativity to take a deep dive into one — perhaps the most important — of Einstein's scientific contributions.

On Page 16, Tom Siegfried describes the challenges that Einstein faced and met to develop his theory, which reimagined gravity as a warping of spacetime. Of course, his equations had much wider implications. As Christopher Crockett explores on Page 24, general relativity's requirement that gravity bend light has been a boon to astronomers seeking to see the most ancient stars and galaxies. Gravitational lenses can help magnify or brighten images of faraway objects, extending scientists' vision. Gravitational waves, another consequence of general relativity, have been detected indirectly; scientists are actively searching for direct evidence.

General relativity has been wildly successful, but it doesn't mesh well with quantum mechanics, the 20th century's other revolutionary advance in physics, as Andrew Grant reports on Page 28. But some physicists believe those two ideas may merge via Einstein's offspring: black holes and wormholes.

Putting together this special report gave me a greater appreciation of Einstein and his work. It also highlighted a bit of our own history: As Siegfried notes in his essay, *Science News Letter* paid for a Czech émigré (an electrical engineer supporting himself by washing dishes) to visit Einstein in 1936. Rudi Mandl realized that if gravity bends light, then massive objects in space could actually act as lenses. With this magazine's help, he nudged Einstein into doing the math to prove it.

General relativity has grown more important in the last 50 years than it was in Einstein's time. Many areas of interest have evolved from issues Einstein raised in 1917, when he applied his theory to the entire universe. General relativity is still inspiring the scientific enterprise, spurring scientists to try to be a bit like Einstein. *— Eva Emerson, Editor in Chief*

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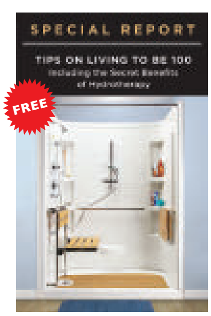

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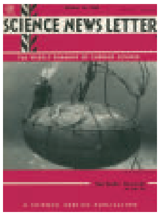


Excerpt from the October 16, 1965, issue of *Science News Letter*

50 YEARS AGO

Satellite TV predicted

Thirty-thousand-watt satellites transmitting radio and television directly into homes without the need for ground stations are the prediction of Radio Corporation of America board chairman David Sarnoff.... Such satellites could handle three TV and three radio channels at once, with little modification necessary in present home antennas. "When we can communicate instantly to everybody, everywhere," he said, "we will set in motion a force whose ultimate political, social and economic impact upon mankind cannot be calculated today...."

UPDATE: Communication satellites provided global coverage just in time for televising the first moon landing, in 1969. Cable companies began using satellites to send TV programming from station to station in 1975, and the following year, a Stanford electrical engineer built an antenna to receive the first home transmission. Now, satellite TV, phone and Internet make instant communication an everyday experience with the world-changing impact that Sarnoff foresaw.

Just 24 hours in each other's company without mating can be enough to bond a pair of prairie voles for life.

AUBREY KELLY

IT'S ALIVE

What *really* changes when a male vole settles down

Bachelor prairie voles can't tell females of their species apart. Yet the clueless fellows can change, forming pair-bonds for life with the opposite sex and even distinguishing between two female strangers.

Bachelors aren't blind or stupid; they recognize individual males among their fellow short-tailed *Microtus ochrogaster* rodents scurrying through old fields in the center of North America.

And males are certainly interested in the interchangeable females. In lab tests, bachelors claw and bite at cage dividers between the sexes, says Alexander Ophir of Cornell University.

Conquering the divide and mating with a female after just six hours of her company can form a lifelong pair-bond between voles. Only about 5 percent of mammal species live this socially monogamous lifestyle, and the voles have played starring roles in studies of the neurobiology of bonding. (Social monogamists, including both voles and some *Homo sapiens*, don't entirely forgo extra-pair encounters.)

A pair-bonded couple can crowd three litters of young into their roughly six to nine months of life in the wild, Ophir says. One aid to speeding through family life: Females can get pregnant as soon as they give birth. "You sometimes see pups being delivered as males are trying to copulate with the female," he says.

Pair-bonding requires recognizing at least one female. "It's all well and good to fall in love, but if you don't know who you fell in love with, it's worthless," Ophir says. And paired-up voles can go further. Tests show they notice the difference between two females they have never mated with, Ophir and former student Tomica Blocker report in the October *Animal Behaviour*.

To test recognition powers, Blocker staged repeated appearances of an unfamiliar female beside a male's cage. As the encounters progressed, a pair-bonded male tended to spend less and less time sniffing her scent — unless Blocker substituted a new and unfamiliar visitor. Then the bonded male reverted to a prolonged investigation. Single males, however, just greeted the stand-in with cursory sniffs as if she were an alluring but already familiar visitor.

Acquiring the gift of distinguishing females only after bachelorhood may have advantages, Ophir muses. For instance, to find a mate in a short life, maybe any willing female is good. And persisting in the effort could be easier if a male can't tell which lovely vole already rejected him. — *Susan Milius*

MYSTERY SOLVED

Bad Karma can ruin palm oil crops

Palm oil producers thought they had nixed future shortages of edible oil and biofuel in the 1980s, when they learned to make genetically identical copies of high–oil-yielding palms. But when the cloned palms matured, some plants made shriveled fruits with very little oil. Exactly how these dry, "mantled" fruits spawned from twins of oil-gushing palms has been a mystery ever since.

Oil-barren plants are a result of *Bad Karma*, researchers report September 9 in *Nature*. Shriveled fruit is not retribution for past actions. *Karma* in palm oil plants is a "jumping gene," or transposon, a selfish bit of DNA that copies and inserts itself in a host's DNA.

Palms usually weigh the transposon down by attaching molecules called methyl groups to the transposon's DNA. Such DNA methylation affects gene activity without changing the gene itself. In dry palms, much of the methylation is missing, Robert Martienssen of Cold Spring Harbor Laboratory in New York and colleagues discovered. Cloning may remove the methyl groups from the *Karma* DNA in some sprouts.

The researchers dubbed *Karma* DNA that is heavily laden with methylation as *Good Karma* because it coincides with oily fruit; the methylation-impoverished transposons are *Bad Karma* because they ruin crops. Tests for *Good* and *Bad Karma* may help growers identify bad clones early and weed them out. — *Tina Hesman Saey*

A tweak to chemical tags on DNA causes normally plump, oily palm fruit (top) to make shriveled, or mantled, fruit (bottom) with little oil.

$61 billion	1 percent	5 percent
Global palm oil market, 2014	Approximate fraction of all oil palms planted annually as clones	Estimated average fraction of cloned palms that produce mantled fruit

SOURCES: GRAND VIEW RESEARCH, *PALM OIL MARKET ANALYSIS*; A. KUSHAIRI *ET AL*/INTERNATIONAL SEMINAR ON ADVANCES IN OIL PALM TISSUE CULTURE 2010; R.E. LITZ, ED., *BIOTECHNOLOGY OF FRUIT AND NUT CROPS*

A newly discovered hominid finger bone dating to at least 1.84 million years ago is shown from two sides (inset) and overlaid on a modern human hand. A team of scientists regards the fossil as the oldest known humanlike hand bone.

FROM TOP: MARTIENSSEN LAB/CSHL; M. DOMÍNGUEZ-RODRIGO (INSET); JASON HEATON

THE -EST

Oldest humanlike hand bone

Excavations at Tanzania's famed Olduvai Gorge have uncovered the oldest known fossil hand bone resembling those of people today.

The bone from a hominid's left pinkie finger dates to at least 1.84 million years ago and looks more like corresponding bones of modern humans than like finger fossils of previously discovered Olduvai hominids, say paleoanthropologist Manuel Domínguez-Rodrigo of Complutense University in Madrid and his colleagues.

This ancient hominid's entire hand probably looked humanlike, the researchers propose August 18 in *Nature Communications*. An Olduvai hominid with humanlike hands would have been capable of making stone tools, they say.

The new finger fossil is more humanlike than comparably ancient Olduvai hand fossils from *Homo habilis*, or handy man, and *Paranthropus boisei*, or Nutcracker Man, the scientists find.

H. habilis and *P. boisei* lived at Olduvai alongside a hominid species represented by the new finger fossil, Domínguez-Rodrigo's team argues. But using just one or a few fossils to define a new hominid species is controversial (*SN: 6/27/15, p. 7*). — *Bruce Bower*

News

BODY & BRAIN

Lower blood pressure target proposed

But full data needed to assess clinical trial's findings, experts say

BY MEGHAN ROSEN

A new study proclaims some dramatic benefits of using medication to lower blood pressure, but some scientists are advising caution.

Aggressive treatment of high blood pressure comes with risks. And the study, a large clinical trial sponsored by the National Institutes of Health, has not yet been peer-reviewed or published. The main findings were announced in a press release without providing any of the actual data.

Changes to blood pressure guidelines and patient treatment plans should wait, says Sripal Bangalore, a cardiologist at New York University Langone Medical Center. "The results look good, there's no doubt about it," he says. "But we need more details. We need to look at the data."

Some experts caution that the study's results may not be as impressive as they initially seem. Plus, a low blood pressure treatment plan might not be right for every patient.

On September 11, the National Heart, Lung and Blood Institute in Bethesda, Md., released a synopsis of the Systolic Blood Pressure Intervention Trial, or SPRINT. This multiyear study used medications to lower the systolic blood pressure of participants to one of two targets: less than 120 millimeters of mercury or less than 140. (Systolic pressure, the pressure in the arteries when the heart contracts, is the top number in a blood pressure reading.)

Keeping patients at a lower blood pressure reduced rates of cardiovascular events (such as heart attack and heart failure) and stroke by almost a third, compared with keeping patients at 140. And compared with the higher-target group, the death rate in the 120 group was cut by almost a quarter.

"The preliminary results are terrific," says Mark Creager, president of the American Heart Association. For healthy people, he says, the association has long argued that systolic blood pressure should be 120 or lower. SPRINT's results "provide the evidence to support that position."

Previous studies have suggested that low blood pressure is linked to low risk of cardiovascular disease, says Paul Whelton, a clinical epidemiologist at Tulane University in New Orleans and the chair of SPRINT's steering committee. "The question was, 'How low should we go?' " when treating people with high blood pressure, he says.

SPRINT's goal was to find out. The study began in 2009 and included 9,361 people ages 50 and older. Each participant had a blood pressure of 130 or higher and at least one other risk factor for cardiovascular disease. Researchers randomly split the participants into two groups and gave them, on average, two medications to lower blood pressure to the 140 target, or three medications to hit the 120 target. Throughout the study, an independent group, the Data Safety and Monitoring Board, kept track of participants' welfare.

The monitoring board saw a striking trend: People in the lower blood pressure group seemed to fare better than those in the higher group. The difference was so dramatic, Whelton says, that the board decided that the intervention should be stopped. "It just didn't seem ethical to continue the study."

So NIH ended the trial on August 20, about a year ahead of the planned end date of fall 2016.

Had scientists let the trial run its course, Bangalore says, they might not have seen such dramatic results. "We've seen this time and time again in prematurely terminated trials," he says. "The relative risk reduction is usually exaggerated."

What's more, the heart, lung and blood institute reported only relative numbers, says Joel Handler, an internist at Kaiser Permanente in Anaheim, Calif. For people maintaining a blood pressure of 120, he says, "we don't know what the absolute benefits are." It's not clear just how much the treatment lowers the risk of having a heart attack, he says. "Is this a fraction of a percent, or is it more than that?"

If the preliminary data from SPRINT hold up, Handler says, adopting the new blood pressure target is the right thing to do. But a lower target might not be for everyone. If elderly patients' systolic pressure drops too low, he warns, they may be more likely to fall.

Though blood pressure drugs are very safe, Whelton says, "typically when we prescribe blood pressure medication, it's for a lifetime."

People taking more medications may have more side effects, Bangalore says. Patients may also be less likely to stick to treatment plans. "Some patients might say, 'Look, I'm already taking 20 medications. I don't want to take more.' "

Bangalore is looking forward to seeing more details when the study results are published. That should happen within the next few months, the heart, lung and blood institute reports.

The American College of Cardiology and the heart association anticipate putting out new blood pressure guidelines in 2016, says Whelton. "We will of course be looking at SPRINT very carefully." ■

29 percent

Fraction of U.S. adults who have high blood pressure

76 percent

U.S. adults with high blood pressure who take medication to control it

SOURCE: CDC

EARTH & ENVIRONMENT

Surprising origins of deadly dirty air

Farming, cook fires top causes of pollution-linked deaths

BY BETH MOLE

There's no doubt air pollution is a killer, causing more than 3 million deaths worldwide each year. But the top culprits behind the deadly air may come as a surprise.

Particles from small-scale energy use, mainly household fires for cooking and heating, are the leading cause of air pollution–related deaths in many areas of Asia, researchers report in the Sept. 17 *Nature*. But in the northeastern United States, Russia and Europe, agricultural fumes from livestock and fertilizer are the deadliest air pollution. In all of these areas, small-scale energy use and agriculture beat out the more expected suspects: traffic and power plant pollution.

Though not all researchers are convinced by the estimates, the findings may help guide new strategies on reducing pollution. In China, for instance, some policy makers battle smoggy days by regulating traffic, says coauthor Johannes Lelieveld, an atmospheric chemist at the Max Planck Institute for Chemistry in Mainz, Germany. "But this has actually done very little" to reduce pollution in some places, he says, because the major source of smog is home energy use.

Lelieveld and colleagues combined population and health data, satellite observations of atmospheric particles and a computer simulation of particles circulating and reacting in the atmosphere. The researchers then considered the sources of those particles in each part of the world, attributing pollution to seven main categories, including agriculture, forest fires, power plants and traffic.

Drawing on earlier studies linking air pollution exposure to risk of death, the group estimated that air pollution causes 3.3 million deaths worldwide each year. Previous estimates pegged the death toll at around 3.2 million.

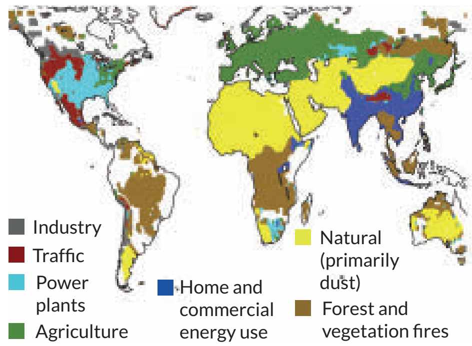
Next, by systematically removing one source of pollution at a time from the simulation, the team estimated each source's deadliness. Small-scale energy use and agriculture were the two leading killers globally, accounting for 1 million and 660,000 deaths.

The researchers also estimated the regional health impacts from each of the seven sources. For instance, in India and Vietnam, cooking and heating fires accounted for up to 60 percent of air pollution deaths.

Looking forward, Lelieveld and colleagues estimate that if there are no new constraints on pollution emissions worldwide, deaths could double by 2050.

Some of the death figures may be overestimates, says UCLA environmental health scientist Michael Jerrett. The calculations assume that all particles are equally toxic. So the agriculture estimate, for instance, would hold true only if the nitrogen-based fumes from fertilizer and livestock urine are really as deadly as the pollution from, say, coal burning or traffic, he says. Some toxicological studies suggest that fumes from agriculture cause few health effects, he notes, although researchers still debate the topic. ■

Main sources of air pollution deaths



Unusual suspects Some of the deadliest air comes from unheeded polluters such as agricultural fertilizer and home cooking. Researchers calculated the largest source of air pollution deaths by different region.

J. LELIEVELD *ET AL*/*NATURE* 2015

LIFE & EVOLUTION

Loss of vision saved cavefish energy

In dark, eyesight can be costly, oxygen measurements show

BY SUSAN MILIUS

Eyes and the brain tissue needed for vision demand about 15 percent of the energy budget of a young Mexican fish, researchers say. This percentage supports the idea that energy cost-cutting helps explain how cavefish go blind.

That 15 percent represents a notable energy demand for a 1-gram juvenile Mexican tetra fish (*Astyanax mexicanus*) at rest, says Damian Moran of Plant and Food Research in Nelson, New Zealand. Vision could therefore become a liability in food-sparse caves, where no sunlight supports energy-catchers such as plants, Moran and colleagues argue September 11 in *Science Advances*.

The cost is greater for juvenile fish than for older ones. As fish grow, their bodies enlarge more than their brains do. By the time a Mexican tetra reaches 8.5 grams, vision demands only about 5 percent of its total resting energy budget.

Some Mexican tetras of this species live in aboveground streams and have functioning eyes. There's debate, Moran says, over what factors, such as simple disuse or repurposing of genes, drove vision loss in the populations that colonized caves.

Flushing artificial bloodlike fluid over excised brains and eyes allowed the team to compare the demands of vision-related body parts in blind cavefish with the demands in tetras with fully functioning eyes. The team calculated energy use based on differences in oxygen demand.

This cost of vision "has not been tested directly before, or as elegantly," says William Jeffery, who studies the same species at the University of Maryland in College Park. He's surprised that vision doesn't use more energy. "I would have expected large differences if this is a key driver of regressive evolution." ■

ATOM & COSMOS

Ocean envelops all of Enceladus

Water hidden under ice not limited to moon's south pole

BY CHRISTOPHER CROCKETT

Forget about a measly southern sea. A global ocean of liquid water lurks beneath the ice of Saturn's moon Enceladus, a new study suggests.

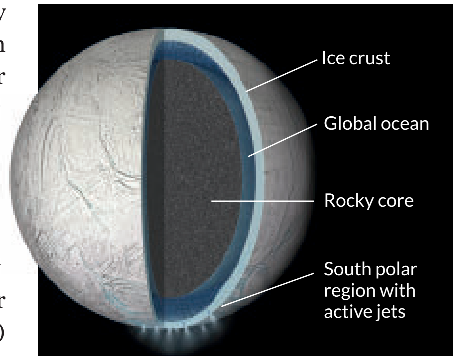
"It's a very exciting result and moves us to the next level," says planetary scientist William McKinnon of Washington University in St. Louis. "We can stop talking about whether the ocean is global or regional."

The ocean on Enceladus announced itself by giving the moon a little extra twist. As Enceladus orbits Saturn, it subtly shimmies about its axis. Images from the Cassini spacecraft show that the moon sways a bit too far for the icy surface to be clinging to the rocky core. The ice instead probably floats on a liquid layer, planetary scientist Peter Thomas and colleagues report in a paper to appear in *Icarus*.

Enceladus has been dropping hints about its ocean ever since Cassini saw water geysers blasting through cracks in the ice in 2005. More recent gravity data pointed toward a large reservoir under the south pole (*SN: 5/3/14, p. 11*) but could not establish whether that water extended to the rest of the moon.

Researchers suspect that several moons of Jupiter and Saturn harbor subterranean seas. "Before we started exploring things with spacecraft, the notion that there are several oceans under the outer planets' satellites would have been regarded as nuts," says Thomas, of Cornell University.

How deep the Enceladus ocean goes is a mystery, as is how long it has been there. "The ocean in some form has probably been around for a long time but might not have been the same ocean," McKinnon says. The ice shell probably waxes and wanes in the gravitational tug-of-war between Enceladus and Saturn that heats the moon. Figuring out how and when the ocean formed depends on bringing together knowledge about not just Enceladus but also the interior of Saturn and how all its other moons influence one another. ■



Saturn's moon Enceladus (illustrated, not to scale) harbors a global ocean of water beneath its icy surface, a new study finds.

BODY & BRAIN

Caffeine resets body's circadian clock

After-dinner coffee could induce 40-minute delay, study shows

BY LAURA SANDERS

Postdinner coffee can lead to sleepless nights — not a surprise. A new study helps reveal why. Caffeine before bed distorts the master clock that tells the body what time it is. An evening dose with less caffeine than in a Starbucks tall medium roast delayed people's clocks by about 40 minutes, scientists report in the Sept. 16 *Science Translational Medicine*.

Clocks tick throughout the body, orchestrating the circadian rhythms that control everything from sleep to appetite to hormone levels (*SN: 7/25/15, p. 14*; *SN: 4/10/10, p. 22*). Caffeine taps directly into the master clock that syncs these far-flung timekeepers, Kenneth Wright of the University of Colorado Boulder and colleagues found. "This suggests that caffeine has a larger impact on us than we may have realized, from the circadian perspective," he says.

The results have implications for the huge number of people who consume one of the world's most popular stimulants, says pharmacologist and sleep researcher Hans Peter Landolt of the University of Zurich. Figuring out the details of how caffeine influences the body's clocks might lead to better ways to prevent or treat sleep disorders, he says.

Over the course of about 49 days, five participants kept track of their sleep schedules at home for some of the days and nights, and came into UC Boulder's Sleep and Chronobiology Laboratory for the others. During some lab stays, the participants were kept awake in rooms with low light and fed hourly snacks, a protocol that eliminated day and night signals. The hormone melatonin, which is plentiful at night and scarce during the day, served as a readout for circadian rhythms.

On some days, participants received caffeine three hours before their usual bedtime. The exact dose depended on body weight; a person weighing 152 pounds would get 200 milligrams of caffeine, about the amount in an 8-ounce cup of strong coffee. That dose shifted their circadian rhythms by about 40 minutes, melatonin levels revealed. The researchers didn't test for sleep shifts or changes in behaviors such as alertness.

Other experiments on cells in lab dishes help explain how caffeine influences cellular clocks. Caffeine interferes with proteins that help detect the chemical messenger adenosine, which carries sleepy signals, the team found.

Caffeine's clock-shifting effects might be harnessed for good. Used in a precise way, caffeine could help regulate people's sleep patterns, Wright says, coordinating rhythms in people who do shift work or suffer from jet lag, for instance.

While the study is a good first step, there's still much more to learn, says Landolt. Factors such as age, genetics and culture can all influence how people respond to caffeine. ■

JPL-CALTECH/NASA

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At first and even second blush, you will think this is the famous brand "X" watch that sells for over $1,000. But this is the Rodell-7 Argonaut™ Watch, the last watch you will ever need to buy. And, incredibly, it can be yours for only ~~$129~~ $69 (or even less) – read on!*

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GENES & CELLS

Old stem cells lose protective barriers

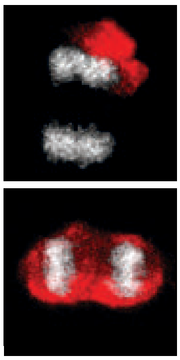
In young brains, bad proteins confined in newly formed neurons

BY TINA HESMAN SAEY

Breaking down barriers usually sounds like a good thing, but it's not for aging stem cells.

When young brain stem cells split in two, they wall off damaged proteins in one daughter cell, leaving the other spry and ready to divide again, researchers report in the Sept. 18 *Science*. With age, the barrier that sequesters damaged proteins breaks down, allowing cellular garbage to spill into both cells, the team discovered. The spillover may diminish older stem cells' ability to divide and replenish tissues. Learning why such barriers fall apart may lead to new kinds of antiaging therapies.

Researchers have previously demonstrated that yeast, fruit fly cells and some types of human cells grown in lab dishes divvy up proteins unequally. The new study is the first to show that lopsided segregation happens in the brain, says UCLA developmental biologist Eddy De Robertis. He was not involved in the study, but his lab has shown that cells unequally divide proteins studded with a molecule called ubiquitin.



A young brain stem cell (shown dividing, top) packs old proteins (red) into a daughter cell. Older cells (one shown, bottom) lose a barrier that segregates these proteins.

Ubiquitin clinging to a protein is one signal that the protein is ready for the garbage. In the new study, researchers tracked ubiquitin-studded proteins as mouse neural stem cells divided into two cells: one remaining a stem cell and the other becoming a nerve cell, or neuron.

"We didn't know who would stay clean, the stem cell or the daughter cell," says study coauthor Sebastian Jessberger, a neuroscientist at the University of Zurich. "It could be that the stem cell keeps the dirt."

But that's not what the researchers found. Instead, De Robertis says, "the stem cell remains pristine and the daughter cell takes with it whatever baggage there is."

As cells age, though, old proteins can be found in both newly divided cells, the researchers discovered, indicating that the barrier that kept the "dirty" proteins in daughter cells has crumbled. Brain stem cells from middle-aged mice (9 months old) no longer divided as often as ones from 1.5-month-old mice did, the team found. That finding suggests that inheriting old junk can make once vigorous stem cells decrepit.

Jessberger and colleagues aren't yet sure how the barrier works. "There's not a complete fence between one side of the cell and the other," he says. Instead, he envisions a mesh of proteins inside the endoplasmic reticulum — a network of tubes in which cells make and package proteins — that catches proteins and other molecules related to aging, while letting others slip through.

A protein called lamin A may be part of the mesh. Children who have a mutation in the gene encoding lamin A develop a fatal premature aging syndrome called

LIFE & EVOLUTION

Dogs flub test of problem solving

Pets and shelter animals more likely than wolves to give up

BY SUSAN MILIUS

Humans may be a bad influence on their best friends — at least when it comes to problem solving. Dogs that have lived around people lagged behind wolves in a task that wasn't very tough: tugging a lid off a food container.

Only one of 20 dogs got the lid off a plastic storage box and gobbled the sausage treat inside, reports Monique Udell of Oregon State University in Corvallis. Yet eight of 10 wolves gnawed, pawed and ripped their way into the container.

The social tendencies of dogs may be getting in the way of persistent, independent struggling that would have freed the treat, Udell suggests September 16 in *Biology Letters*. The dogs (10 pets and 10 shelter dogs with some history as pets) typically spent 10 to 15 percent of their time gazing at the nearest person and 5 percent or less touching the container. Wolves raised and fed by people but living outdoors, however, barely looked at a nearby person. They typically devoted about 90 percent of the two-minute trial to grappling with the treat box.

Even with no person around, the dogs didn't paw or mouth the box much, Udell found. Once again, only one dog retrieved the treat. When a person hovered over the dogs and actively encouraged them to keep trying to open the box, the dogs did spend more time engaged with the problem — and a few more opened the box — but they still did not match the wolves.

One way to look at the results is that "wolves are practical problem solvers and dogs are social problem solvers," says Clive Wynne of Arizona State University in Tempe, who worked with Udell on earlier dog research but not on this project. But Wynne suspects that "we teach our dogs to be stupid." He suggests early and abundant exposure to human outrage at a sandwich stolen off a plate, or a kitchen cabinet ravaged, may have taught pets to proceed cautiously in helping themselves.

A tidbit of preliminary data in the paper suggests a way to test that idea. An 8-week-old puppy did open the box. If puppies with less training in the etiquette of sharing human houses do better than adults at ripping open food boxes, then learned caution may be a factor.

Udell's test grew out of an urge to reverse an experimental scenario in a line of experiments going back to a 2003

D.L. MOORE *ET AL*/*SCIENCE* 2015

Hutchinson-Gilford progeria. The mutation leads to a buildup of a form of lamin A known as progerin, which also builds up in the cells of aging people who don't carry the mutation. Progerin interferes with lamin A's ability to build a scaffold that supports the nucleus, the compartment where cells store DNA.

Forcing young mouse brain stem cells to make progerin also weakened the barrier that excludes aging proteins from the stem cells. The protein probably isn't the only component of the barrier, but the researchers don't yet know which other proteins are involved or how the barrier sorts aging factors.

"Finding that barrier's molecular nature will be very interesting," says De Robertis.

Inheriting cellular garbage might not be so great for newborn daughter cells, and may help explain why some brain cells die soon after they are born, says Jessberger. On the other hand, many brain cells live a long time, leaving plenty of time to clean up the mess handed down by their parent stem cells. And the new neurons may get helpful heirlooms from their parent cells, Jessberger says. "It doesn't mean it's always bad." ■

paper from Ádám Miklósi of Eötvös Loránd University in Budapest and his colleagues. As part of a surge of interest in how dogs differ from wolves, the researchers had trained nine dogs and nine human-raised wolves to open a box and score a treat. When presented with a box with a lid attached in a way that it couldn't be opened, dogs were more likely than wolves to turn their gaze toward a human face.

That gazing has been interpreted as a clever move, something Udell's study questions. Miklósi points out that he was more cautious in interpreting the results in his paper. His larger idea, though, is that "dogs were selected to some extent for being able to cooperate with humans." And this deep history helps explain dog sensitivity to human social cues, a sensitivity that encourages people to tolerate canine company. ■

EARTH & ENVIRONMENT

Tsunami forecasts get speed boost

Chilean quake tests simple method for rapid warning

BY THOMAS SUMNER

The magnitude 8.3 earthquake off Chile on September 16 sent an enormous pulse of water racing away from the quake's epicenter, prompting an evacuation of over 1 million Chileans. This surging seawater provided an unanticipated test for a new, faster way to forecast tsunamis.

Using simplified mathematical estimates of how quakes trigger tsunamis, scientists approximated the height of the Chilean tsunami in a matter of seconds after quake data flowed in. When paired with upgraded earthquake-sensing technology, the technique could deliver accurate tsunami forecasts in half the time of current methods, the scientists report in a paper to be published in the *Journal of Geophysical Research: Solid Earth*.

Faster predictions will help emergency managers dispatch resources to areas most likely to be devastated, says Sebastián Riquelme, a seismologist at the University of Chile in Santiago. "With our model, you'll know where the damage will likely be within five minutes after the earthquake occurred." A tsunami's height partly determines how far inland waters will flood.

Offshore quakes frequently rattle Chile. The abrupt movement of the seafloor displaces seawater like a stone hurled into a pond, creating tsunami waves that can travel at speeds akin to a commercial airliner. In Chile, tsunamis can reach the coast 15 minutes after a quake, Riquelme says.

A tsunami's size depends on the quake's characteristics. For powerful tremors, however, local seismometers go off the charts and they stop providing usable data. Seismologists must wait for seismic waves to travel farther away from the epicenter to get accurate readings, costing valuable minutes.

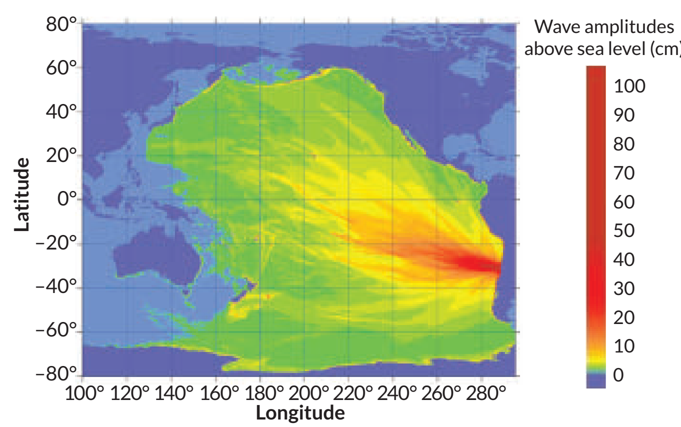
Some tsunami forecasts forgo these detailed data and calculate possible scenarios in advance. When a quake occurs, seismologists search a premade list for a close match. This method provides fast, though generalized, predictions.

Soon GPS networks, which measure ground shifts, could supplement seismometers (*SN: 9/5/15, p. 14*), allowing seismologists to calculate earthquake properties in minutes. With such rapid earthquake data on the horizon, tsunami forecasts needed a speed boost to keep up.

Riquelme and colleagues crafted a simple mathematical method. Using the properties of a just-occurred earthquake, the system estimates the amount of displaced water and forecasts the height of the tsunami — all in about 15 seconds.

The Chile quake provided the first real-time test of the method. The researchers predicted a maximum tsunami height of 5 to 6 meters, which closely matched early reports of a 4.75-meter swell.

The method's simplicity goes too far, says Eddie Bernard of the National Oceanic and Atmospheric Administration's Center for Tsunami Research in Seattle. Quakes often trigger underwater landslides that produce even larger tsunamis than the initial tremor, he notes. ■



Wave race A magnitude 8.3 quake struck September 16 off the coast of Chile, triggering a tsunami that radiated across the Pacific Ocean (projected here using existing methods). The event provided a test of a new method that can offer faster tsunami predictions.

NATIONAL TSUNAMI WARNING CENTER/NOAA

BODY & BRAIN

Alzheimer's acts like prion disease

Misfolded proteins implicated in more neurological disorders

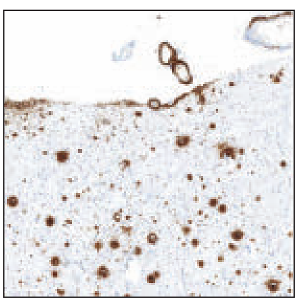
BY LAURA SANDERS

In some brain diseases such as Alzheimer's, distorted proteins behave like infectious agents, spreading among brain cells and corrupting other proteins. New studies suggest that such diseases should be classified among disorders caused by the infectious particles known as prions.

Classic prion infections, such as Creutzfeldt-Jakob disease, are fatal. Some scientists hope that recasting Alzheimer's and other neurodegenerative disorders as prion diseases will help reveal ways to halt or prevent neural destruction. Yet others caution that this radical reclassification may unnecessarily evoke fear of contagion.

Mindful of public panic, researchers are quick to say that there is no evidence that Alzheimer's, Parkinson's and other neurodegenerative diseases can be transmitted through normal everyday contact. "There is not one iota of evidence whatsoever that infectivity can occur from one individual to another," says cell biologist and neuroscientist George Bloom of the University of Virginia in Charlottesville.

But scientists can't rule out a jump from person to person under special circumstances, such as when contaminated tissue makes its way into a healthy body via certain medical procedures.



Amyloid-beta (brown) accumulated in the brain of a person who received cadaver-derived growth hormone as a child.

That exact scenario may have occurred in people who, during their youth, received injections of growth hormone derived from cadaver pituitary glands, scientists report in the Sept. 10 *Nature*. A postmortem study of eight such people who died between the ages of 36 and 51 found that four had substantial amyloid-beta buildup in their brains, a sign of Alzheimer's disease.

"This was a highly unusual finding," study coauthor John Collinge of University College London said September 8 in a media briefing. "You wouldn't have expected to see this Alzheimer's pathology in this age group."

The patients had all developed Creutzfeldt-Jakob disease from prion-contaminated injections. Finding A-beta deposits in the brains of these relatively young people, who had not been diagnosed with Alzheimer's, suggests that those contaminated injections may have also been laced with A-beta.

Scientists can't rule out other explanations for the presence of A-beta in these people's brains. But the results raise the possibility that given the right opportunity, A-beta and other proteins, such as the Alzheimer's-related tau and Parkinson's-linked alpha-synuclein, may propagate through the brain like prions.

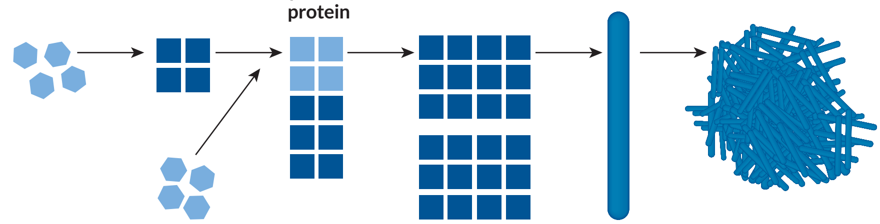
Thinking of the proteins involved in neurodegenerative diseases as prions "brings conceptual unity to the whole field," says Michel Goedert, a neurobiologist at the University of Cambridge.

At the heart of prion diseases lie deformed proteins. Like bad apples, these contorted proteins coax normal proteins to change shape into misfolded forms. A benign shape of looping structures called alpha helices, for instance, might transform into more tightly packed shapes called beta-sheets. Through a process that remains mysterious, these bundles of beta sheets then turn dangerous.

Most of what's known about these infectious prions — short for "proteinaceous infectious particles" — comes from the original prion protein identified by University of California, San Francisco researcher Stanley Prusiner in the 1980s. Prion proteins exist in a normal form in the body. When shape-shifted into a dangerous conformation, the protein causes diseases such as Creutzfeldt-Jakob disease and kuru, a neurodegenerative disorder acquired through ritualistic cannibalism of brain tissue among tribal New Guineans (*SN: 7/11/15, p. 11*).

In classic prion diseases, the infectious agents spur other proteins to misfold as they move from cell to cell and from animal to animal. A-beta seems to do something similar, recent animal studies suggest. Buildup of A-beta has been spotted in the brains of mice that received injections of tissue from mouse brains with signs of Alzheimer's, scientists reported in 2011 in the *Journal of Neuroscience*. A-beta can also spread from cell to cell, Kurt Giles of UC San Francisco, Prusiner and colleagues reported in the *Proceedings of the National Academy of Sciences* in 2012. Similar behavior has been spotted for the Alzheimer's-related protein tau.

And like the original misfolded prion



Protein corruption Prions (dark blue) can form spontaneously or be introduced into the brain. Prions incite normal versions of the same proteins (light blue) to misfold. These prions aggregate to form clumps of fibrils. This process may be at the heart of neurodegenerative diseases, some researchers propose. SOURCE: M. GOEDERT/*SCIENCE* 2015, L.C. WALKER AND M. JUCKER/*ANNU. REV. NEUROSCI.* 2015

FROM TOP: E. OTWELL; Z. JAUNMUKTANE *ET AL/NATURE* 2015 protein, A-beta seeds seem to persist for long periods. When scientists put clumps of A-beta into mice that lacked even normal A-beta, nothing happened. But when brain tissue from those mice was injected into mice that did have A-beta, the formerly inert seeds sprang into action and regained their damaging behavior, neurobiologist Mathias Jucker of the University of Tübingen in Germany and colleagues report September 9 in *Nature Neuroscience*.

Scientists have also observed troublesome behavior by alpha-synuclein, which aggregates in Parkinson's disease and a related neurological disease called multiple system atrophy, or MSA. Mice genetically altered to have a faulty copy of the human alpha-synuclein protein received injections of brain tissue from 14 people who suffered from MSA. After 120 days, alpha-synuclein had accumulated in the mice's brains and caused damage, Giles, Prusiner and colleagues report August 31 in the *Proceedings of the National Academy of Sciences*.

These results could pose a problem for surgical teams, Giles and colleagues write. Hardy prions resist standard decontaminating procedures used by hospitals, so surgical equipment that comes into contact with brain tissue may need more thorough cleaning procedures. What's more, lab workers who study tissue from MSA or other disorders may need to be extra cautious, Giles says.

Older, less direct evidence for alpha-synuclein's spread comes from people with Parkinson's who received fetal stem cell transplants. When participants died, their transplanted cells were rife with alpha-synuclein, two 2008 postmortem analyses revealed. That finding suggested that the misfolded alpha-synuclein proteins had spread to the healthy young grafts. "That was the first indication that the protein can infect the surrounding cells," says neuroscientist Jiri Safar of Case Western Reserve University, who also runs the National Prion Disease Pathology Surveillance Center in Cleveland.

So far, brain tissue from people with Parkinson's disease doesn't seem infectious in mouse experiments, Giles says, suggesting that the alpha-synuclein at work in MSA might be different from the one in Parkinson's. That idea raises one of the biggest outstanding mysteries in the field: defining what constitutes an infectious "seed."

A-beta, for instance, comes in multiple shapes and sizes. It's possible that A-beta and other proteins that aggregate exist as large, complex mixtures called "clouds." Scientists don't know which form is the most likely to spread, or which form is most dangerous for cells. Those two attributes may very well rely on different forms, Goedert says.

While animal studies have proved useful in illuminating how these proteins can behave in certain situations, there's still much to learn about how they actually work in the human brain, Goedert says. "The question is, what do they mean for human disease?"

> "Within the scientific community, everyone seems to have their own definition of what a prion disease is."
> KURT GILES

Because the research tying these neurodegenerative diseases to prions is in its infancy, scientists are still wrangling over what to call these disorders. "Within the scientific community, everyone seems to have their own definition of what a prion disease is," Giles says.

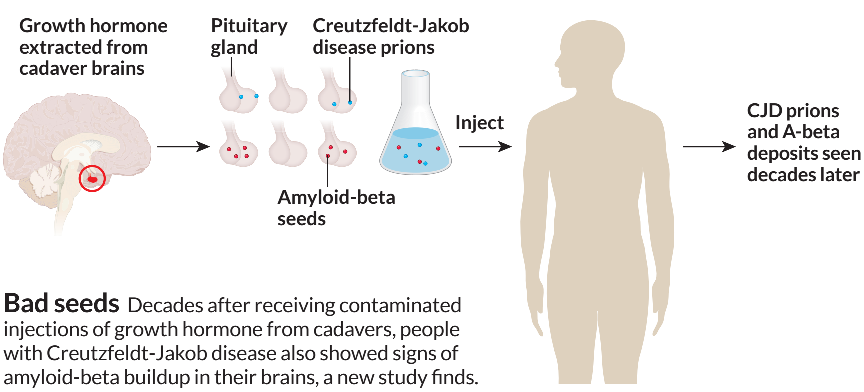
Some oppose expanding the definition of prion diseases. "The word 'prion' induces a lot of fear," says neurologist Valerie Sim of the University of Alberta in Edmonton, Canada. And an outsized public reaction could have consequences such as denials of surgeries for people with these disorders and shuttering of research labs, she says. This expanding umbrella of prion disease is "trying to redefine a scary word," she says.

Others, such as Goedert, prefer to say these diseases are "prionlike." That could convey that in some ways, the diseases are similar to classic prion diseases, as in their the cell-to-cell spreading; in other ways, such as their lack of infectivity through everyday contact, prionlike diseases differ. "I think one should not call Alzheimer's disease and Parkinson's disease prion diseases at this point," he says. "But I think it's true to say there are similarities."

Semantics aside, researchers agree that approaching these neurodegenerative diseases as disorders of protein folding and spreading may lead to insights on how to stop or prevent them, helping to provide therapies that are desperately needed and have proven elusive so far.

One approach borrowed from the prion field would be to lower the number of uncorrupted proteins in the brain. Much like the clearing away of dry kindling can prevent forest fires, getting rid of normal proteins might be a way to combat their ultimate destruction.

The field is young, and evolving quickly, Giles says. "Watch this space," he says. "I think the next few years will tell us whether or not this is a useful way to go." ■



Bad seeds Decades after receiving contaminated injections of growth hormone from cadavers, people with Creutzfeldt-Jakob disease also showed signs of amyloid-beta buildup in their brains, a new study finds.

M. JUCKER AND L.C. WALKER/*NATURE* 2015

Northern elephant seals collect toxic mercury in their hair; shedding then boosts local pollution levels, a study finds.

EARTH & ENVIRONMENT

Molting seals shed mercury along with fur

Along with smokestacks and industrial waste, researchers can add lounging seals to the list of mercury polluters. Hair from northern elephant seals (*Mirounga angustirostris*) is loaded with the toxic metal. And when shed, that hair can boost mercury levels in surrounding seawater by about 17 times, researchers report online September 8 in the *Proceedings of the National Academy of Sciences*.

The finding may solve a long-standing mystery of why remote, seemingly pristine coastal areas where seals congregate can be hot spots for mercury pollution, harboring hazardous levels of the neurotoxicant, the authors say.

Jennifer Cossaboon, now at San Diego State University, and colleagues analyzed seawater from Año Nuevo State Reserve in 2012 and 2013. About 70 kilometers south of San Francisco, the park is a seal destination far from traditional sources of mercury. The team noted a spike in methylmercury, the form of mercury that amasses in sea life, that coincided with the northern elephant seals' spring molt.

Seals get mercury from their prey — which accumulate it from industrial and natural sources in the environment — and expel it through their coats. The researchers estimated that about 4,000 adult seals shedding 54,000 kilograms of fluff per year in Año Nuevo could release 0.2 kilograms of mercury — enough to explain the pollution spike. That mercury could then be gobbled up by small marine life or seafloor microbes and get passed up the food chain. *— Beth Mole*

ATOM & COSMOS

Mars' ionosphere mystery explained

Confusion about how many layers of charged particles exist in the Martian atmosphere might be due to what time of day measurements were made.

Several spacecraft have detected two ionosphere layers on the Red Planet. But both Viking landers noticed only one layer during their 1976 descents. The other spacecraft probed the atmosphere at sunrise and sunset when conditions favor the formation of two layers, Majd Mayyasi and Michael Mendillo report online September 10 in *Geophysical Research Letters*. The Vikings, however, landed around 10 a.m. and 4 p.m. (local time), when the midday sun blends the layers together.

Ultraviolet light and X-rays from the sun strip electrons from, or ionize, molecules in the atmosphere, creating a layer of charged particles. Mayyasi and Mendillo, of Boston University, simulated how the ionosphere changes. UV light forms a layer on the planet's dayside. Higher-energy X-rays burrow deeper along Mars' flank and, combined with subtle changes in atmospheric chemistry, develop a second layer where day turns to night. Spacecraft pick up this lower layer when they beam radio waves through the atmosphere toward Earth. The alignment between probe, Mars and Earth limits the radio signal to slice through a part of the Martian sky where it's either dawn or dusk. *— Christopher Crockett*

MATTER & ENERGY

Invisibility cloaks slim down

A new invisibility cloak offers more stealth in a thinner package.

The 80-nanometer-thick "skin cloak," reported in the Sept. 18 *Science*, drapes over a micrometer-sized object and renders it undetectable for a specific wavelength of red light. Light waves bounce off the shielded entity as if rebounding off a flat surface. Unlike previous prototypes known as carpet cloaks, the skin cloak is extremely thin, works in open air and doesn't leave a signature in light that makes the cloak itself detectable.

Penn State optical physicist Xingjie Ni and colleagues say the cloak, which is made of tiny gold antennas stuck on a gold and magnesium fluoride base, can be scaled up to hide even larger items. But scientists say they are still a long way from building cloaks that conceal macroscopic objects in all the wavelengths of light that are visible to the naked eye. *— Andrew Grant*

LIFE & EVOLUTION

Invading Argentine ants carry virus that attacks bees

The first survey of viruses in the globally invasive Argentine ant brings both potentially bad and good news.

One of two viruses found to be actively reproducing in the ants (*Linepithema humile*) is a known threat to honeybees, says Philip Lester, a community ecologist at Victoria University of Wellington in New Zealand. Called deformed wing virus, it might use ants as a reservoir, spreading to bees that are visiting the same flowers or getting raided for honey by the ants, Lester and colleagues suggest September 9 in *Biology Letters*.

The other virus is new to science. Christened LHUV-1 (pronounced "love-one"), it belongs to the dicistrovirus family, which includes many insect pathogens. Whether LHUV-1 actually sickens Argentine ants remains to be seen. If it does, Lester says, the virus might prove useful to check the spread of the ants. *— Susan Milius*

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Special Report: Gravity's Century

In 1915, the universe was small and static. Space was smooth. Gravity pulled things to the ground. At least that's the way it was in the minds of all but one exceptional physicist — Albert Einstein.

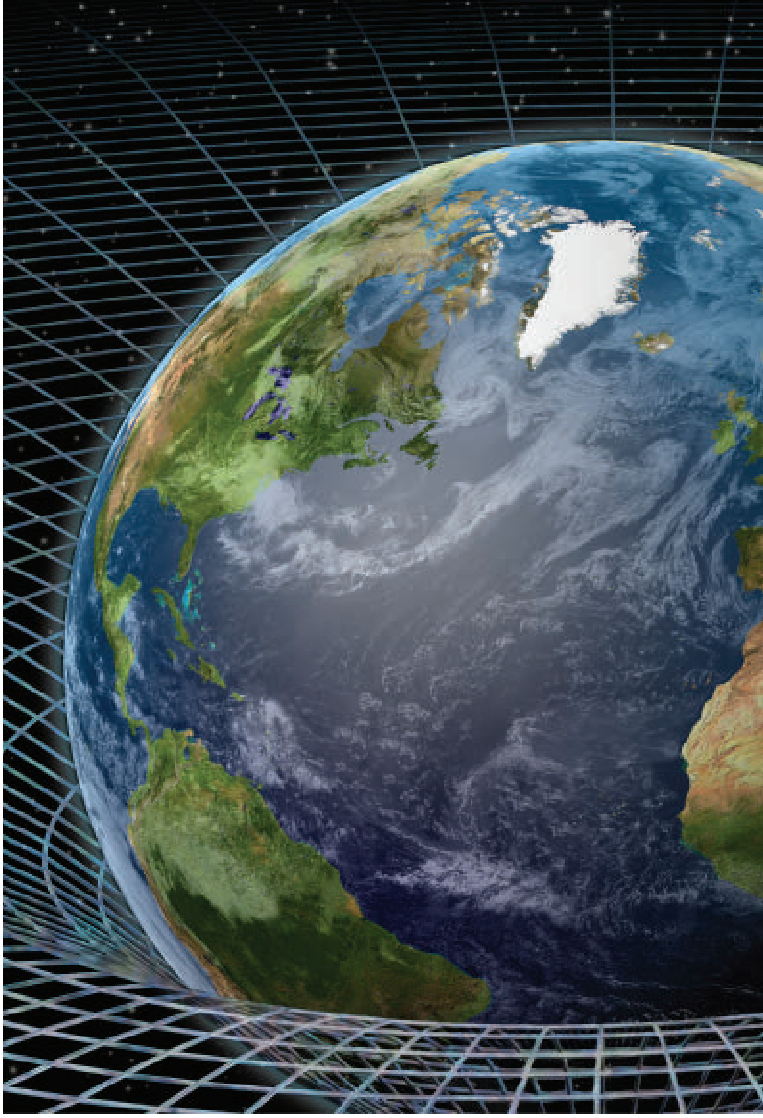
After years of pondering the interplay of space, time, matter and gravity, Einstein produced, in a single month, an utter transformation of science's conception of the cosmos: the general theory of relativity.

His special theory of relativity, introduced a decade earlier, had united space with time, and matter with energy. Soon thereafter he saw that a generalized version of relativity would merge spacetime and matter-energy to produce gravity. Rather than "pulling" each other together, masses warped the fabric of spacetime — and then moved through spacetime along the curves that such warping produced.

Einstein's space-bending theory was mind-bending. It not only succeeded in explaining gravitational mysteries where Newton's law failed, but it also predicted amazing unsuspected natural phenomena, from black holes to the expansion of the universe itself. No longer small and static, Einstein's universe is expansive and dynamic, home to a zoo of bizarre astrophysical beasts inexplicable without general relativity's help.

Today astrophysicists manipulate those phenomena to probe the heavens (Page 24), while other physicists seek ways to reconcile general relativity with the past century's other revolutionary theory, quantum mechanics (Page 28). It may now be that general relativity's confluence with quantum mechanics is on the verge of producing a new theory, glimpsing more deeply into the essence of existence than even Einstein was able to see. But it wouldn't have been possible without him.

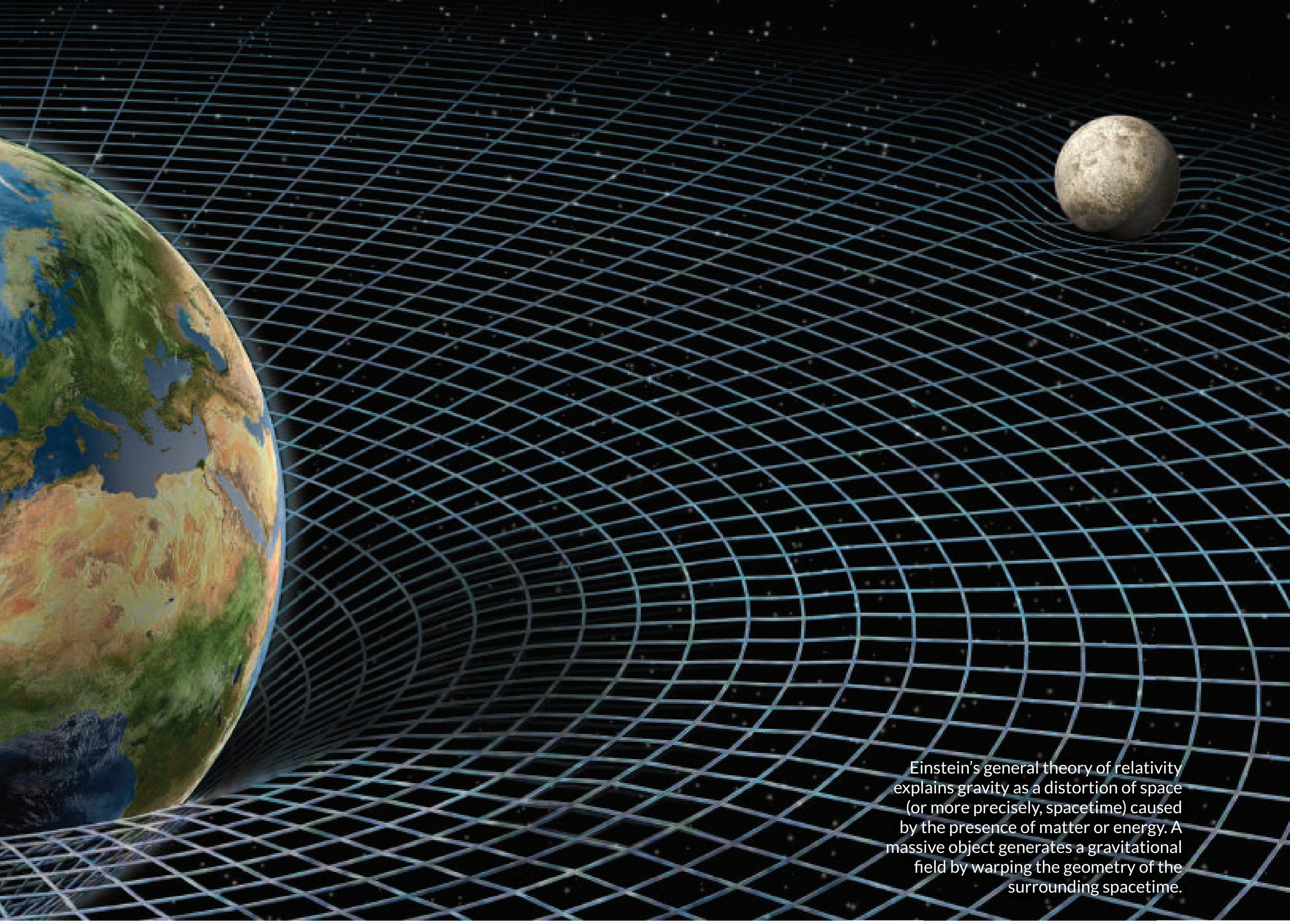
"Even if some modified version of general relativity must be adopted ultimately to accommodate new observations," writes physicist Clifford Will, Einstein's theory "will very likely still be its foundation."
— Tom Siegfried



Getting a Grip on Gravity

Einstein's genius reconstructed science's perception of the cosmos **By Tom Siegfried**

Einstein coverage from the *SN* archives: **bit.ly/SN_generalrelativity**



Einstein's general theory of relativity explains gravity as a distortion of space (or more precisely, spacetime) caused by the presence of matter or energy. A massive object generates a gravitational field by warping the geometry of the surrounding spacetime.

NICOLLE RAGER FULLER

Albert Einstein opened humankind's eyes to the universe.

Before Einstein, space seemed featureless and changeless, as Isaac Newton had defined it two centuries earlier. And time, Newton declared, flowed at its own pace, oblivious to the clocks that measured it. But Einstein looked at space and time and saw a single dynamic stage — spacetime — on which matter and energy strutted, generating sound and fury, signifying gravity.

Newton's law of gravity had united the earthly physics of falling apples with the cosmic dances of planets and stars. But he couldn't explain how, and he famously refused to try. It took an Einstein to figure out gravity's true modus operandi. Gravity, Einstein showed, did not just make what goes up always come down. Gravity made the universe go 'round.

Gravity's secrets succumbed to Einstein's general theory of relativity, unveiled in a series of papers submitted a century ago this November to the Prussian Academy in Berlin. A decade earlier, his special theory of relativity had merged matter with energy while implying the unity of space and time (soon to be christened as spacetime). After years of struggle, Einstein succeeded in showing that matter and spacetime mutually interact to mimic Newton's naïve idea that masses attract each other. Gravity, said Einstein, actually moved matter along the curving pathways embodied in spacetime — paths imprinted by mass and energy themselves. As expressed decades later by the physicist John Archibald Wheeler, mass grips spacetime, telling it how to curve, and spacetime grips mass, telling it how to move.

Einstein's theory explained a famous observation that Newtonian gravity could not: a subtlety in the orbit of the planet Mercury. And his equations implied further slight deviations from Newtonian calculations. Over the last century, general relativity's predictions have been repeatedly verified by modern precision measurements. To physicists today, general relativity and gravity are essentially synonyms.

But general relativity is about more than just understanding gravity. It's about explaining the totality of existence. General relativity inspired a new vision of the entire fabric of the cosmos. From general relativity flowed the realization that the universe is expanding, that it contains spacetime bottomless pits called black holes, that it is traversed by ripples in space triggered by cataclysmic collisions.

"The implications for the further reaches of the universe were more surprising than even Einstein ever realized," physicist Stephen Hawking has written.

General relativity explains how the universe can obey physical laws that apply to any form of motion. It's at the heart of identifying and investigating crucial questions about space and time, existence and reality. And its implications are not limited to esoteric concerns on cosmic scales — it has its down-to-Earth impacts as well. Without general relativity, for instance, GPS devices would be worthless. Satellite signals designed to keep your car on the right road would be off by miles if not corrected for the effects predicted by Einstein's math.

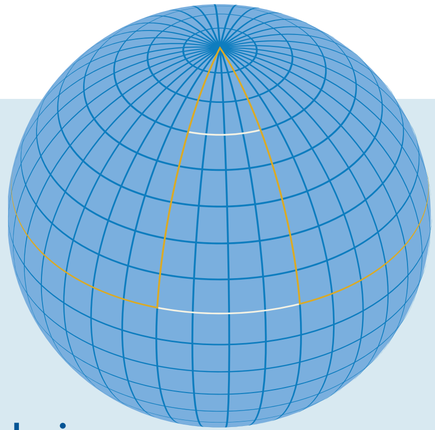
Gravitation revolution

On his road to general relativity, Einstein himself took many wrong turns. From 1907 to 1914 he struggled with what the physicist Abraham Pais called "one of the hardest problems of the century" — explaining gravity in a way that permits the laws of nature to be the same for all observers, no matter how they are moving. Einstein had to learn new math and jettison common prejudices, such as the universal belief that Euclidean geometry described reality accurately. He struggled with distractions, both in his personal life and in physics problems posed by quantum theory. And he found that nature stubbornly refused to cooperate. By 1914 he had essentially given up, believing that a partially successful attempt — a sort of general relativity lite — was the best that nature would allow.

But then somehow Einstein's brain rebooted. His theory began to solidify, and he swiftly composed four papers, one a week, during November 1915. By the last paper he had finally found the decisive equation that launched his gravitation revolution.

Four years later, general relativity made Einstein himself a celebrity. If gravity curves space, he had realized early on, a light beam passing near a massive object (say, the sun) would be deflected from its course. That deflection would shift the apparent position of the source of the light (say, a distant star). During a solar eclipse, such a shift could be photographed and measured. Such measurements, made during eclipse expeditions in 1919, confirmed Einstein's calculation. Even without Twitter to spread the word, Einstein's triumph sparked a media sensation.

"Lights all askew in the heavens, men of science more or less agog," proclaimed one of the most famous newspaper headlines in science history, in the Nov. 10 *New York Times*.

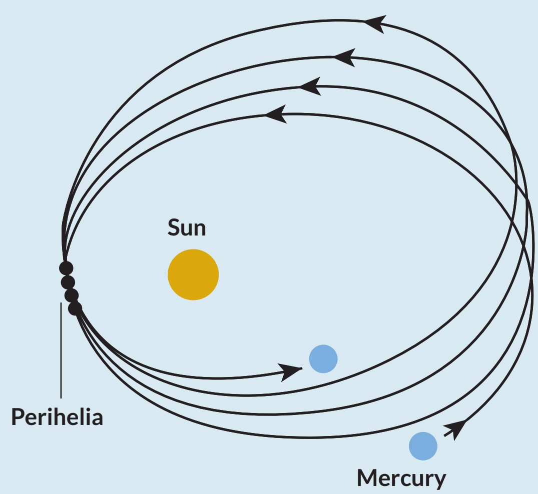


Geodesics

The curvature of spacetime lies at the heart of general relativity. The theory predicts that anything moving through a gravitational field undisturbed by other forces will follow a curved path called a geodesic. Geodesics on two-dimensional curved surfaces, like the Earth's, illustrate how curvature creates gravity. From any point on the equator, for instance, the shortest path to the North Pole follows a curve — the geodesic corresponding to a meridian. If two people start out on such a trek, starting some distance apart, they pursue different curved meridians to the pole but grow closer together as they travel northward. It would appear that the curvature was pulling them towards each other — just as Newton's gravity described.

Explaining Mercury's odd orbit

In the middle of the 19th century, astronomers discovered that the orbit of Mercury doesn't quite conform to the path predicted by Newtonian gravity. On each trip around the sun, Mercury's closest approach, or perihelion, shifts forward by a slight amount, less than 2 degrees of arc per century (as seen from Earth). Most of that shift could be explained by the gravitational effects exerted by other planets in the solar system. But 43 seconds of arc remained unexplained. For decades, astronomers sought a solution by searching for a postulated planet, called Vulcan, nearer to the sun than Mercury. Gravity from such a planet could explain the deviation in Mercury's orbit. But such a planet was never found. In November 1915, Einstein used his new theory of gravity to calculate Mercury's orbit and found that it explained the discrepancy precisely, a key argument for convincing other physicists that his theory was correct.



And from the *Times* of London on November 7: "Revolution in Science, New Theory of the Universe, Newtonian Ideas Overthrown."

Einstein became a legend, his name forevermore synonymous with genius.

As it turned out, some bending of light would have been expected even with Newtonian gravity, as Johann von Soldner had calculated (unknown to Einstein) more than a century earlier. But Einstein predicted precisely twice as much bending as von Soldner had. And although the earliest measurements were crude, they were much closer to Einstein's predictions than Newton's. In subsequent eclipses, Einstein's calculation has been repeatedly confirmed. Gravity deflects light just as general relativity requires.

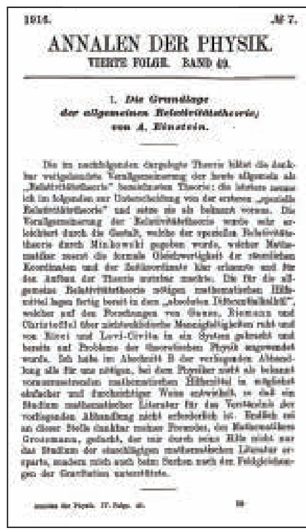
General relativity's light-bending effect proved valuable for much more than affirming Einstein's theory. By bending light, masses act like a lens; such "gravitational lensing" alters the apparent position of a distant object, creating multiple images of it, or (if the images overlap) appearing to brighten it. Such effects can be used to probe matter's distribution in space or detect the presence of unseen masses.

"Since the discovery of the first gravitational lens, the phenomenon has been exploited to map the distribution of mass around galaxies and clusters, and to search for dark matter, dark energy, compact objects, and extrasolar planets," physicist Clifford Will notes in a recent paper (online at arxiv.org/abs/1409.7812).

Gravitational lensing was first observed in 1979, but Einstein had suspected its possibility in 1912, even before his theory had been completed. Only in 1936 did he publish a paper about it, Will notes, "primarily, it seems, to get a Czech electrical engineer named Rudi Mandl to stop pestering him about it." Will, of the University of Florida in Gainesville, does not mention that Mandl had first approached *Science News Letter* (*Science News*' predecessor) with the gravitational lens idea; the magazine paid his expenses to visit Einstein, who then agreed to do the calculation that Mandl had suggested (*SNL: 12/19/36, p. 388*). Einstein's paper, published in *Science*, suggested that the effect would never be noticed. But modern astronomical explorations proved the contrary.

Einstein was also ambivalent about other consequences of general relativity. In 1916, for instance, he raised the possibility of gravitational radiation — waves rippling through spacetime after a massive body abruptly changes its motion, as when colliding with another mass. Such waves should exist, Einstein reasoned, because general relativity required gravity's influence to propagate at the speed of light (whereas Newton's gravity transmitted itself instantaneously). But later Einstein changed his mind. In 1936, he and Nathan Rosen submitted a paper arguing that such waves did not exist after all. But their paper contained a mistake. Today, gravitational waves' reality has been established convincingly by indirect methods, and experiments to detect them directly are under way (see Page 24).

Timeline: Einstein and relativity



1916. № 7.

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 49.

1. *Die Grundlage der allgemeinen Relativitätstheorie; von A. Einstein.*

1879
Albert Einstein born

1902
Einstein begins working at the Swiss patent office

1905
Einstein introduces the special theory of relativity, implying the equivalence of mass and energy

1907
Einstein introduces the equivalence principle: Gravity is equivalent to acceleration

1908
Hermann Minkowski shows that special relativity implies a combination of space and time as four-dimensional spacetime

1913
Einstein and Marcel Grossmann publish the *Entwurf* theory, an early version of general relativity

1915
Einstein submits four papers establishing the general theory of relativity

1916
Karl Schwarzschild uses general relativity to calculate how space warps around a massive body

1916
Einstein's "The Foundation of the General Theory of Relativity" is published

1917
Einstein applies general relativity to the universe as a whole, introducing the "cosmological constant" to maintain a static universe

1919
Eclipse expeditions confirm general relativity's prediction for the bending of light in a gravitational field

1929
Edwin Hubble reports that the universe is expanding

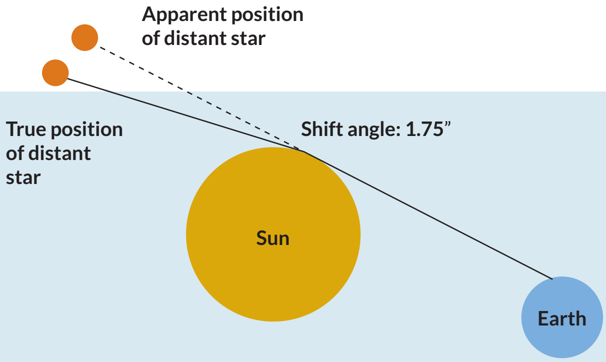
1932
Einstein retracts the cosmological constant, acknowledging the expanding universe

1955
Einstein dies in Princeton, N.J.

Read more about Rudi Mandl at **bit.ly/SN_Mandl**

Bending light

One of the first predictions of general relativity to be tested involved the bending of light. Because a massive body, such as a star, warps spacetime around it, a light beam passing nearby should be deflected from a straight-line path. From Earth, light from a distant star passing near the sun would be bent in such a way as to alter the apparent position of the distant star. In 1919, astronomers photographed stars near the sun during a solar eclipse. Comparing the positions of the stars in those photos with nighttime photos taken earlier showed that the stars' positions did appear to shift by about the amount Einstein predicted. Actually, calculations based on Newton's gravity also predicted light bending, but only by half as much as Einstein calculated. General relativity requires twice as much bending because the light ray is bent while passing through space already curved to begin with.



Astronomers have already detected another offspring of general relativity, black holes, throughout the cosmos. But Einstein didn't believe they would exist, either.

Black holes' existence had been foreshadowed only weeks after Einstein presented his general relativity papers to the Prussian Academy. Karl Schwarzschild, a German astronomer serving in World War I on the Russian front, worked out solutions to Einstein's complicated equations for the spacetime geometry around a massive sphere. It was the first mathematical step toward describing black holes in space. But Schwarzschild didn't pursue the topic; he died a few months later from a skin disease. Not until the late 1960s did black holes emerge as general relativity's most prominent advertisement, stimulating both science and the popular imagination. They became the most glamorous product of a theory conceived by science's best imaginer.

Falling freely

Einstein's imagination gave birth to general relativity's core idea as he gazed out his office window while he was supposed to be evaluating patents. "All of a sudden I was struck by a thought," Einstein later said. "If a person falls freely, he will certainly not feel his own weight."

It was 1907, two years after his special theory of relativity had rewritten textbook notions about time and motion. Special relativity showed that the laws of nature don't depend on how you are moving, as long as it's uniform motion — constant speed in a straight line. But in real life, objects and people move in all sorts of nonuniform ways. (Let the air out of a balloon, for instance.) Even some "simple" motions, like the rotation of a sphere or orbit of a planet, are nonuniform, as they constantly change direction and are therefore accelerating. Einstein wanted to extend relativity to all forms of accelerated motions. But he didn't know how.

Then his happy thought in the patent office raised hope. A person falling freely accelerates toward the ground because of gravity but feels no force (until impact). Therefore, Einstein realized, gravity and acceleration are two sides of a coin. The upward thrust of an accelerating rocket ship pins the occupants to the floor just as the gravitational pull of the Earth keeps your feet on the ground. This acceleration-gravity equivalence explained a curious Newtonian coincidence: A body's mass (its inertial resistance to changes in motion) is equal to its weight (or gravitational mass), its response to gravity. Einstein built special relativity on the principle that light's velocity was constant; he suspected that general relativity could be built on the principle that inertial and gravitational mass are equivalent. If he succeeded, it would mean that nature's laws could be the same for all forms of motion.

At first progress was slow. Then a key clue emerged in 1908, when the mathematician Hermann Minkowski showed how special relativity required the merger of space with time (*SN: 9/13/08, p. 26*). In special relativity, measures of space or time differ for different observers. But Minkowski showed that space and time combined — spacetime — yielded a mathematical description of events that all observers could agree on. Any event's location could be specified by a set of space and time coordinates.

Establishing such coordinates requires a frame of reference, or origin point. Different observers will choose different origins. So if nature's laws are the same for everybody, then any one person's set of coordinates should in some sense be equivalent to anybody else's. Einstein's quest, then, became an effort to find the formula for transforming any one coordinate system into any other, while maintaining the equivalence between gravity and acceleration.

By 1912, Einstein realized that his goal would require abandoning Euclidean geometry. Real space, he realized, could not conform to the idealized lines and angles of the textbooks. Gravity distorted the coordinates, just as a grid of straight lines on a rubber sheet would curve if you placed a heavy cannonball on it.

But Einstein did not possess the mathematical skills to cope with non-Euclidean geometry. Fortunately, his college friend Marcel Grossmann, an accomplished mathematician, was eager to help. Familiar with 19th century–mathematician Bernhard Riemann's work on the math for describing curved surfaces, Grossmann helped Einstein produce the outline

E. OTWELL

(*Entwurf* in German) of a new gravity theory. It had one drawback, though — it worked for some coordinate systems, but not all possible systems. Einstein was dismayed, writing to the physicist Hendrik Lorentz in August 1913 that "there are still such major snags in the thing that my confidence in the admissibility of the theory is still shaky." If acceleration is equivalent to a gravitational field, Einstein noted, every kind of acceleration should be describable by the equations for gravity. If not, "the theory refutes its own starting point; then it has no foundation whatsoever."

Two days later, Einstein seemed much happier, writing to Lorentz that the *Entwurf* theory's deficiency had been solved. In November, Einstein described that solution in a letter to physicist Paul Ehrenfest, asserting that equations describing all accelerations simply couldn't exist; some coordinate systems get special status in order to preserve the law of energy-momentum conservation. That made his original goal impossible. But Einstein seemed satisfied that he had done the best that nature would permit.

"Can there be anything more beautiful than this, that the necessary specialization follows from the conservation laws?" Einstein asked Ehrenfest. It turned out that there actually was something more beautiful. But to find it, Einstein had to move to Berlin.

Breakthrough in Berlin

Einstein's life until then had been peripatetic. Born in Ulm, Germany, in 1879, he moved when an infant to Munich and then as a teenager to Milan, Italy, having dropped out of high school. He went back to school in Switzerland, eventually graduating from college in Zurich. Failing to find an academic job, he joined the Swiss patent office in 1902, and the next year married Mileva Marić.

During his years at the patent office, Einstein produced an explosive output of papers poking holes in traditional physics, including reports on his special theory of relativity and Nobel Prize–winning work on quantum physics. Eventually those papers led to sufficient recognition in the physics world to get a faculty appointment in Prague. But at the first chance he returned to Zurich, where Grossmann now taught math. There Einstein and Grossmann developed the *Entwurf* theory. And then Berlin, the pinnacle of German (and world) physics, called. Prominent physicists at the university there made Einstein an offer he couldn't refuse: no teaching responsibilities. As he wrote to Lorentz: "I could not resist the temptation to accept a position in which I am relieved of all responsibilities so that I can give myself over completely to rumination."

Throughout all these moves, Einstein's personal life deteriorated. Growing apart from Mileva, he pursued a relationship with his cousin Elsa. And Mileva did not relish the idea of life in Berlin. In July 1914 she took their two sons back to Zurich, and Einstein was left in Berlin free to ruminate about general relativity to his heart's content. During the

The Einstein field equations

Because mass and energy distort the shape of spacetime, the Euclidean geometry of standard textbooks can't accurately describe it. Einstein's general relativity uses more complicated math built on the non-Euclidean geometry devised in the 19th century by Bernhard Riemann. With help from his friend Marcel Grossmann, Einstein adopted further advances by the mathematicians Gregorio Ricci-Curbastro, Tullio Levi-Civita and Elwin Christoffel to describe spacetime geometry in terms of mathematical expressions called tensors. Tensors are a lot like vectors — quantities, such as velocity, composed of two components (in velocity's case, speed and direction). Tensors are similar but can encompass more than just two components. Einstein used tensors to develop his equation describing the gravitational field, known as the Einstein field equation.

THE EINSTEIN FIELD EQUATION

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

On the left side of the equation is a tensor describing the geometry of spacetime — the gravitational field. On the right is the tensor describing the matter and energy density — the source of the gravitational field. The equation shows that spacetime geometry equals mass-energy density when adjusted with the proper units and numerical constants. (Actually, the equation stands for a set of multiple equations owing to the complexity of tensors. So experts usually speak of the Einstein field equations, plural.)

THE EINSTEIN FIELD EQUATION WITH LAMBDA

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}$$

When he applied this equation to the entire universe, Einstein found that the universe would be unstable, easily disturbed into a state in which spacetime would be either expanding or collapsing. So he added a term that came to be called the cosmological constant, symbolized by the Greek letter lambda. It represents a constant amount of energy density throughout space that would supposedly keep the universe stable and changeless.

Later, evidence that the universe was indeed expanding led Einstein to renounce lambda. But it has been revived by modern cosmologists to explain the apparent increase in the universe's rate of expansion that was discovered in the late 1990s.

following year his freedom nourished a fertile few months in which he saw a new path to success. In mid-1915 he saw that there was a way to make relativity truly general. Rather than imposing energy-momentum conservation on the equations, he worked on devising equations that would impose the conservation law on the universe.

Einstein now applied the full force of all the mathematical wizardry he had mastered in the preceding years, adopting embellishments of Riemann's math called tensors. By November 1915, Einstein sensed victory. On November 4, he submitted a paper on general relativity to the Prussian Academy, following up with an addendum November 11. The next week, he presented yet another new paper, this time in a lecture to the academy, showing how general relativity's spacetime curvature solved the outstanding gravitational problem in all of physics, the anomaly in the orbit of Mercury. During the following week, he finally found the correct form for the equations describing the gravitational field, presenting his result on November 25. Einstein's quest was completed. General relativity worked.

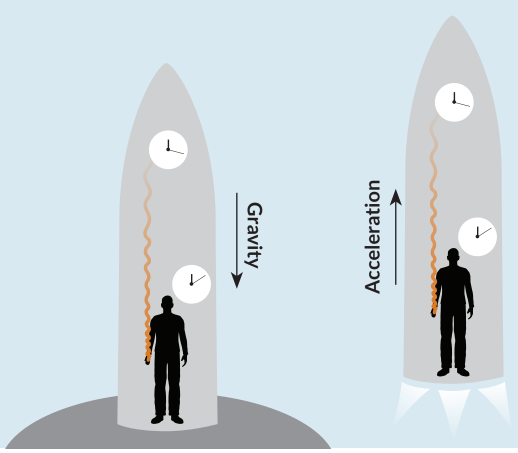
Universal implications

Einstein quickly realized (or had known all along) that his new theory of gravity was really a theory of the cosmos. In 1917, he wrote a famous paper applying general relativity to the universe as a whole. Today that paper stands as the foundation for modern cosmology. But at the time, Einstein was troubled — his equations implied an unstable universe, either growing or collapsing. In those days, the universe was supposed to be eternal, everlasting and changeless. So Einstein altered his equation, adding a factor called the cosmological constant, representing a constant energy density in space that kept the universe static.

Others didn't buy it. Alexander Friedmann, a Russian meteorologist-mathematician, developed a description of an expanding or contracting universe from Einstein's original equations. Einstein first thought Friedmann to be in error, but then relented, although still viewing the "expanding universe" as of mathematical interest only. But a few years later, when Edwin Hubble's analysis of light from distant galaxies confirmed the universe's expansion, Einstein gave

Gravity's pull on time

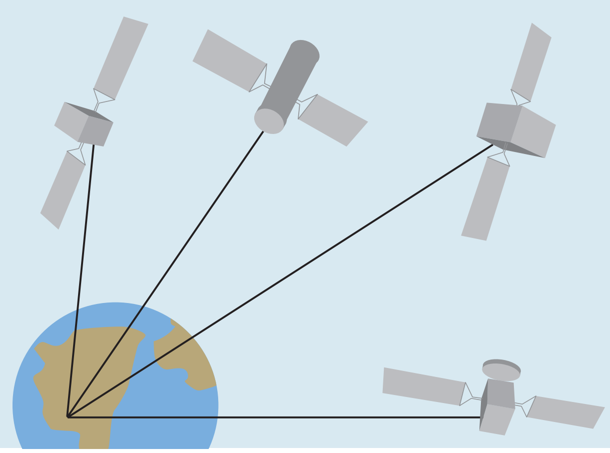
Imagine a rocket ship in free space, accelerating upward (from the perspective of an astronaut on the ship's floor). The astronaut shoots laser pulses from the floor to a sensor on the ceiling at a rate of one per second. Because the ship is accelerating, the sensor is moving away from the laser beam during its trip to the ceiling, so the pulses arrive at intervals longer than one second. But the speed of the laser light remains constant. Therefore a clock on the ceiling must tick more rapidly than the clock on the floor to measure the speed of light accurately. Because, as general relativity requires, acceleration is equivalent to a gravitational field, the same effect should occur for laser pulses fired from the bottom to the top of a ship parked on Earth. Similarly, a clock at sea level would tick more slowly than a clock atop a mountain. This slowdown of clocks in a gravitational field is known as gravitational time dilation.



General relativity and GPS

The Global Positioning System, used to pinpoint locations on the Earth's surface, depends on signals sent from satellites orbiting about 20,000 kilometers high. A GPS receiver records the precise time that signals arrive from multiple satellites; those arrival times can be used to calculate how far away the satellites are. The receiver can then compute its own position based on the distances to the satellites and their locations.

This approach requires clocks on the ground to be synchronized with clocks on the satellites. But because of gravitational time dilation, clocks on the ground run slower than those on the satellites. After just a day, your GPS would misplace your location by about 10 kilometers (six or seven miles) if the calculations weren't corrected for relativity's effects. (Actually, a correction is also needed for special relativity, since the satellites' rapid motion slows their clocks. But the effect from general relativity is much greater.)



E. OTWELL

in. Despite his own reluctance to accept it, Einstein's general relativity math did in fact imply what Wheeler later called the "most dramatic prediction that science has ever made" — the expansion of the universe.

Today, Einstein's cosmological constant has been revived. Rather than preventing the universe from collapse, the vacuum energy it describes can explain why the universe now expands at an accelerating pace. General relativity, cosmological constant and all, today forms the core science for analyzing the history of the universe and forecasting its future.

But apart from its use in cosmology, general relativity was not widely applied to scientific problems in its first four decades. For the most part, general relativity languished in departments of mathematics, rarely studied in physics.

"General relativity was essentially a dead subject for a long time," says the prominent relativity theorist Wolfgang Rindler of the University of Texas at Dallas. "People considered it a dormant science."

Only after Einstein died in 1955 did general relativity come to life. About that time Wheeler, at Princeton University, began a program to explore its implications and train students to pursue them. By the early 1960s, new astronomical phenomena demanded explanations that Newtonian physics could not provide, and general relativity was poised for its renaissance. In the decades that followed, general relativity proved crucial for describing all sorts of celestial phenomena. At the same time, physicists devised ever more precise tests of its predictions, and Einstein passed them all. As Will has noted, "It is remarkable that this theory, born 100 years ago out of almost pure thought, has managed to survive every test."

Even harder than finding the equations for general relativity is explaining how, out of almost pure thought, Einstein did it. Science historian Gerald Holton once remarked, while describing Einstein in the context of defining scientific genius, that "there is a mutual mapping of the mind and lifestyle of this scientist, and of the laws of nature." Einstein himself ascribed his success to discovering the deep relationship between mathematics and the physical world.

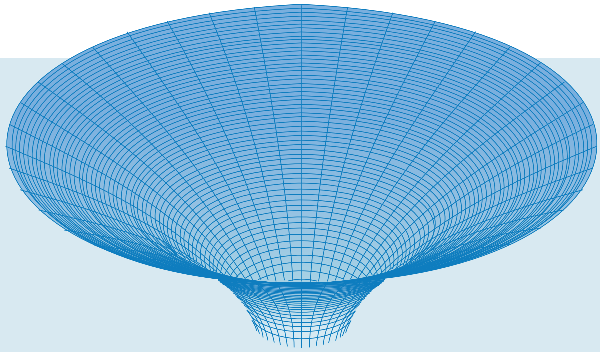
In creating general relativity, Einstein's path was forked; he had to envision physical processes governing matter, space and time, while at the same time formulating abstract mathematical expressions corresponding to that reality. As a student, Einstein testified, he neglected mathematics. His intuition was not strong enough to guide him to the most profound of math's many subfields. But in the physical realm of natural phenomena, "I soon learned to scent out that which was able to lead to fundamentals and to turn aside from ... the multitude of things which clutter up the mind and divert it from the essential." At first he didn't realize that "a more profound knowledge of the basic principles of physics is tied up with the most intricate mathematical methods." He learned that from his pursuit of general relativity.

In the end, Einstein's mind produced a mathematical theory so rich that it entailed unsuspected cosmic novelties. Fantastic physical phenomena were first discovered not through the lenses of telescopes, but within the squiggles Einstein had scratched out on paper to make the world make sense — to him. And now physical nature makes sense to modern science only because of Einstein's insights.

"Einstein's ideas," his friend the physicist Max Born wrote over half a century ago, "have given the physical sciences the impetus which has liberated them from outdated philosophical doctrine, and made them one of the decisive factors in the modern world of man." ■

Explore more

- C.M. Will. "Was Einstein Right? A Centenary Assessment." Sept. 28, 2014. arxiv.org/pdf/1409.7871v1.pdf

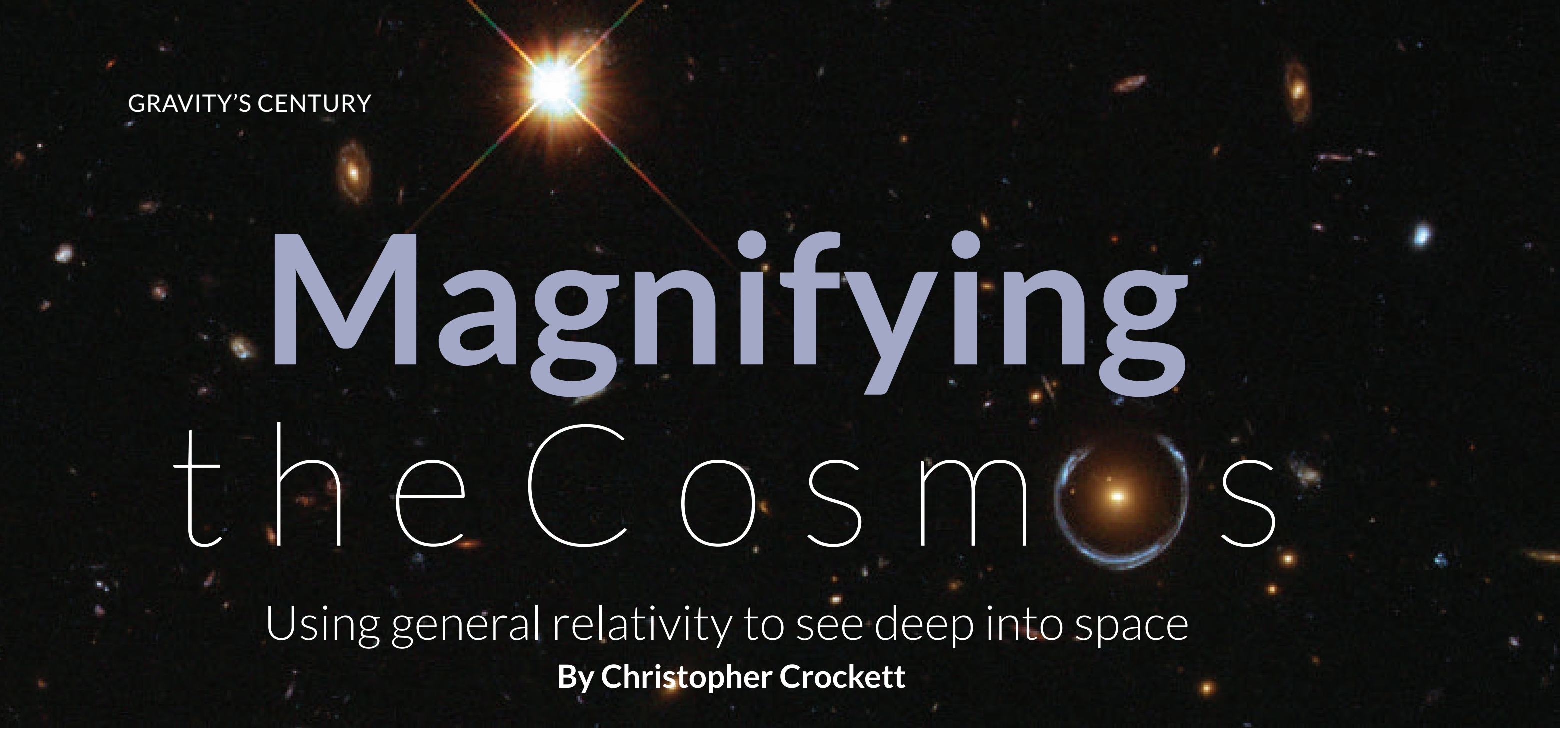


Gravitational collapse

Shortly after Einstein introduced general relativity, Karl Schwarzschild calculated its implications for the gravity of a massive sphere. Schwarzschild determined that for any given mass there existed a "critical radius" — a limit, he believed, to how small that amount of mass could be compressed. In 1939, Einstein concluded that mass could not be compressed to within that "Schwarzschild radius." But in the same year, J. Robert Oppenheimer and Hartland Snyder calculated otherwise, claiming that a sufficiently massive object could indeed collapse within that radius, disappearing from view and leaving only its gravitational field behind.

At the time, nobody paid any attention. But in the 1960s, newfound astrophysical anomalies suggested that gravitational collapse was at work in the cosmos, and Oppenheimer and Snyder's idea was revived as what came to be known as black holes. Famous for swallowing anything they encounter and allowing nothing to escape, black holes are probably the most bizarre astrophysical consequences of general relativity. Small black holes have been detected throughout space and supermassive black holes reside in the cores of most galaxies.

More recently black holes (schematic of one above) have been used as thought-experiment laboratories for investigating several outstanding mysteries about the nature of space and time (see Page 28).



Magnifying the Cosmos

Using general relativity to see deep into space

By Christopher Crockett

One of the most powerful known magnifying lenses isn't found on Earth. The lens is built from stars, gas and dark matter and lies about 4 billion light-years away. As astronomers peer through it, they are finding the seeds of galaxies that were scattered around the universe more than 13 billion years ago.

The lens is known as Abell 2744, a cosmic pileup where four groups of galaxies are colliding to create one gargantuan gathering with the mass of about 2 quadrillion suns *(SN: 6/13/15, p. 32)*. The gravity from all that mass redirects any light that tries to sneak past, bending and focusing it, creating bigger and brighter images of galaxies far beyond the cluster.

Abell 2744 is useful as an astronomical tool because the universe obeys Albert Einstein's general theory of relativity. That theory describes how gravity, mass, space and time work together to build a universe. It forms the bedrock of science's understanding of the cosmos. And for astronomers today, two primary consequences of general relativity — mass's power to focus light plus the ripples in spacetime generated when masses accelerate — provide robust tools for investigating the cosmos. Giant lenses in space are at the forefront of efforts to explore the origins of galaxies. Elusive gravitational waves, meanwhile, can reveal unseen collisions between stellar corpses, such as black holes and neutron stars.

Gravitational lenses and waves are not new ideas. Einstein knew that his theory implied that both exist. In 1937, Caltech astrophysicist Fritz Zwicky proposed that lenses should be found around some massive galaxies. Decades passed before astronomical technology verified that idea: It wasn't until 1979 that astronomers detected a real-life example of a gravitational lens in the double image of a quasar — side-by-side glimpses of a galaxy's blazing heart, resembling a pair of oncoming headlights.

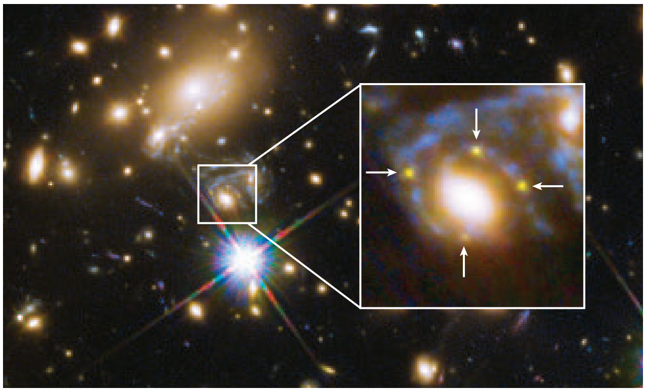
Einstein calculated how the gravity of one star could amplify the light of another more distant star, but he also reasoned that the odds of seeing it are abysmally low. In recent years, the Optical Gravitational Lensing Experiment, one of several efforts to detect celestial bodies wandering in front of stars in the galaxy, has recorded about 2,000 possible events annually.

"It's amusing how today lensing is so respected," says Richard Ellis, an astrophysicist at the European Southern Observatory in Garching, Germany. "I'm old enough to remember when it was regarded as a bit wacky."

Over the last couple of decades, lensing has been used to study all manner of things. Some nearby lenses forged from single stars have revealed planets in our own galaxy, including a few orphans that drift through the Milky Way without a sun to call home (*SN: 4/4/15, p. 22*). Other lenses, like Abell 2744, let astronomers peer across the cosmos to see galaxies growing up in the early universe.

Seeds of modern galaxies

Telescopes look back in time; light from the most distant locales travels for nearly the entire 13.8-billion-year history of the



Top: The light from a distant galaxy (second "o" in "Cosmos") is warped by the gravity of a closer, massive galaxy (bright blur in center). Right: One supernova appears four times (arrows) as its light follows multiple paths around an intervening galaxy.

FROM TOP: NASA, ESA; INSET: NASA, ESA, S. RODNEY/JHU, THE FRONTIERSN TEAM; T. TREU/UCLA, P. KELLY/UC BERKELEY, THE GLASS TEAM; J. LOTZ/STSCI, THE FRONTIER FIELDS TEAM; M. POSTMAN/STSCI, THE CLASH TEAM; Z. LEVAY/STSCI universe. As astronomers poke around for galaxies so far away (and so far back in time), they hope to find the seeds of what eventually became modern galaxies. Only abnormally bright galaxies, however, can typically be spotted across such distances.

"Everything seen so far at the edge of the universe is the brightest, biggest, craziest at that time," says Jennifer Lotz, an astrophysicist at the Space Telescope Science Institute in Baltimore. Our galaxy, though, "is not big and crazy; it's more typical." To find those more classic, less showy protogalaxies requires a really big magnifying glass.

Lotz is leading a three-year effort, known as the Frontier Fields project, to stare at six massive clusters with the Hubble Space Telescope and hunt for the seeds of galaxies similar to our own. Four clusters have been analyzed; the remaining two are now coming under scrutiny.

While peering through one of the clusters, Abell 2744, astronomers recently found a candidate for one of the most distant galaxies known, a toddler growing up about 500 million years after the Big Bang. The galaxy appears as a faint red smudge — or rather, three smudges — as its light traverses multiple paths through the cluster. This remote galaxy is tiny and dense, squeezing the mass of about 40 million suns into a ball just several hundred light-years across. It's a pale dot compared with the Milky Way. Images such as these add to astronomers' scrapbook of how galaxies grew over the history of the universe.

The building blocks of galaxies aren't the only things lurking behind these lenses. In March, researchers announced that they saw the same supernova explode not once but four times (*SN Online: 3/5/15*).

"I just did not expect to see that at all," Lotz says. "We got so lucky. The timing was perfect."

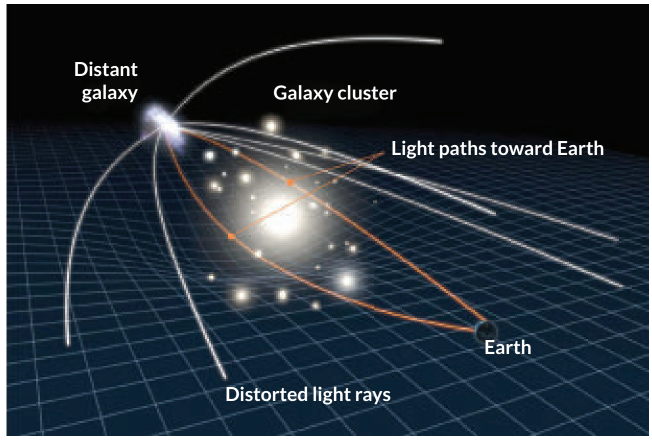
The light from the exploding star, which took 9.4 billion years to reach Earth, fell squarely on one galaxy sitting in one of the Frontier Fields clusters. That galaxy's gravity steered the light along four different paths, creating a quadruple replay, with each additional flash appearing days to weeks after its predecessor.

"The story's not done," she says. "We expect yet another one to show up in the next year or two." By studying how the lens warps the light from background galaxies, researchers have calculated that there's a fifth road for the light to travel along. Astronomers now have a rare opportunity to know about a supernova before it appears. "It's an amazing example of gravitational lensing," Lotz says.

Expansion ramped up

Strong gravitational lenses built by massive clusters are powerful tools. But they're not that common. The light from most galaxies doesn't pass near a cluster such as Abell 2744 on its way to Earth. But there are plenty of smaller clusters and long rivers of galaxies, known as galaxy filaments, that fiddle with the light and create weak lenses. "Every distant object has its image distorted by a small amount," says Joshua Frieman, an astrophysicist at the Fermi National Accelerator Laboratory in Batavia, Ill.

NASA, ESA AND L. CALÇADA



Cosmic looking glass The gravity of a galaxy cluster warps space-time (grid) and creates a lens that redirects light from a more distant galaxy (upper left). Some of the light rays bend toward Earth (orange). Multiple images of the galaxy might appear as the light traverses several paths through the cluster.

That subtle distortion could be a key to unraveling one of the thorniest mysteries in modern astronomy: what's causing the expansion of the universe to speed up.

Supernovas in other galaxies appear farther away than would be expected from a gradually expanding universe. Around 7 billion years ago, something stepped on the cosmic accelerator and picked up the pace of the expansion.

Researchers call this repulsive force "dark energy" (*SN: 5/5/12, p. 17*). They don't know exactly what it is, but one idea is that it is some intrinsic property of space that has always been there, lurking in the background. At some point, as the universe stretched out, the density of matter and energy dropped enough for dark energy to become dominant.

The idea started with Einstein when he realized that his theory described an unstable universe, one in which gravity could pull all its stars inward in a massive collapse. That clearly hadn't happened, so he fudged his equations and added in a "cosmological constant" to set things right.

"In order to arrive at this consistent view," Einstein wrote in 1917, "we admittedly had to introduce an extension of the field equations of gravitation which is not justified by our actual knowledge of gravitation."

He dropped the idea after Edwin Hubble reported in 1929 that galaxies appeared to recede from each other at ever greater speeds the farther away they were — a discovery that implied the universe was expanding. But Einstein's creative accounting has come back into vogue. Today his cosmological constant might be the parameter that describes how dark energy inflates the universe.

Astronomers need to know a few more things about dark energy, though. For example, is dark energy truly constant, Ellis asks, or has it changed over time? "Until we measure it as a function of time," he says, "we don't know."

Dark energy competes with dark matter — an elusive substance that holds together galaxies and their clusters — to erect the scaffolding for the universe, the places where atoms can get together and form stars and planets. Dark matter pulls things together and dark energy tries to pry it all apart. "It's an epic struggle," Frieman says.

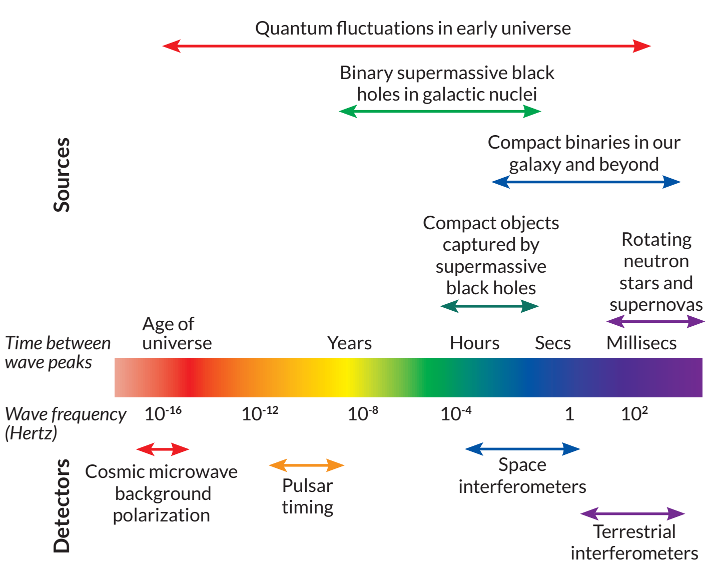
Frieman leads a project called the Dark Energy Survey, one part of which is spending five years tracking how this tug-of-war has changed over time. The survey is looking for weak gravitational lenses created by that scaffolding. Hidden caches of dark matter slightly skew images of thousands of galaxies that share the same patch of sky. By measuring the very subtle distortions of about 200 million galaxies, researchers are mapping dark matter clumps back to a time when the universe was about half its current size (*SN: 5/16/15, p. 9*). Knowing how the cosmic clumpiness changed since then will help researchers get a sense of how, or if, dark energy changed as well.

The Dark Energy team is in its third year and is beginning to analyze the data from its first season. Frieman expects that the combined data from the first two years should start to rule out some ideas about what dark energy is.

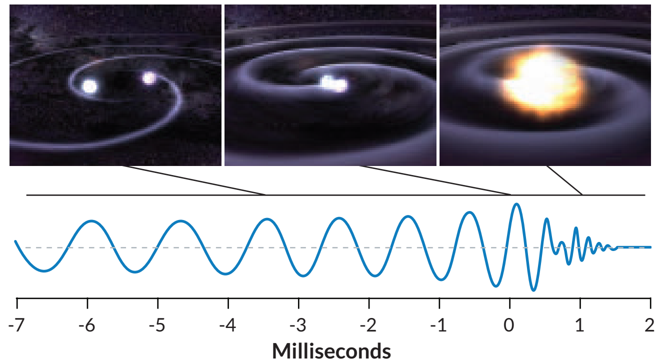
Ripples in space

Even with gravitational lenses, some things are just too far or too faint to be seen. Einstein's universe, fortunately, has a work-around: gravitational waves. Gravity is caused when mass puckers the fabric of spacetime. Like a ball bouncing off a rubber sheet, any accelerating mass should send out gravitational waves, ripples that cause space itself to stretch and squeeze.

Gravitational wave spectrum



Tuning into gravity Like the tuner on a radio, different detectors (bottom row) pick up different frequencies of gravitational waves. The frequency depends on what created the ripples (sources, top row). Waves from binary supermassive black holes oscillate slowly compared with supernovas, which generate high-frequency waves. Pulsar timing detectors are best for sensing waves in which years pass between peaks; ground-based interferometers perk up when hit by waves oscillating hundreds of times per second. SOURCE: NASA



When stars collide As two neutron stars spiral toward each other, as in this illustration, they radiate gravitational waves (blue line) that are detected only during the final fraction of a second before the two merge.

FROM TOP: T. STROHMAYER/GSFC/NASA, CXC/NASA; K. KIUCHI *ET AL*/*PHYSICAL REVIEW LETTERS* 2010. ADAPTED BY A. STONEBRAKER; M. TELFER

Creating detectable flutters requires cataclysmic events. Colliding black holes, merging neutron stars and even the Big Bang itself (*SN: 2/21/15, p. 13*) should send out ripples in space that echo across the cosmos. If there were a way to sense these spacetime swells, astronomers could investigate entities whipping around the universe that might otherwise remain unseen.

Searches for such signals have been under way at the Laser Interferometer Gravitational-Wave Observatory, or LIGO, twin facilities in Louisiana and Washington state. Should a wave wash over the Earth, the precise distance between pairs of mirrors suspended at the ends of perpendicular 4-kilometer-long tubes will oscillate as the space between the mirrors expands and contracts. Lasers that ricochet within these tubes can sense changes in distance far less than a thousandth of the width of a proton.

Astronomers have already detected gravitational waves indirectly. In 1974, Joseph Taylor (*SN: 7/11/15, p. 4*) and Russell Hulse, then at the University of Massachusetts Amherst, discovered the first binary pulsar, a rapidly spinning neutron star orbiting a companion. Over the next several years, the pulsar drifted toward its unseen partner at the rate of 3.5 meters per year — an orbital tightening predicted by general relativity if the duo is radiating gravitational waves. The discovery netted Taylor and Hulse the 1993 Nobel Prize in physics.

The ripples from the Hulse-Taylor binary are too subtle to be seen directly. But as the two stars snuggle up, the waves will get stronger. In the final milliseconds before the stars collide, spacetime will ring loud enough for LIGO to hear. That collision won't happen for another 300 million years, though.

"We don't want to wait that long," says Martin Hendry, an astrophysicist at the University of Glasgow in Scotland. "What we're banking on is that there are many such systems in our galaxy and beyond, and that's what we're waiting to detect."

LIGO's first eight-year search wrapped up in 2010 with nothing to show. In September, LIGO began another go at hunting its elusive quarry. The second attempt, dubbed Advanced LIGO, uses better instruments, and mission scientists are confident that they will see something in the next few years.

"The real astrophysics begins just after that," Hendry says. Once researchers have a handful of detections, then LIGO and other similar facilities become just another astronomical tool, but one that is sensitive to changes in gravity rather than light. And unlike telescopes, which typically look at only one place at a time, gravitational wave detectors can listen to the entire sky.

Cosmic metronomes

LIGO should be able to pick up the relatively high frequencies of any neutron stars or black holes spiraling together within about 600 million light-years of Earth. Collisions between supermassive black holes (*SN Online: 8/31/15*) can be heard from much farther away, but they send out long, undulating waves to which LIGO is deaf. To sense these enormous waves — the peak-to-peak distances are measured in light-years — researchers are turning to pulsars.

Race toward a pulsar, and the tempo of radio bursts will appear to pick up as you run more quickly into successive pulses. Pull away from a pulsar, and the beat appears to slow. As Earth bobs on the spacetime ocean, it pulls away from some pulsars and moves toward others. By monitoring the pulses from dozens of these cosmic metronomes, researchers will know when Earth is riding the wave from a supermassive black hole collision.

"It's like you're detecting waves on the ocean by being able to measure the movement of a boat," says Ryan Lynch, an astronomer at McGill University in Montreal.

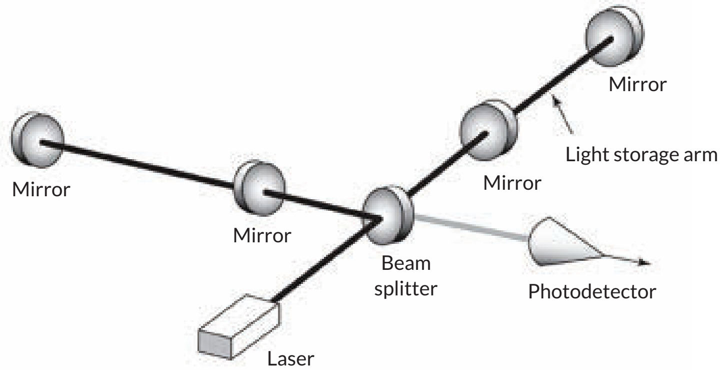
> "It's like you're detecting waves on the ocean by being able to measure the movement of a boat."
> RYAN LYNCH

The change in distance between Earth and one of these pulsars is staggeringly small: about one part in a quadrillion. That's like trying to measure a one-kilometer change across roughly 100 light-years.

Three projects known as pulsar timing arrays, in North America, Europe and Australia, are using some of the largest radio telescopes to identify pulsars and look for these waves. The first thing they'll probably pick up, Lynch says, is not a single event, but the background hum of many supermassive black holes colliding across the universe. Only the closest and biggest will rise above the noise.

Should LIGO or the pulsar timing arrays not detect anything, that wouldn't necessarily mean there's something wrong with general relativity, Hendry says. It could just mean the assumptions about these collisions are incorrect (*SN Online: 9/24/15*). That's one reason some researchers are trying to persuade the European Space Agency to launch a space-based version of LIGO known as eLISA (for evolved Laser Interferometer Space Antenna) in 2028. In the stillness of space, far removed from the shaky ground, eLISA should hear what LIGO cannot: the buzz from a wide variety of tightly coupled binary stars that litter the Milky Way.

"We'll see hundreds or thousands of them, and they're virtually guaranteed," says Guido Mueller, a physicist at the University of Florida in Gainesville.



Wave catcher Researchers hope to detect gravitational waves from colliding black holes and neutron stars using an interferometer. Laser light is bounced off mirrors down two perpendicular tubes before recombining, where it is measured by a light-sensitive detector. A passing gravitational wave will change the lengths of the tubes, which will make the brightness of the recombined light change because light waves in the combining beams will interfere with one another.

These snuggling stars, which are already well studied, will test both eLISA's capabilities and predictions from general relativity. eLISA will also listen for binary supermassive black holes in other galaxies, a population that astronomers know very little about. And for eLISA, the sky is quite literally the limit.

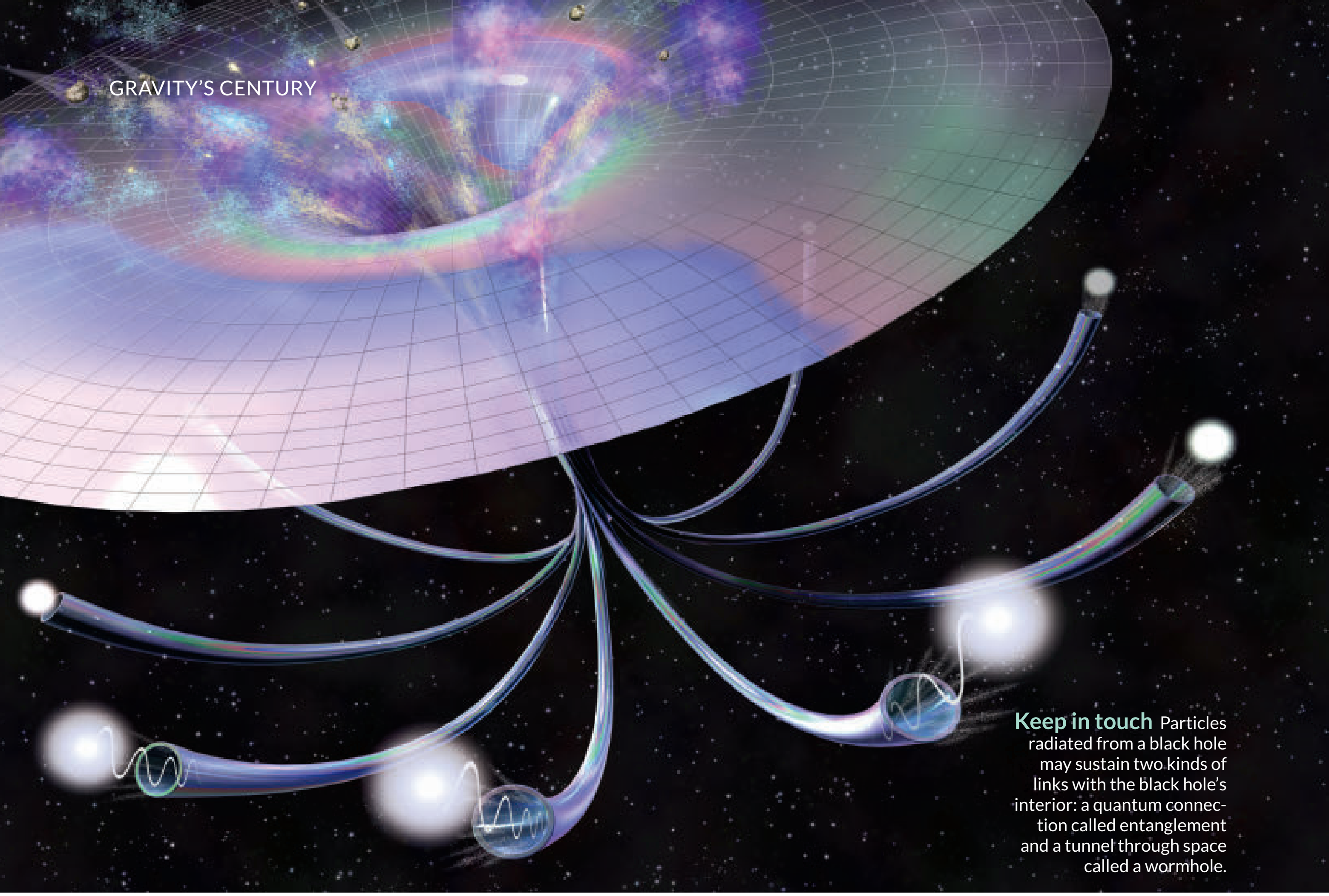
"eLISA should basically see [the black holes] out as far as they exist," Hendry says. The orbiting watchtower will sense collisions clear to the edge of the visible universe, back to the dawn of time. "There will eventually come a point where there aren't any more black holes because they haven't had time to form yet," Hendry says. And putting together a census of binary supermassive black holes from the early universe, he adds, might help researchers understand what role (if any) these dark duos had in shaping galaxies during the billion or so years following the Big Bang.

General relativity came on the scene before anyone knew that the universe is expanding, a time when astronomers could not be certain that those fuzzy splotches of light in the sky were actually other galaxies. Now astronomers are ready to start poking at some fundamental truths about the universe, from the formation of the first stars and galaxies to what makes the cosmos tick. One hundred years after its publication, Einstein's theory is poised to peel back the cosmic curtain even farther. ■

Explore more

- R. Ellis. "Gravitational lensing: a unique probe of dark matter and dark energy." *Philosophical Transactions of the Royal Society A*. March 13, 2010.
- C. Moore, R. Cole and C. Berry. "Gravitational-wave sensitivity curves." *Classical and Quantum Gravity*. January 8, 2015.

LIGO



Keep in touch Particles radiated from a black hole may sustain two kinds of links with the black hole's interior: a quantum connection called entanglement and a tunnel through space called a wormhole.

NICOLLE RAGER FULLER

Gravity's LONG-DISTANCE CONNECTION

Wormhole links between black holes could broker quantum–general relativity merger

By Andrew Grant

When Albert Einstein scoffed at a "spooky" long-distance connection between particles, he wasn't thinking about his general theory of relativity.

Einstein's century-old theory describes how gravity emerges when massive objects warp the fabric of space and time. Quantum entanglement, the spooky source of Einstein's dismay, typically concerns tiny particles that contribute insignificantly to gravity. A speck of dust depresses a mattress more than a subatomic particle distorts space.

Yet theoretical physicist Mark Van Raamsdonk suspects that entanglement and spacetime are actually linked. In 2009 he calculated that space without entanglement couldn't hold itself together. He wrote a paper asserting that quantum entanglement is the needle that stitches together the cosmic spacetime tapestry.

Multiple journals rejected his paper. But in the years since that initial skepticism, investigating the idea that entanglement shapes spacetime has become one of the hottest trends in physics. "Everything points in a really compelling way to space being emergent from deep underlying physics that has to do with entanglement," says John Preskill, a theoretical physicist at Caltech.

In 2012, another provocative paper presented a paradox about entangled particles inside and outside a black hole. Less than a year later, two experts in the field proposed a radical resolution: Those entangled particles are connected by wormholes — spacetime tunnels imagined by Einstein that nowadays appear as often in sci-fi novels as in physics journals. If that proposal is correct, then entanglement isn't the spooky long-distance link that Einstein thought it was — it's an actual bridge linking distant points in space.

Many researchers find these ideas irresistible. Within the last few years, physicists in seemingly unrelated specialties have converged on this confluence of entanglement, space and wormholes. Scientists who once focused on building error-resistant quantum computers are now pondering whether the universe itself is a vast quantum computer that safely encodes spacetime in an elaborate web of entanglement. "It's amazing how things have been progressing," says Van Raamsdonk, of the University of British Columbia in Vancouver.

Physicists have high hopes for where this entanglement-spacetime connection will lead them. General relativity brilliantly describes how spacetime works; this new research may reveal where spacetime comes from and what it looks like at the small scales governed by quantum mechanics. Entanglement could be the secret ingredient that unifies these supposedly incompatible views into a theory of quantum gravity, enabling physicists to understand conditions inside black holes and in the very first moments after the Big Bang.

Holograms and soup cans

Van Raamsdonk's 2009 insight didn't materialize out of thin air. It's rooted in the math of the holographic principle, the idea that the boundary enclosing a volume of space can contain all the information about what's inside. If the holographic principle applied to everyday life, then a nosy employee could perfectly reconstruct the inside of a coworker's office cubicle — piles of papers, family photos, dust bunnies in the corner, even files on the computer's hard drive — just by looking at the cubicle's outer walls. It's a counterintuitive idea, considering walls have two dimensions and a cubicle's interior has three. But in 1997, Juan Maldacena, a string theorist then at Harvard, perceived an intriguing example of what the holographic principle could reveal about the universe (*SN: 11/17/07, p. 315*).

He started with anti-de Sitter space, which resembles the universe's gravity-dominated spacetime but also has some quirky attributes. It is curved in such a way that a flash of light emitted at any location eventually returns to where it started. And while the universe is expanding, anti-de Sitter space neither stretches nor contracts. Because of these features, a chunk of anti-de Sitter spacetime with four dimensions (three spatial, one time) can be surrounded by a three-dimensional boundary.

Maldacena considered a cylinder of anti-de Sitter spacetime. Each horizontal slice of the cylinder represented the state of its space at a given moment, while the cylinder's vertical dimension represented time. Maldacena surrounded his cylinder with a boundary for the hologram; if the anti-de Sitter space were a can of soup and its contents, then the boundary was the label.

Just as nobody would mistake a Campbell's label for the actual soup, the boundary seemingly shared nothing in common with the cylinder's interior. The boundary "label," for instance, observed the rules of quantum mechanics, with no gravity. Yet gravity described the space inside containing the "soup." Maldacena showed, though, that the label and the soup were one and the same; the quantum interactions on the boundary perfectly described the anti-de Sitter space it enclosed. "They are two theories that seem completely different but describe exactly the same thing," Preskill says.

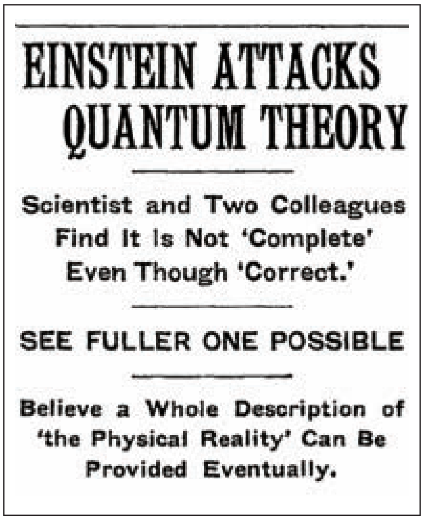
Maldacena added entanglement to the holographic equation in 2001. He considered the space within two soup cans, each containing a black hole. Then he created the equivalent of a tin can telephone by connecting the black holes with a wormhole — a tunnel through spacetime first proposed by Einstein and Nathan Rosen in 1935. Maldacena looked for a way to create the equivalent of that spacetime connection on the cans' labels. The trick, he realized, was entanglement.

Like a wormhole, quantum entanglement links entities that share no obvious relationship. The quantum world is a fuzzy place: An electron can seemingly be spinning up and down simultaneously, a state called superposition, until a measurement provides a definitive answer. But if two electrons are entangled, then measuring the spin of one enables an experimenter to know what the spin of the other will be — even though the partner electron is still in a superposition state. This quantum link remains if the electrons are separated by meters, kilometers or light-years.

Maldacena demonstrated that by entangling particles on one can's label with particles on the other, he could perfectly describe the wormhole connection between the cans in the language of quantum mechanics. In the context of the holographic principle, entanglement is equivalent to physically tying chunks of spacetime together.

Inspired by this entanglement-spacetime link, Van Raamsdonk wondered just how large

> "Everything points in a really compelling way to space being emergent from deep underlying physics that has to do with entanglement."
> JOHN PRESKILL



EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

Quantum skeptics
A *New York Times* article on May 4, 1935, highlighted Einstein's concerns about quantum mechanics, especially its feature now known as entanglement. Today physicists are exploring links between entanglement and Einstein's general theory of relativity.

NEW YORK TIMES/WIKIMEDIA COMMONS

a role entanglement might play in shaping spacetime. He considered the blandest quantum soup-can label he could think of: a blank one, which corresponded to an empty disk of anti-de Sitter space. But he knew that because of quantum mechanics, empty space is never truly empty. It is filled with pairs of particles that blink in and out of existence. And those fleeting particles are entangled.

So Van Raamsdonk drew an imaginary line bisecting his holographic label and then mathematically severed the quantum entanglement between particles on one half of the label and those on the other. He discovered that the corresponding disk of anti-de Sitter space started to split in half. It was as if the entangled particles were hooks that kept the canvas of space and time in place; without them, spacetime pulled itself apart. As Van Raamsdonk decreased the degree of entanglement, the portion connecting the diverging regions of space got thinner, like the rubbery thread that narrows as a chewed wad of gum is pulled apart. "It led me to suggest that the origin of having space at all is having this entanglement," he says.

That was a bold claim, and it took a while for Van Raamsdonk's paper, published in *General Relativity and Gravitation* in 2010, to garner serious attention. The spark came in 2012, when four physicists at the University of California, Santa Barbara wrote a paper challenging conventional wisdom about the event horizon, a black hole's point of no return.

Insight behind a firewall

In the 1970s, theoretical physicist Stephen Hawking showed that pairs of entangled particles — the same kinds Van Raamsdonk later analyzed on his quantum boundary — can get split up at the event horizon. One falls into the black hole, and the other escapes as what's known as Hawking radiation. The process gradually saps the mass of a black hole, ultimately leading to its demise. But if black holes disappear, then so would the record of everything that ever fell inside. Quantum theory maintains that information cannot be destroyed.

By the 1990s several theoretical physicists, including Stanford's Leonard Susskind, had proposed resolutions of the issue. Sure, they said, matter and energy fall into a black hole. But from the perspective of an outside observer, that stuff never quite makes it past the event horizon; it seemingly teeters on the edge. As a result, the event horizon becomes a holographic boundary containing all the information about the space inside the black hole. Eventually, as the black hole shrivels away, that information will leak out as Hawking radiation. In principle, the observer could collect the radiation and piece together information about the black hole's interior.

In their 2012 paper, Santa Barbara physicists Ahmed Almheiri, Donald Marolf, James Sully and Joseph Polchinski claimed something was wrong with that picture. For an observer to assemble the puzzle of what's inside a black hole, they noted, all the individual puzzle pieces — the particles of Hawking radiation — would have to be entangled with each other. But each Hawking particle also has to be entangled with its original partner that fell into the black hole.

Unfortunately, there is not enough entanglement to go around. Quantum theory dictates that the entanglement required to link all the particles outside the black hole precludes those particles from also linking up with particles inside the black hole. Compounding the problem, the physicists found that severing one of those entanglements would create an impenetrable wall of energy, called a firewall, at the event horizon (*SN: 5/31/14, p. 16*).

Many physicists doubted that black holes actually vaporize everything trying to enter. But the mere possibility that firewalls exist had disturbing implications. Previously, physicists had wondered what the space inside a black hole looked like. Now they weren't sure whether black holes even had an inside. "It was kind of humbling," Preskill says.

Susskind was not so much humbled as restless. He had spent years trying to show that information wasn't lost inside a black hole; now he was just as convinced that the firewall idea was wrong, but he couldn't prove it. Then one day he received a cryptic email from Maldacena: "It had very little in it," Susskind says, "except for ER = EPR." Maldacena, now at the Institute for Advanced Study in Princeton, N.J., had thought back to his 2001 paper on interconnected soup cans and wondered whether wormholes could resolve the entanglement mess raised by the firewall problem. Susskind quickly jumped on the idea.

In a paper in the German journal *Fortschritte der Physik* in 2013, Maldacena and Susskind argued that a wormhole — technically, an Einstein-Rosen bridge, or ER — is the spacetime equivalent of quantum entanglement. (EPR stands for Einstein, Boris Podolsky and Rosen, authors of the 1935 paper that belittled entanglement.) That means that every particle of Hawking radiation, no matter how far away it is from where it started, is directly connected to a black hole's interior via a shortcut through spacetime. "Through the wormhole, the distant stuff is not so distant," Susskind says.

Susskind and Maldacena envisioned gathering up all the Hawking particles and smushing them together until they collapse into a black hole. That black hole would be entangled, and thus connected via wormhole, with the original black hole. That trick transformed a confusing mess of Hawking particles — paradoxically entangled with both a black hole and each other — into two black holes connected by a wormhole. Entanglement overload is averted, and the firewall problem goes away.

Not everyone has jumped aboard the ER = EPR bandwagon. Susskind and Maldacena admit they have more work to do to prove the equivalence of wormholes and entanglement. But after pondering the implications of the firewall paradox, many physicists agree that the spacetime inside a black hole owes its existence to entanglement with radiation outside. That's a major insight, Preskill says, because it also implies that the entire universe's spacetime fabric, including the patch on which we reside, is a product of quantum spookiness.

"It led me to suggest that the origin of having space at all is having this entanglement."
MARK VAN RAAMSDONK

Cosmic computer

It's one thing to say the universe constructs spacetime through entanglement; it's another to show how the universe does it. The trickier of those assignments has fallen on Preskill and colleagues, who have come to view the cosmos as a colossal quantum computer. For two decades scientists have worked on building quantum computers that use information encoded in entangled entities, such as photons or tiny circuits, to solve problems intractable on traditional computers, such as factoring large numbers. Preskill's team is using knowledge gained in that effort to predict how particular features inside a soup can would be depicted on the entanglement-filled label.

Quantum computers work by exploiting components that are in superposition states as data carriers — they can essentially be 0s and 1s at the same time. But superposition states are very fragile. Too much heat, for example, can destroy the state and all the quantum information it carries. These information losses, which Preskill compares to having pages torn out of a book, seem inevitable.

But physicists responded by creating a protocol called quantum error correction. Instead of relying on one particle to store a quantum bit, scientists spread the data among multiple entangled particles. A book written in the language of quantum error correction would be full of gibberish, Preskill says, but its entire contents could be reconstructed even if half the pages were missing.

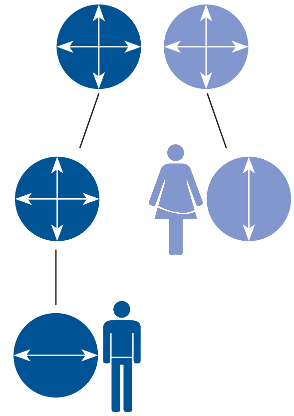
Quantum error correction has attracted a lot of attention in recent years, but now Preskill and his colleagues suspect that nature came up with it first. In the June *Journal of High Energy Physics*, Preskill's team showed how the entanglement of multiple particles on a holographic boundary perfectly describes a single particle being pulled by gravity within a chunk of anti-de Sitter space. Maldacena says this insight could lead to a better understanding of how a hologram encodes all the details about the spacetime it surrounds.

Physicists admit that their approximations have a long way to go to match reality. While anti-de Sitter space offers physicists the advantage of working with a well-defined boundary, the universe doesn't have a straightforward soup-can label. The spacetime fabric of the cosmos has been expanding since the Big Bang and continues to do so at an increasing clip. If you shoot a pulse of light into space, it won't turn around and come back; it will just keep going. "It is not clear how to define a holographic theory for our universe," Maldacena wrote in 2005. "There is no convenient place to put the hologram."

Yet as crazy as holograms, soup cans and wormholes sound, they seem to be promising lenses in the search for a way to meld quantum spookiness with spacetime geometry. In their paper on wormholes, Einstein and Rosen discussed possible quantum implications but didn't make a connection to their earlier entanglement paper. Today that link may help reconcile quantum mechanics and general relativity in a theory of quantum gravity. Armed with such a theory, physicists could dig into mysteries such as the state of the infant universe, when matter and energy were packed into an infinitesimally small space. "We don't really know the answers yet by any means," Preskill says. "But we're excited to find a new way of looking at things." ■

Explore more

- M. Van Raamsdonk. "Building up spacetime with quantum entanglement." *General Relativity and Gravitation*. October 2010.



Spooky entanglement
The polarizations of entangled photons (top row) are initially uncertain — in essence they are horizontal and vertical simultaneously. But once the light blue person measures her photon and sees it is vertically polarized, the fate of the dark blue person's photon is set: When measured, it will be horizontally polarized.

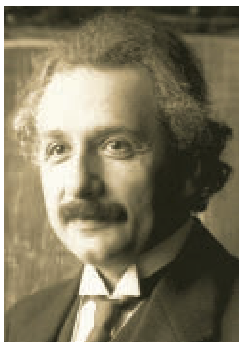
J. HIRSHFELD

BOOKSHELF

Centennial books illuminate Einstein's greatest triumph

You don't need an anniversary as an excuse to write a book about Albert Einstein. But the centennial of his general theory of relativity has nonetheless provided an occasion for several new entries in the Einstein library. And even though general relativity — Einstein's theory of gravity — has been thoroughly explored many times, some 2015 publications do offer new twists and insights.

Thomas Levenson's *The Hunt for Vulcan*, for instance, places Einstein's general relativity in a broader context than usual. Rich in historical detail, if not so much the science, Levenson's book is a skillful popularization of the backstory to one of Einstein's key accomplishments — explaining an oddity in the orbit of Mercury. That mystery had been around since the middle of the 19th century, when the French mathematician Urbain Jean Joseph Le Verrier established that Newtonian gravity could not account for the continual shift in Mercury's closest point to the sun, or perihelion. For decades, astronomers sought a new planet, called Vulcan, that would disturb Mercury's orbit enough to explain the discrepancy. As Levenson recounts, Vulcan's "discovery" was in fact reported more than once, but never confirmed. Levenson explores the human motivations and foibles that drove the drama, which was unresolved until Einstein explained that gravity alone accounted for Mercury's orbit. It's just that it was Einstein's gravity, not Newton's.



FERDINAND SCHMUTZER/WIKIMEDIA COMMONS

While Levenson skims across the surface of general relativity's complicated science and math, Hanoch Gutfreund and Jürgen Renn immerse themselves and their readers in it, via a guided tour of Einstein's 50-page handwritten general relativity manuscript. Gutfreund (a physicist) and Renn (a physics historian) dissect every page of the manuscript, explaining the meaning of each passage and describing Einstein's thought processes leading up to it. If you want more depth than just popularized images of curved space and bending light beams, Gutfreund and Renn's *The Road to Relativity* is accessible and engaging. Besides the annotated manuscript, it includes a useful chronology, short biographies (with pictures) of the physicists, mathematicians and philosophers whose work was relevant to the general relativity story, and an English translation of the published version of the manuscript.

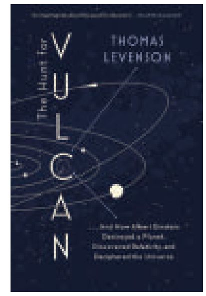
Readers more interested in details about Einstein's life should try *An Einstein Encyclopedia* by Alice Calaprice, Daniel Kennefick and Robert Schulmann. It doesn't ignore the physics — there's an especially nice section providing readable synopses of the key concepts related to Einstein's science, from quantum entanglement to gravitational waves. But otherwise, the encyclopedia is a bit like an Einstein museum in print. You can view his birth certificate, death certificate and one of his high school report cards. You can trace the places he lived and his job history, and read brief biographical sketches of his friends, colleagues and collaborators. You can even peruse nine pages outlining his romantic interests. Einstein apparently did not spend all of his time on equations.

But he did spend a fair amount of time writing about his work, and his most famous popularization, *Relativity: The Special and General Theory*, has been republished for the general relativity centennial. Nobody is better at explaining relativity than Einstein himself; his account provides a combination of depth and clarity that only he could confidently produce. Comprehending it does not require familiarity with advanced mathematics, but the book does, as Einstein states, presume "a fair amount of patience and force of will on the part of the reader."

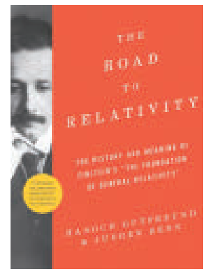
This 100th anniversary edition is complemented by commentary from Gutfreund and Renn, who clarify some key points and add historical perspective, making Einstein's own words even more accessible and meaningful.

No one book could capture all the nuances of general relativity and the complications Einstein faced on his road to developing the theory. But all of these books provide glimpses into Einstein's mind and his methods. They should not fail to generate a sense of awe and appreciation for one of the greatest intellectual accomplishments in the history of human thought. — *Tom Siegfried*

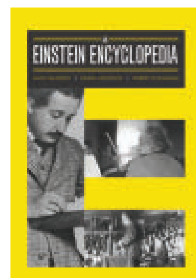
Buy Books Reviews on the *Science News* website include Amazon.com links that generate funds for Society for Science & the Public programs.



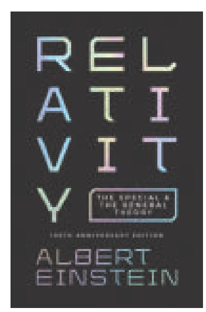
The Hunt for Vulcan
Thomas Levenson
RANDOM HOUSE, $26



The Road to Relativity
Hanoch Gutfreund and Jürgen Renn
PRINCETON UNIV., $35



An Einstein Encyclopedia
Alice Calaprice, Daniel Kennefick and Robert Schulmann
PRINCETON UNIV., $39.95



Relativity: The Special and General Theory, 100th Anniversary Edition
Albert Einstein
PRINCETON UNIV., $26.95

Congratulations Broadcom MASTERS!

Broadcom Foundation salutes the amazing young scientists and engineers nominated by their science fair judges to compete in the 2015 Broadcom MASTERS. Congratulations to the 6,000 nominees, 2,230 entrants, 300 semifinalists and 30 finalists! Good luck to the top 30 finalists as they compete for top prizes at the Broadcom MASTERS Finals Week in California this October!

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Burlington, New Jersey

Pranav Anandarao
Rochester, Minnesota

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Cupertino, California

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Jacksonville, Florida

Hannah O. Cevasco
San Carlos, California

Soyoun Choi
Melbourne, Florida

Natasha Chugh
Plano, Texas

Avery P. Clowes
Bolton, Massachusetts

Maximilian Du
Manlius, New York

Andy Eggebraaten
Rochester, Minnesota

Audrey Glende
Salt Lake City, Utah

Glenn Manuel Grimmett
Jupiter, Florida

Joseph A. Huitt
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Mikayla A. Lindsay
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Society alumni gather to reminisce

Society for Science & the Public alumni had two opportunities to get together in September and relive their history with our competitions, share their accomplishments and meet fellow alumni. Attendees had participated in one or more of our educational competitions: Intel Science Talent Search (formerly Westinghouse STS), Intel International Science and Engineering Fair (formerly the National Science Fair) and Broadcom MASTERS (formerly the Discovery Channel Young Scientist Challenge and the SSP Middle School Program).

On September 4, around 40 alumni arrived at the Yale Center for Engineering Innovation and Design in New Haven, Conn., to celebrate with a pizza party. They played alumni bingo, viewed videos and photos of past competitions, talked about what they are up to now and discussed what they could do to become more involved in science education.

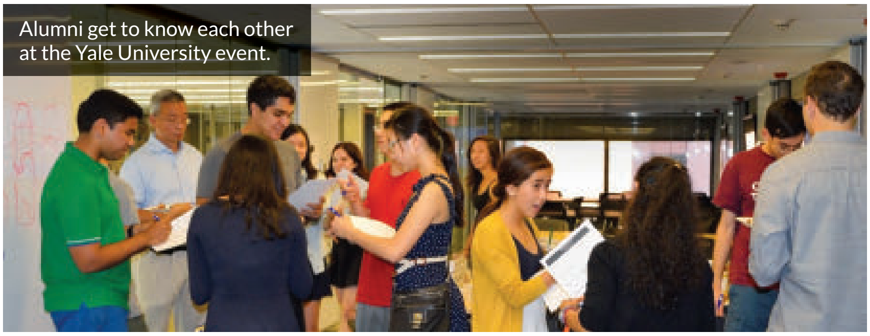
One highlight of the evening was a slideshow of the 1984 Westinghouse Science Talent Search, the year that Sandy Chang, an event attendee and a professor of biophysics and biochemistry at Yale, was the second-place winner.

On September 9, more than 100 Science Talent Search alumni gathered at Akamai Technologies headquarters in Cambridge, Mass., for a panel discussion of distinguished alumni. Speakers included Maya Ajmera, president and CEO of Society for Science & the Public, publisher of *Science News* and a member of the 1985 STS Honors Group; Tom Leighton, CEO and cofounder of Akamai Technologies, SSP board member and a finalist at STS 1974; Erika Ebbel Angle, CEO of Counterpoint Health Solutions, founder of Science from Scientists and a finalist at STS 1999; Karen Gleason, cofounder and chief scientific advisor of GVD Corp., associate provost and professor of chemical engineering at MIT and a member of the 1978 STS Honors Group; Eric Lander, founder of

Distinguished Science Talent Search alumni gathered for a panel discussion in September. From left to right: Tom Leighton, Erika Ebbel Angle, Karen Gleason, Eric Lander, Frank Wilczek and Maya Ajmera.

the Whitehead Institute/MIT Center for Genome Research, founding director of the Broad Institute of MIT and Harvard, cochair of the President's Council of Advisors on Science and Technology, professor of biology at MIT and a finalist at STS 1974; and Frank Wilczek, Nobel laureate, professor of physics at MIT, SSP board member and a finalist at STS 1967. Wilczek also signed and gave away copies of his new book, *A Beautiful Question* (*SN: 9/19/15, p. 29*).

To learn more about upcoming alumni events, including the 75th anniversary of the Science Talent Search, or to reconnect with the Society, please contact alumni coordinator Carolyn Carson at ccarson@societyforscience.org.



Alumni get to know each other at the Yale University event.

FROM TOP: E. NGUYEN/SSP; C. CARSON/SSP

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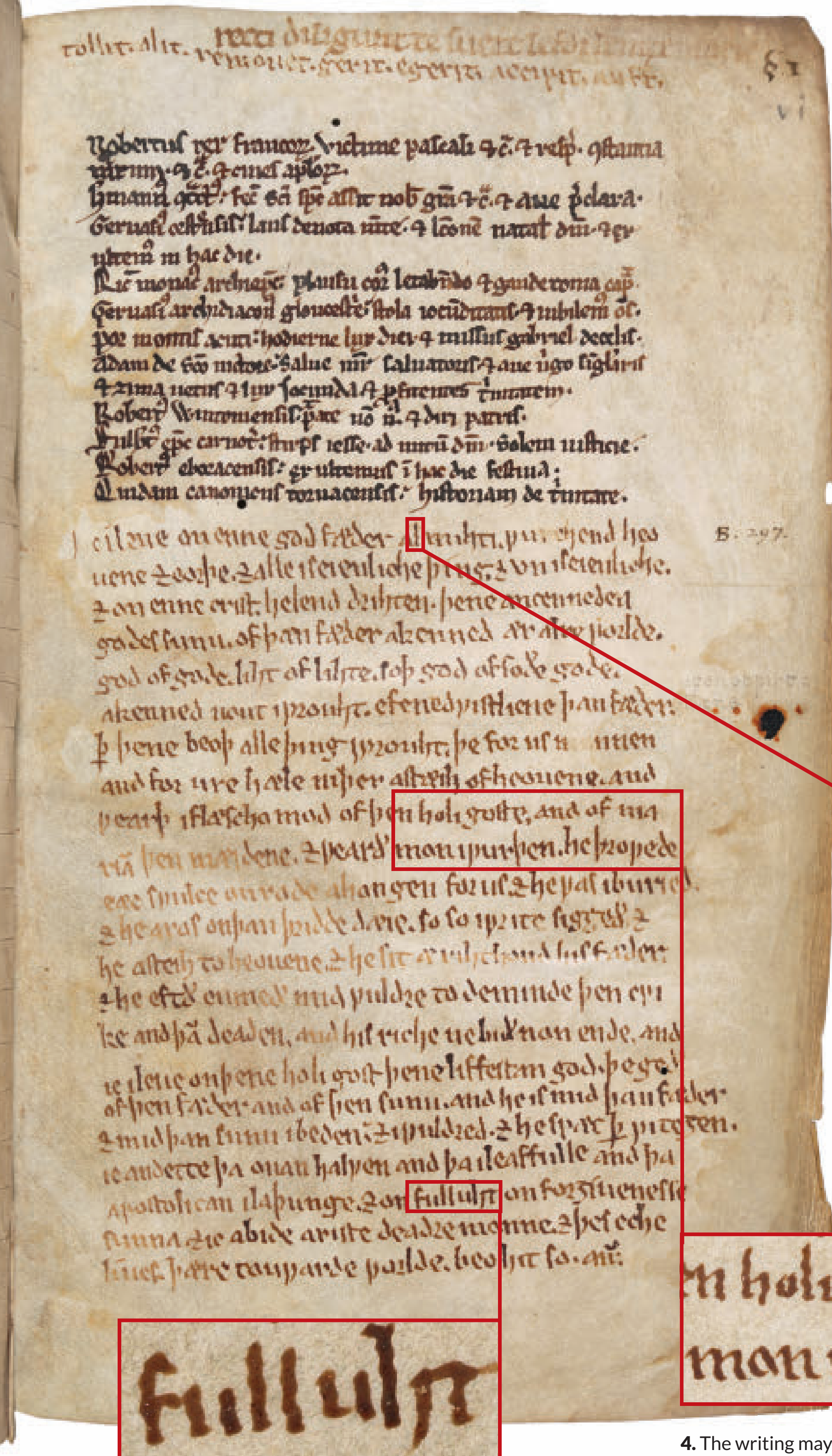
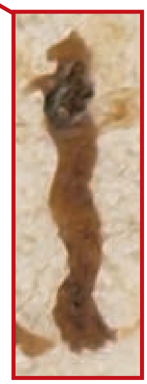
Diagnosing what caused a medieval trembling hand

Scribes usually have pretty good handwriting. That's not the case for one prolific 13th century writer known to scholars only as the Tremulous Hand of Worcester. Now scientists suggest the writer suffered from a neurological condition called essential tremor. Neurologist Jane Alty and historical handwriting researcher Deborah Thorpe, both of the University of York in England, made the retrospective diagnosis August 31 in *Brain* after studying the spidery wiggles that pervade the scribe's writing. Essential tremor can cause shaking of the hands, head and voice and is distinct from other tremor-causing conditions such as Parkinson's disease.

Here, the anonymous writer's peculiar script is evident (lighter portion of text) in an early Middle English version of the *Nicene Creed*, a summary of the Christian faith. Buried in the manuscript are clues that helped the researchers conclude that essential tremor plagued the Tremulous Hand. *—Laura Sanders*



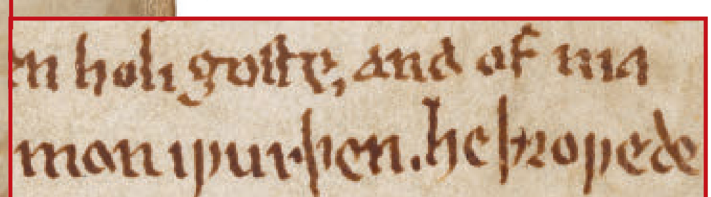


Signs in the script

1. Wiggles have a consistent size within individual letters. This uniformity rules out other types of tremor, such as dystonic tremors, which can result in small wiggles followed by large, jerky deviations.

2. The writing has the right number of wiggles. Assuming each downward stroke took less than half a second, researchers estimate the writing was marked by six to eight shakes a second. That frequency rules out other tremor diagnoses.

3. The wiggles are oriented in the same direction, toward 8 and 2 on a clockface. In other tremors, this axis changes frequently.



4. The writing may have improved after rest or alcohol. Hydrating with weak alcohol was common in the Middle Ages, so it's possible that booze calmed the scribe's jitters. Essential tremor can ease in response to alcohol, whereas other tremor types such as cerebellar tremors sometimes worsen.

5. The lines that compose the letters have roughly the same thickness, so the writing pressure appears steady. Variable nib pressure can lead to blotches and width differences in lines, a feature consistent with Parkinson's and dystonic tremors.