SCIENTIFIC AMERICAN

SPECIAL ISSUE

SEPTEMBER 2004
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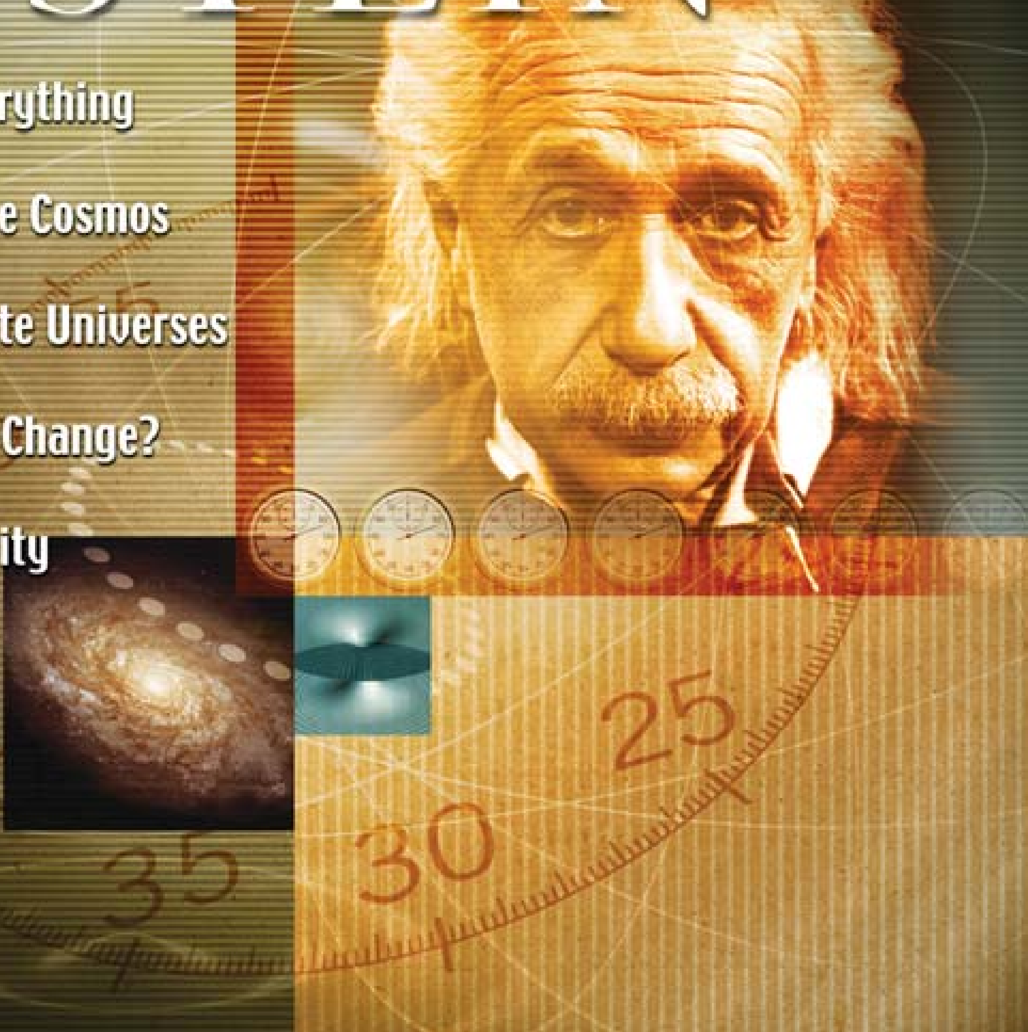
For a century, his ideas have reshaped the world. But discover how physicists are now venturing

BEYOND EINSTEIN



Toward a Theory of Everything

Energy That Expands the Cosmos

Different Physics, Infinite Universes

Does the Speed of Light Change?

Computing with Relativity

Einstein vs. Newton

And More ...

september 2004

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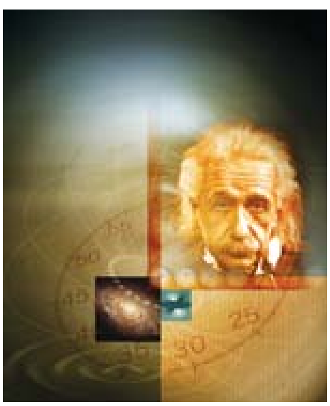
About the Cover

The 1947 Philippe Halsman photograph of Einstein included in Tom Draper's cover montage is one of many testaments to the humanity and activism of the great scientist. On two separate occasions, Einstein came to the aid of Halsman, a Latvian Jew now acclaimed as one of the 20th century's top portrait photographers. In the late 1920s, after Halsman was unjustly imprisoned in an increasingly anti-Semitic Austria, Einstein (and other notables) wrote letters protesting his innocence. Again in 1940, as Halsman struggled to leave France after the arrival of the Nazis, Einstein contacted Eleanor Roosevelt on his behalf, thereby helping the photographer escape to America.



columns

Cover image by Tom Draper Design; Einstein photograph by Philippe Halsman, © 1947 Philippe Halsman Estate.

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SA Perspectives

Einstein = Man of Conscience²

Sketch a thicket of unruly hair, a soup-straining moustache, a pair of knowing eyes and perhaps a thought balloon full of equations—people around the world will know who you mean as easily as if you had drawn Mickey Mouse's ears or Superman's cape. Not only is "$E = mc^2$" one of science's best-known equations, but as a catchphrase it is probably as familiar to much of the public as any line from Shakespeare. Every list of the 20th century's most outstanding figures must include Albert Einstein because that era—and our own—is unimaginable without him and his influence. Even today, a century after his earth-shaking 1905 papers on relativity, quantum theory and molecular theory, the questions that preoccupied Einstein remain at the forefront of science.

EINSTEIN SPEAKS in Washington, D.C., in 1940.

It's only natural that a man who showed how to bend space and stretch time should become a titan of science. Yet Einstein also attained a wider renown than many of his equally brilliant peers in physics—such as Niels Bohr, Max Planck, Paul Dirac or Erwin Schrödinger. Surely the reason is that the public had feelings for him beyond admiration.

People loved Einstein. He did not originate the stereotype of the avuncular, eccentric scientific genius, but he personified it charmingly. Even during the 1950s, when fears of radiation fed the public's unease about arrogant or heedless ambitions among "mad scientists" in the nuclear physics community, Einstein remained free of that taint.

This cultural status did not fall to Einstein through the mere fact of his intellect. The public responded to him sympathetically in part because of his modest but forceful use of his celebrity for good political ends.

His involvement in politics was motivated less by a craving for power than by a heartfelt desire to set right injustices and to fulfill the responsibilities incumbent on him as an unwilling co-author of history's most terrifying weapon. Documents suggest that the bloodshed of World War I was what turned him from a mute critic of militarism into a protestor. When observations of the total eclipse in 1919 detected gravitational bending of light in keeping with his theories, Einstein used his newfound international fame to speak out on issues and to advocate for a just world government. In 1939 he and physicist Leo Szilard wrote a letter to President Franklin D. Roosevelt that led to the Manhattan Project and a race with the Nazis to build an atomic bomb. Yet after Hiroshima, Einstein remarked, "If I knew they were going to do this, I would have become a shoemaker!"

Reactions to Einstein's politicking differed. In 1952 Israel offered him its presidency. FBI director J. Edgar Hoover believed Einstein was an instigator and kept him on an enemies list.

Were Einstein alive now, he would undoubtedly still find causes for outrage. Though a Zionist, he had always insisted that Jews must live peaceably with Arabs. It is easy to speculate that Einstein, as a staunch opponent of unilateralist military actions, would have opposed his adoptive nation's foray into Iraq.

Today, when prominent researchers comment on environmental policies, missile defense, health care priorities and similar matters, critics sometimes suggest that science and politics should not mix. But Einstein knew that scientists have a moral responsibility to explain their work, including its political implications. To argue otherwise is to say that science does not matter.

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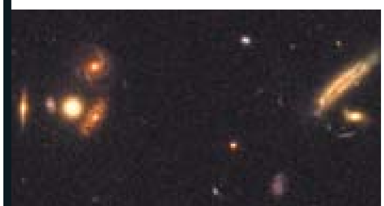
Mature Galaxies in Young Universe at Odds with Theory

The discovery of massive galaxies in the infant universe has astrophysicists puzzling over how such objects could have formed so early on. The leading model of galaxy evolution assumes that the first galaxies were relatively tiny—only through the merging of these smaller entities did larger galaxies slowly develop. The new find may force scientists to reexamine how stars arise.



Prickly Pear May Be Hangover Preventive

Overindulging in wine or spirits often makes the following morning much less enjoyable. Now there's some good news for those looking to avoid the dread hangover. Taking an extract of the fruit of a prickly pear cactus before drinking may cut the risk of a severe hangover in half.

Old Age Was Secret of Modern Humans' Success

Humans began to live long and prosper only about 30,000 years ago, researchers report. A recent survey of hominid dental remains reveals that the number of people surviving to old age increased fourfold during the Upper Paleolithic period. This newfound longevity may have given anatomically modern humans an advantage over other hominids.

Ask the Experts

How does decanting red wine affect its taste?
Andrew L. Waterhouse, a professor in the department of viticulture and enology at the University of California at Davis, explains.

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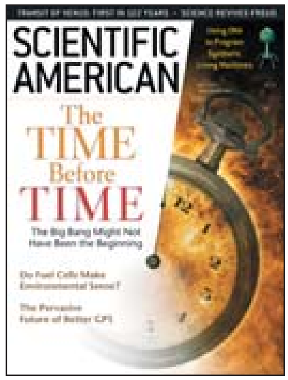
COURTESY OF PIERO ROSATI AND BOB FOSBURY *ESO Garching* (*top*); COURTESY OF *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES USA* (*bottom*)

Letters

EDITORS@SCIAM.COM

RESPONSES TO "Questions about a Hydrogen Economy," by Matthew L. Wald, in the May issue reminded the editors of a well-known formula for magazine articles: Automobiles + Hydrogen Fuel ÷ Future Speculation = (Letters × 10). Many writers took the magazine to task for not highlighting an alternative of choice, including biodiesel fuel, nuclear fusion and even ocean-wave energy generation. Skeptics of hydrogen argued that the article was too soft on the concept, whereas others were put off by the critical take. The science policy of the Bush administration, examined in "Bush-League Lysenkoism" [SA Perspectives], also drew large numbers on both sides of the equation. Calculate your own responses to the letters that follow.



EMISSION OMISSIONS

"Questions about a Hydrogen Economy," by Matthew L. Wald, failed to address an important advantage of a hydrogen fuel system: when automobiles do not produce pollution, as is the case with hydrogen fuel cells, emissions are confined to fuel-production plants. This centralizing of emitters eases monitoring and disposal of the waste, as well as making upgrades with new pollution-reducing technology.

Stuart Hicks
Columbus, Ohio

The article states that hydrogen fuel cells are twice as efficient as internal-combustion engines, but the actual difference is much smaller because of the accessory support systems a fuel cell requires. General Motors's best-published fuel-cell thermal efficiency is 43 percent, compared with 40 percent for a conventional internal-combustion engine using diesel. Given the cost and the problems of fuel production and storage, the incentive to pursue the idea of automotive fuel cells is hard to identify.

Robert J. Templin
via e-mail

Whereas emissions of carbon monoxide will drop in a hydrogen economy, accidental atmospheric releases of hydrogen—an even more potent greenhouse gas—will rise. The hydrogen economy could be worse for the climate than the current, petroleum-based system.

William Donelson
Wimbledon, London

There is no doubt that handling leaks of hydrogen is more difficult than those of natural gas. Yet the cause for worry is not as dire as it seems: thousands of electrical generators in power plants all over the world are cooled by hydrogen with few or no problems.

F. Gautschi
West Hartford, Conn.

Hydrogen may have its disadvantages, but technological advances will make the gas the key to safer, more efficient global functioning. By 2050 all energy sources will produce hydrogen, which will be accumulated in a worldwide piping system that is hidden and harmless. The ugly, fragile electrical distribution system will be gone. The by-product oxygen will be used to treat sewage; purify rivers and oceans; and incinerate solid waste.

The car of 2050 will probably have a fuel cell to charge batteries in a system similar to that of current hybrid automobiles. The thermodynamic efficiency of the system will be in the vicinity of 50 percent, and the vehicle will have a driving range of 500 kilometers. The overall benefits of hydrogen may currently seem to be lacking, but the future is promising.

Laurence Williams
Alliance, Ohio

THE SCIENCE OF POLITICS

Regarding "Bush-League Lysenkoism" [SA Perspectives], the Bush administration is doing exactly what President Bill Clinton did during his term—but most of the permanent government science bureaucracy was more politically in tune with Clinton's politics. The fact that *Scientific American* and the Union of Concerned Scientists (UCS) don't like Bush's policies is no excuse to suddenly discover that elected officials can affect research directions, squander tax dollars on self-serving scientific sideshows and tailor research results to fit political agendas.

Michael P. Rethman
Kaneohe, Hawaii

Your editorial cites accusations from the UCS yet neglects to mention that the Office of Science and Technology Policy provided a detailed response to these claims. The response brings many other facts to light surrounding each of the claims, making it clear that they do not add up to the kind of systematic manipulation your editorial criticizes. You also fail to mention that the Treasury Department reversed its restrictions on the editing of scientific papers from embargoed nations and that the Office of Management and Budget recently released its peer-review proposal, which William Colglazier, executive officer of the National Academy of Sciences and the National Research Council, called "significantly improved."

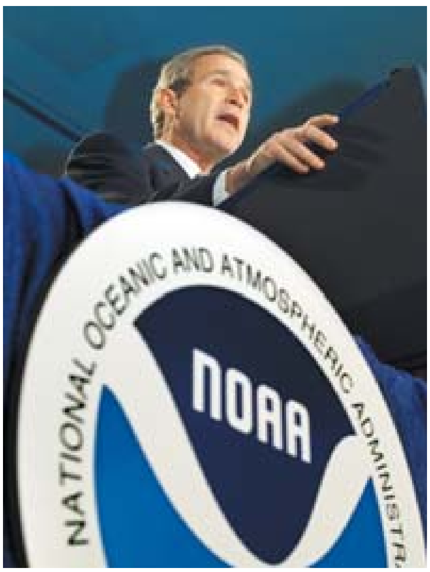
Robert Hopkins
Special Assistant for Public Affairs
Office of Science and Technology Policy
Executive Office of the President

Shortly after your editorial was printed, the Bush administration took another step to muzzle American scientists in the service of a political agenda. A new policy requires the World Health Organization to seek the approval of the U.S. Department of Health and Human Services before soliciting scientists' opinions. According to Representative Henry Waxman of California, "For the first time, political appointees will routinely be able to keep the top experts in their field from responding to WHO requests for guidance on international health issues." The government has also tightened restrictions on who may attend the International AIDS Society conference in Bangkok, Thailand, in July.

Don Bay
Froson, Sweden

THE EDITORS REPLY: Rethman's argument might be more convincing if the signatories to the petition accompanying the UCS report did not include advisers to conservative, Republican administrations who insist the willingness of the current White House to ignore and suppress scientific advice is unparalleled.

The Office of Science and Technology Policy did not release its response to the UCS report until well after our editorial went to press. Hopkins is no doubt aware that many researchers consider that rebuttal to be inadequate (for example, see the UCS rejoinder at www.ucsusa.org). Similarly, the Treasury Department and the OMB changed their positions only after our editorial's release—and after loud outcry by scientists and the public.



STANDING UP for science—or stepping on it?

FREUDIAN FEEDBACK

In "Freud Returns," Mark Solms is right to note that we are learning much about the mechanisms of mind, and Freud's observations can be roughly mapped onto current knowledge. But to claim that this correspondence supports Freud does a disservice to the current sophistication of the field. Freud's historical contribution to psychology was inestimable, but his views are now little more than dead weight—what other branch of medicine still clings so to theories 100 years old? Is it the self-consistency of the theory (It makes so much sense, it must be true!) or the self-interest of the practitioners (You mean everything I know about human psychology is wrong?) that fuels this desperation to "prove Freud right" yet again?

Darien S. Fenn
Wilsonville, Ore.

I applaud Solms's efforts to link the findings of modern neuroscience with some of Freud's intuitive hunches. Freud said a few absurd things, but to ignore all his ideas would be a "phallusy." The so-called Freudian defense mechanisms—such as rationalization, denial, repression and reaction formation—are a vital and very real part of our mental life, although most neuroscientists are in denial about this.

V. S. Ramachandran
Center for Brain and Cognition
University of California, San Diego

GET THE BEAT

Per Enge's article ["Retooling the Global Positioning System"] states that two audible tones in air would produce a beat note. This is not true—if it were, music would be a cacophony with all the beat notes produced. Beat notes occur only in nonlinear media such as an electronic mixer.

Eric Sundberg
President, Southern Electronics
Richmond, Va.

ENGE REPLIES: Sundberg is correct. The electronic or software mixer in the GPS receiver creates our GPS beat note.

ERRATUM "Freud Returns," by Mark Solms, misattributed the statement "It is not a matter of proving Freud right or wrong, but of finishing the job." These words were penned by Fred Guterl (not said by Jaak Panksepp of Bowling Green State University) in the November 11, 2002, issue of *Newsweek*.

J. SCOTT APPLEWHITE *AP Photo*

Prolific Stars ▪ Clever Horse ▪ Busy Worms

SEPTEMBER 1954

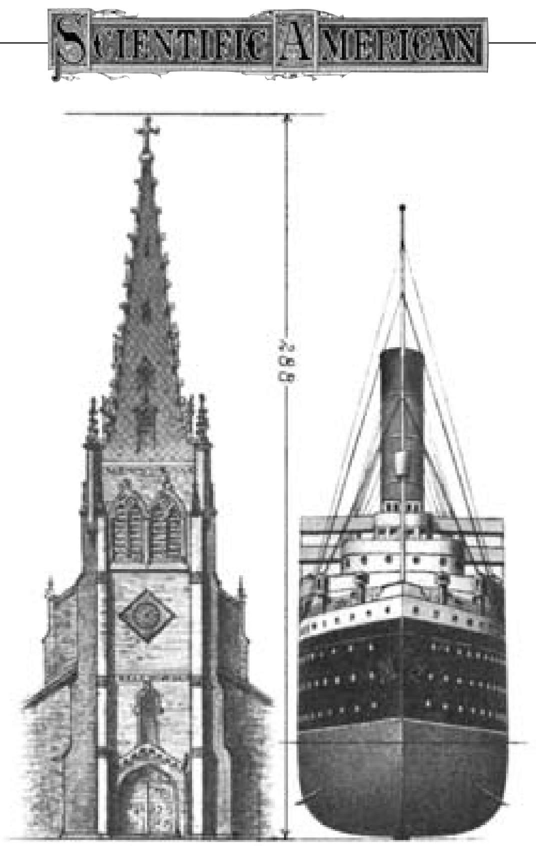
WHAT IS HEAT?—"Heat is disordered energy. So with two words the nature of heat is explained. The rest of this article will be an attempt to explain the explanation.—Freeman J. Dyson"

COSMIC ELEMENTS—"It is tempting to suggest that all the chemical elements we know have been synthesized from hydrogen by thermonuclear processes inside stars. Why should hydrogen be the primeval element from which all the others are built? If that riddle is not difficult enough, here is a harder one: how did hydrogen itself come into being? We cannot beg the question by supposing that it has always existed. Hydrogen is steadily being converted into other elements by processes that seem irreversible. In spite of this, hydrogen is the most abundant element in the universe. We must, therefore, suppose that it has a finite age, for if it had existed for an infinite time, it should all have been used up by now.—Fred Hoyle"

SEPTEMBER 1904

THINKING HORSE—"Hardly a day passes but the newspapers have something to say of the wonderful mental performances of 'clever Hans,' 'der kluge Hans,' as Herr Von Osten's stallion is called. An investigation conducted by scientists, however, would seem to indicate that the horse is really what his owner claims him to be, an intelligent four-footed animal, capable of making simple arithmetical calculations. Dr. Heinroth, of the Berlin Zoological Garden, has questioned the horse in his stall in the absence of its owner, and he has received answers as clear-cut and as precise as those given in the presence of Von Osten." [*Editors' note: Apparently, Hans was only reacting to the subtle cues unconsciously broadcast by onlookers.*]

OIL PRODUCTION—"The world's petroleum production for 1903 stands at 20,000,000 tons, and of this more than one half is furnished by Russia, the rest coming from the United States and Canada, Roumania and Borneo. The demand for production greatly exceeds the present production."



THE NEW OCEAN LINER compared to Trinity Church, 1904

THE NEW CUNARDERS—"Among the nautical exhibits at the St. Louis Exposition, the model that attracts the most attention is that of the new 25-knot, 40,000-ton turbine steamers of the Cunard Steamship Company. If the new liner were placed in the churchyard alongside Trinity Church in New York, its smokestack would reach half way up the spire—that old-time standard of lofty measurements, 288 feet in height [*see illustration*]."

SPEED DEMONS—"The previous record for an automobile running under its own power overland from San Francisco to New York was beaten by Messrs. L. L. Whitman and C. S. Carris in a 10-horsepower, four-cylinder, air-cooled Franklin runabout, upon which they had made the 4,500 miles in 33 days without any serious mishaps. That this particular make of air-cooled motor car could so successfully break all records for a long transcontinental trip over roads, trails, mountains and across trackless wastes of alkali and sage brush, was something that came as a surprise to all automobilists."

SEPTEMBER 1854

THE ACTION OF WORMS—"Beneath the city of Berlin, in Prussia, there is a deep bog of black peat. Professor Ehrenberg, a gentleman whose explorations into the mysteries of microscopic life have attained for him a high position among the scientific men of the age, says that this peat, at the depth of fifty feet, swarms with infusorial life; that countless myriads of microscopic animals live there and wriggle and die. The perpetual motion of these little animals causes the whole mass of peaty matter to be in a state of constant though generally imperceptible movement. In Berlin, the houses are wont to crack and yawn sometimes, in an exceedingly curious manner, even though built on apparently stable foundations; and Professor Ehrenberg believes this to be owing to the combined efforts of infinite million of tiny forms."

news SCAN

DEFENSE

Test Drive

WILL A PLANNED DEFENSE SHIELD DEFEAT REAL MISSILES? **BY DANIEL G. DUPONT**

NUTS-AND-BOLTS TRIALS of missile defense, such as the tracking of this Minuteman III launched from Vandenberg Air Force Base on June 23, have been few.

U.S. AIR FORCE, STEPHEN CLINE *AP Photo*

Perhaps as early as this month, President George W. Bush is expected to declare that a handful of prototype missiles in California and Alaska are ready to protect the U.S. from long-range missile attacks. The Pentagon calls the system a "test bed," one that still needs more sophisticated radar, interceptors and space-based lasers to realize Ronald Reagan's dream of a "Star Wars" antimissile program. The Defense Department, however, maintains that it can defeat North Korea's small arsenal of long-range missiles—a claim that may be hard to swallow given the limited number of tests done so far.

The ground-based midcourse defense system, as it is called, will start off with no more than 10 "hit-to-kill" interceptors designed to collide directly with incoming missiles in space. To date, the program has intercepted target missiles in five of eight heavily scripted tests.

But critics say those trials prove little. The Union of Concerned Scientists, in a report released earlier this year, concluded that the initial system "will be ineffective against a real attack" and also slammed the administration for "irresponsible exaggerations" about its abilities. In June opponents in Congress tried unsuccessfully to postpone deployment on grounds that the system should be tested further. During a Senate debate, Senator Barbara Boxer of California likened the plan to the Wizard of Oz, who "was scary, but when you pull back the curtain, it was just some little guy," she said.

The Pentagon's Missile Defense Agency (MDA) has long held that live tests, which are costly, difficult to plan, and limited by range and safety concerns, are not the only means of proving the system's efficacy. According to the Pentagon, sophisticated modeling, simulations and exercises can offset the paucity of real intercepts. In April, Air Force Lt. Gen. Ronald Kadish, then head of the MDA, told Congress: "We use models and simulations, and not flight tests, as the primary verification tools."

But the Center for Defense Information's Philip Coyle, the Pentagon's top tester during the Clinton administration, argues that such technology "simply doesn't capture the basic physics and the variables in a missile defense engagement." His successor under Bush, Thomas Christie, told Congress in March that such virtual assessment is "not a good substitute for integrated system testing." And the Pentagon's Defense Science Board, a high-level advisory group, concluded in a May report that the MDA's current models and simulations are "legacy" items that are "not well designed to fit together." As a result, Coyle says, the military will be "operating blind" once the program is up and running. The science board also stated that the MDA models of the system's ability to discriminate between actual targets and decoys are "oversimplified."

Richard Matlock, named the MDA's first director of modeling and simulation after the science board report was released, says current models "do a very good job at predicting the performance of system components." But the report did confirm the need to enhance those models as missile defense evolves, he remarks. According to the MDA, an aggressive evaluation program will occur over the next few years as the test bed is upgraded. "We will constantly improve our capabilities through operationally realistic testing," an MDA spokesman comments. "We can't operationally test the system until we put it into place."

That will happen shortly before voters decide between Bush and presidential candidate Senator John Kerry of Massachusetts, who says missile defense research is important but believes the Bush approach has not been sufficiently tested. The Pentagon asserts that the timing of the deployment is a coincidence, but opponents are skeptical. "I believe that's a big part of the push for deployment this year," Coyle says.

Daniel G. Dupont edits InsideDefense.com, an online news service. He wrote about the threat of high-altitude nuclear explosions in the June issue.

DETERRENCE OVER PERFORMANCE

For the White House, actual performance may not matter as much as perception. According to *Hit to Kill,* a 2001 book on missile defense by *Washington Post* journalist Bradley Graham, President George W. Bush once received a briefing from an Israeli general on Israel's Arrow missile defense system. The general assured Bush, who was governor of Texas at the time, that Arrow worked well, but Bush later expressed some doubt: "Of course their line is it does, because the minute somebody thinks it doesn't, then the country is much more vulnerable," he said, as quoted by Graham. "I found that to be an interesting concept unto itself. Deterrence, real or not real, is still deterrence."

EPIDEMICS

Nipah's Return

THE LETHAL "FLYING FOX" VIRUS MAY SPREAD BETWEEN PEOPLE **BY CHARLES CHOI**

In February the Nipah virus reemerged, killing 35 people in Bangladesh in two outbreaks. Although the number of victims is small, the deaths have health officials worried. Unlike its first appearance in Malaysia in September 1998, the virus in Bangladesh may have jumped from person to person, raising concern about its ability to spread farther and faster.

Nipah is a henipavirus, a family named after its two only known members, Hendra and Nipah (both take their appellations from the places they first struck). Distant relatives of measles, henipaviruses appear to reside naturally in flying foxes, the world's largest bats. The virus spreads through bodily fluids such as saliva or urine.

Flying foxes live across the Pacific lands and Africa. Roughly a third of those in Malaysia and Australia harbor antibodies against the infections, suggesting that the bats and viruses evolved together. The bats, which are critical to rain-forest ecology as pollinators and seed dispersers, apparently do not get sick from the viruses, "which makes them particularly good carriers," says veterinary epidemiologist Jon Epstein of the Wildlife Trust's Consortium for Conservation Medicine in Palisades, N.Y. Intrusions on and fragmentation of the bats' natural habitat as the result of logging and other human activities help to create the conditions "for a spillover disease event from animals to humans," he explains.

When Nipah reappeared this past winter, it came deadlier than ever. In contrast to its original outbreak in Malaysia, which claimed nearly 40 percent of those infected, the mortality rate of the Bangladeshi outbreaks was 74 percent. "That's approaching Ebola levels," Epstein observes. (SARS has a mortality of about 9 percent.) It remains unclear whether the Bangladeshi strain is inherently more deadly than the Malaysia strain or whether it proved more lethal because of poorer access to health care.

VIRUS HUNTING: Australian scientists, part of an international team, autopsy a pig in the Malaysian village of Sepang, about 30 miles south of Kuala Lumpur, in 1999. The animal was suspected of being infected with the deadly Nipah virus.

© CSIRO AUSTRALIA, 1999

Equally unclear is how the Bangladeshi patients became infected. Previously Hendra and Nipah leaped from bats to humans via intermediate animal hosts. Victims in the first Nipah outbreaks, for instance, caught the sickness from pigs. The bats frequented mango trees that grew directly over pigpens, leading medical researchers to suspect that the bats either dropped saliva-tainted fruit or excreted waste into the pens. The sickened pigs coughed and wheezed—and amplified the virus population in their bodies to levels far greater than those in bats.

Many victims in Bangladesh, however, had no direct contact with animals, and no infected domestic animals were seen. Reports suggest that children picked fruit from trees before dawn, perhaps roughly the same time bats finished nightly feeding. But without an identifiable intermediate vector, transmission among people cannot be ruled out. A human vector would allow henipaviruses to expand beyond the natural range of the bats, says Peter Daszak, director of the Consortium for Conservation Medicine.

Human-to-human transmission would also make henipaviruses even more desirable to bioterrorists. "If you want to cause serious human disease and even more serious animal biowarfare, Nipah's your guy," comments virologist Chris Broder of the Uniformed Services University of the Health Sciences. "These viruses in fruit bats can be isolated with just rudimentary skills in microbiology." The Centers for Disease Control and Prevention ranks them in the same bioterrorism class as the hantavirus (category C), though not as high as anthrax or cholera.

To prevent outbreaks, Malaysia now screens pig blood samples for Nipah. For Bangladesh, the recommendations include precautions among health care workers such as wearing goggles, masks and gloves, along with improved local hygiene that includes washing of fruit and hands.

Two international collaborations—one taking place between Malaysia and France, the other between Australia and Broder's U.S. team—are experimenting with vaccines. One therapeutic approach being pursued by Broder and his colleagues are proteins that inhibit Nipah's fusion with cells in the body. Antibody therapies to neutralize the viruses are also possible but prohibitively expensive, Broder says.

Controlling new diseases also means good surveillance; to date, groups such as the Food and Agriculture Organization of the United Nations and the World Organization for Animal Health monitor diseases in internationally traded animals, but no global group yet exists to keep track of wildlife diseases. "Seventy-five percent of all emerging infectious diseases are known to come from animals, and wildlife is part of that equation," Epstein notes. "The more we can identify the natural reservoirs of a disease and understand the conditions that allow them to emerge," he says, "the more we can predict and ultimately prevent diseases."

Charles Choi is based in New York City.

FAST FACTS: LETHAL PAIR

HENDRA VIRUS

First definitive outbreak: 1994

Identification of virus: 1995

Incubation time: Eight to 16 days

Symptoms: Severe flulike signs; subsequent encephalitis, respiratory and kidney failure

Outbreak in Australia: Three infected, two deaths

NIPAH VIRUS

First definitive outbreak: 1998

Identification of virus: 1999

Incubation time: Four to 18 days

Symptoms: Three to 14 days of fever, headache and muscle pains, followed by drowsiness and confusion; may progress to convulsions and coma in a day or two

Outbreak in Malaysia and Singapore: 265 infected, 105 deaths

First outbreak in Bangladesh: 23 infected, 17 deaths

Second outbreak in Bangladesh: 30 infected, 18 deaths

BIOCHEMISTRY

Bad Rap for Nitrate?

INFAMOUS PRESERVATIVE MAY HELP DEFEND AGAINST BACTERIA **BY JR MINKEL**

Nitrate, a preservative in hot dogs and other meats as well as a natural ingredient in greens such as lettuce and spinach, was once considered a dietary scourge for its potential link to stomach cancer. But biologists are now starting to think that dietary nitrate is actually part of the body's inherent defense against infection and have begun testing treatments based on the idea.

Nitrate (NO_3^-) became suspect in the 1950s, when researchers found that a class of its derivatives, called *N*-nitrosamines, damages DNA and causes cancer in laboratory rats and farm animals. A score of subsequent epidemiological studies generally found no consistent association between nitrate intake and human stomach cancer, however.

HEALTHFUL EATING? Not really, but the nitrate preservative may ward off microbes.

The story of nitrate's positive side began in 1994, when Jon Lundberg of the Karolinska Institute in Stockholm and Nigel Benjamin of Peninsula Medical School in Exeter, England, independently observed that the human stomach harbors large amounts of the gas nitric oxide (NO). Lundberg and Benjamin immediately suspected that the gas might be killing germs in the stomach, because nitric oxide, when presented to microbes by white blood cells, weakens them.

The question was where the gas was coming from. Nitric oxide performs several vital functions in the body, including dilating blood vessels, and for these activities, a cellular enzyme called nitric oxide synthase extracts the gas molecule from arginine, an amino acid. Chemists have long known another mechanism: at low pH, nitrite (NO_2^-) forms a stew of nitrogen-oxygen compounds, including nitric oxide. Bacteria in the mouth convert nitrate to nitrite, which gets swallowed, so the stomach can naturally produce nitric oxide. If nitric oxide were truly beneficial to the stomach, harmless bacteria feeding on nitrate-rich saliva might have a symbiotic relationship with humans.

Benjamin's group confirmed the antimicrobial effect right away by exposing bacteria responsible for stomach infections to stomach acid both alone and mixed with nitrite. Although acid is often thought to be the stomach's main line of defense against invading bugs, the researchers found that *E. coli, Salmonella* and other bacteria could survive for hours in it, whereas high normal concentrations of nitrite plus acid killed the bacteria in less than an hour. Next, Lundberg and his coworkers placed saliva from people who had ingested nitrate tablets onto the inside surface of the stomachs of rats. The mucous membranes lining their stomachs thickened and received more blood, both of which are important barriers to infection and ulcers. Rats that received nitrate-poor saliva showed no change. Benjamin has also observed that cavity-causing bacteria self-destruct in a high-nitrite environment, suggesting an experiment to see if a high-nitrate diet prevents cavities.

"We've gone from considering all of these things to be toxic and carcinogenic to realizing that [nitrates are] playing a fundamental homeostatic role," says microbiologist Ferric Fang of the University of Washington.

Both groups are working on antimicrobial therapies based on nitrate chemistry. Benjamin has prepared a nitric oxide cream to treat bacterial skin infections common in developing countries, and Lundberg is conducting a study at Karolinska to see if giving saliva to dry-mouthed intubated patients can prevent ulcers. Researchers are still far from understanding how to treat systemic infections with nitric oxide, Fang says: "It has so many biological activities, how do you really deliver nitric oxide only to that bug without dropping your blood pressure? We don't know how to do that."

JR Minkel is based in New York City.

NITRATES: CANCER OR NOT?

Nitrate's relation to cancer is still unclear: epidemiological studies have found no consistent link between stomach cancer and nitrate ingestion. In the July *Nature Reviews Microbiology,* Jon Lundberg of the Karolinska Institute in Stockholm, Nigel Benjamin of Peninsula Medical School in Exeter, England, and their colleagues note that an overgrowth of bacteria in the stomach encourages the formation of *N*-nitrosamine, a carcinogen that can be made from nitrates. But as long as the stomach stays acidic and healthy, the chemical seems to pose no risk, they state. A December 2003 study proposed a mechanism by which nitrate could lead to *N*-nitrosamine that could cause esophageal cancer. Cancer epidemiologist David Forman of the University of Leeds in England finds the work "fascinating" but says epidemiological analysis has not substantiated such a link.

ARTHUR BECK *Corbis*

COSMOLOGY

Scaled-Up Darkness

COULD A SINGLE DARK MATTER PARTICLE BE LIGHT-YEARS WIDE? BY GEORGE MUSSER

In 1996 *Discover* magazine ran an April Fools' story about giant particles called "bigons" that could be responsible for all sorts of inexplicable phenomena. Now, in a case of life imitating art, some physicists are proposing that the universe's mysterious dark matter consists of great big particles, light-years or more across. Amid the jostling of these titanic particles, ordinary matter ekes out its existence like shrews scurrying about the feet of the dinosaurs.

This idea arose to explain a puzzling fact about dark matter: although it clumps on the vastest scales, creating bodies such as galaxy clusters, it seems to resist clumping on smaller scales. Astronomers see far fewer small galaxies and subgalactic gas clouds than a simple extrapolation from clusters would imply. Accordingly, many have suggested that the particles that make up dark matter interact with one another like molecules in a gas, generating a pressure that counterbalances the force of gravity.

The big-particle hypothesis takes another approach. Instead of adding a new property to the dark particles, it exploits the inherent tendency of any quantum particle to resist confinement. If you squeeze one, you reduce the uncertainty of its position but increase the uncertainty of its momentum. In effect, squeezing increases the particle's velocity, generating a pressure that counteracts the force you apply. Quantum claustrophobia becomes important over distances comparable to the particle's equivalent wavelength. Fighting gravitational clumping would take a wavelength of a few dozen light-years.

SMALL GALAXIES such as NGC 3109 are rarer and less compacted than they would be if matter clumped freely, perhaps because colossal particles that might be the universe's "missing mass" resist clumping.

What type of particle could have such astronomical dimensions? As it happens, physicists predict plenty of energy fields whose corresponding particles could fit the bill—namely, so-called scalar fields. Such fields pop up both in the Standard Model of particle physics and in string theory. Although experimenters have yet to identify any, theorists are sure they're out there.

Cosmologists already ascribe cosmic inflation, and perhaps the dark energy (distinct from dark matter) that is now causing cosmic acceleration, to scalar fields. In these contexts, the fields work because they are the simplest generalization of Einstein's cosmological constant. If a scalar field changes slowly, it resembles a constant, both in its fixed magnitude and in its lack of directionality; relativity theory predicts it will produce a gravitational repulsion. But if the field changes or oscillates quickly enough, it produces a gravitational attraction, just like ordinary or dark matter. Physicists posited bodies composed of scalar particles as long ago as the 1960s, and the idea was revived in the late 1980s, but it only really started to take hold four years ago.

Two leaders of the subject are Tonatiuh Matos Chassin of the Center for Research and Advanced Studies in Mexico City and Luis Ureña López of the University of Guanajuato. At a workshop at the Central University of Las Villas (UCLV) in Cuba in June, they described how scalar particles can reproduce the internal structure of galaxies: when the particles clump on galactic scales, they overlap to form a Bose-Einstein condensate—a giant version of the cold atom piles that experimenters have created over the past decade. The condensate has a mass and den-

BRYAN J. MÉNDEZ *University of California, Berkeley*, AND KECK OBSERVATORY

GETTING BY IN CUBA

On my first visit to Cuba in 2002, scientists had to take me on circuitous routes around their campuses to avoid my being spotted by apparatchiks, and some research institutes were off limits to me entirely. This past June, I was the only American attending a cosmology workshop there; the U.S. government allows journalists to go but puts tight restrictions on researchers. Thus, Cuban scientists suffer the double whammy of two governments that put politics above the free exchange of ideas. But they make a virtue of penury, doing simple yet insightful science ignored in more developed nations. For instance, to probe complexity and self-organization, Ernesto Altshuler Álvarez of the University of Havana and his colleagues dribble beach sand from an hourglasslike contraption to form a pile. Rather than randomly joining the pile, the grains form a narrow stream running downslope. In the case of sand from one particular beach (and none other), this stream revolves around the pile, a behavior never before documented (see the September/October 2004 *American Scientist*).

sity profile matching those of real galaxies.

That inflation, dark energy and dark matter can all be laid at the doorstep of scalar fields suggests that they might be connected. Israel Quiros of UCLV argued at the workshop that the same field could account for both inflation and dark energy. Other physicists have worked on linking the two dark entities. "As my senior colleagues used to say, 'You only get to invoke the tooth fairy once,'" says Robert Scherrer of Vanderbilt University. "Right now we have to invoke the tooth fairy twice: we need to postulate a yet to be discovered particle as dark matter and an unknown source for dark energy. My model manages to explain both with a single field."

But all these models suffer from a nagging problem. Because the wavelength of a particle is inversely proportional to its mass, the astronomical size corresponds to an almost absurdly small mass, about 10^{-23} electron volts (compared with the proton's mass of 10^{9} electron volts). That requires the laws of physics to possess a hitherto unsuspected symmetry. "Such symmetries are possible, although they appear somewhat contrived," says physicist Sean Carroll of the University of Chicago. Moreover, the main motivation for big particles—their resistance to clumping—has become less compelling now that cosmologists have found that more prosaic processes, such as star formation, can do the trick. Still, as physicists cast about for some explanation of the mysteries of dark matter, it is inevitable that some pretty big ideas will float around.

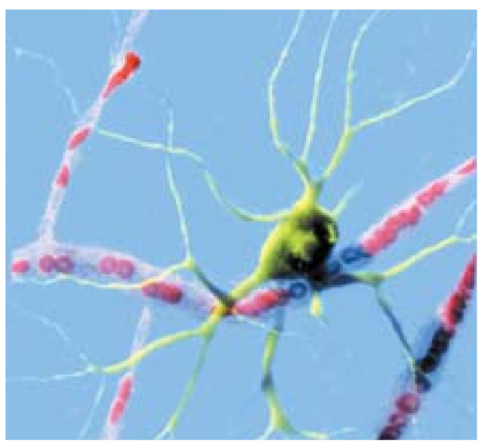
PROSTHETICS

Chemical Conversations

SYNAPSE CHIP ADOPTS THE NEURON'S TONGUE **BY NICOLE GARBARINI**

If you want to blend in with the locals, it helps to speak their language. So when Stanford University scientists wanted to converse with retinal and other nerve cells, they looked to the language of neurotransmitters. Nerve cells release these chemicals into a specialized adjacent gap called a synapse, enabling them to communicate with neighboring cells. Creating a device that speaks the neurons' lingo will contribute to a new generation of implantable substitutes for some retinas compromised by macular degeneration. Such "artificial synapse chips" might replace other kinds of diseased neurons, too.

Neurons normally convert chemical messages into electrical impulses, so the conventional strategy in creating artificial retinas involves electrically stimulating remaining healthy nerve cells. But the Stanford group says that chemical stimulation has various advantages over electrical stimulation. One major plus stems from the fact that neurons use different neurotransmitters to fine-tune the responses they evoke. Moreover, the same neurotransmitter can induce different responses depending on the target cell's



NERVE CELLS signal one another via chemicals, a strategy behind a nascent breed of prosthetics.

DAVID BECKER *Science Photo Library*

characteristics. “Not all pathways are equal,” states team leader Harvey Fishman, who directs the Stanford Ophthalmic Tissue Engineering Laboratory. Electrical stimulation could indiscriminately activate functions in the neighboring cell.

The Stanford chip, with an active area just smaller than a pencil eraser, releases minute and precise quantities of fluid. Rather than a pumping mechanism, a low electric field prompts fluid movement from reservoirs, through tiny channels and out of holes on the chip’s surface. “Ink-jet printers use this technology to propel fluids from a cartridge to a page,” Fishman states. “We’ve adapted this technology to project fluids on the scale of subcellular distances.” In the team’s study, the researchers showed that neurotransmitterlike chemicals spritzed from this chip could activate pathways in cells and mimic what happens in neuronal communication.

Turning the artificial synapse chip into a retinal prosthesis, however, will take several years. “The two biggest engineering improvements needed are more stimulation sites, while retaining control over each one, and biocompatible materials,” explains Mark Peterman, one of Fishman’s collaborators. The current chip contains only four apertures, whereas an artificial retina chip would need thousands of apertures to imitate the normal retina’s array of stimulatory inputs. The chip designers will also have to tackle issues such as whether or not the channels could get clogged by cells or scar tissue after implantation. Additionally, whereas the Stanford chip has appropriate lateral dimensions, its thickness will have to be reduced to make it thinner than the width of two human hairs, the approximate width of the human retina.

Mark Humayun, an ophthalmologist at the University of Southern California who designed one of the original electric retinal prosthetics, notes some drawbacks in the practicality of using the artificial synapse chip, such as fastening the chip to within a synapse’s distance of its target in a moving eye. But he adds that “it could be the next stage of a retinal prosthesis and is very exciting.”

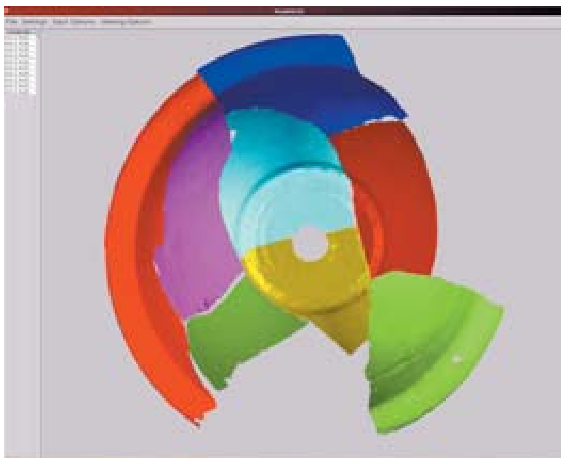
GEOMETRY

Piecing the Past

AN ALGORITHM QUICKLY FITS TOGETHER POTSHERDS **BY LISA DEKEUKELAERE**

A 1,000-piece jigsaw puzzle of the Rocky Mountains not challenging enough? Imagine assembling it without knowing how it looked or if all the pieces were there. And what if the pieces actually made up several separate puzzles? Now pretend the pieces are three-dimensional and 4,000 years old.

That's what archaeologists face when they find the scattered remnants of cups, bowls and other containers. Putting the fragments together can provide vital clues about the culture of interest, but the process can take months.



EIGHT-PIECE SET: A computer program provides a virtual glimpse of an urn after quickly fitting together eight of the 13 fragments. The algorithm could prove to be a boon to archaeology.

FROM "STOCHASTIC 3D GEOMETRIC MODELS FOR CLASSIFICATION, DEFORMATION, AND ESTIMATION," PH.D. THESIS, ANDREW WILLIS, BROWN UNIVERSITY, 2004

Recently computer-vision engineers Andrew R. Willis and David B. Cooper of Brown University developed a program that can assemble and model a 13-sherd pot in less than two hours using only 10 of its pieces. Researchers have been devising methods that assemble 2-D jigsaw puzzles and compare 3-D data sets for almost 20 years, but Willis and Cooper are the first to combine developments in piece matching and shape modeling in the assembly of pots. They got going thanks to Martha Joukowsky, an archaeologist at Brown, who proposed the idea.

In reconstructing a pot, archaeologists first sort potsherds based on color, curvature, thickness and visible designs. From there, they "match them by feel, trying to see which sherd clicks into another sherd," explains Joyce C. White, an archaeologist at the University of Pennsylvania.

For an engineer, "assembling a pot from the sherds involves solving the huge combinatorics problem of comparing all the pieces," Willis says. "It is difficult because pieces can match for any length along any boundary, and there are an infinite number of relative alignments between two boundaries." The trick is getting a computer to "see" the pieces and make visual inferences, as a human would. Willis and Cooper created an algorithm that translates specific visual points of comparison into calculable mathematical differences.

The program works with 3-D image scans of the potsherds. Reassembling a pot involves assigning scores to groupings of sherds based on how well they match up—namely, the fit between edges and the consistency of the global surface geometry. "The resulting surface that you generate when you put two pieces together should look like something that came off of a potter's wheel," Willis remarks. By keeping a running stack of these scores while trying new configurations, the program produces a set of pieces with the highest probability of resembling a valid pot. Recent advances in computing power allow scoring and comparisons to be done reasonably quickly, but reconstruction can still be time-consuming, because missing pieces force the program to infer the overall shape of the pot.

In the future, Willis and Cooper hope to tackle a wider variety of objects. "Eventually we would like to be able to reconstruct whole sites—statues, column capitals, et cetera—based only on measurements from the site," Cooper says.

Although this research represents a breakthrough in reconstruction, many puzzles remain that can be solved only by the scientists themselves. "Archaeology is all about context," White explains. "There is no magic bullet. While in theory often the computer is very helpful, sometimes it just helps you use your own brain better."

ASSEMBLY REQUIRED

Once an archaeologist knows the shape and style of a reconstructed pot, the contextual location of the sherds can be used to help develop the overall cultural picture. For example, if the sherds were found at a grave site, one can infer differences in the way men and women were treated based on the characteristics of the pottery with which they were buried.

Oil Haves and Have-Nots

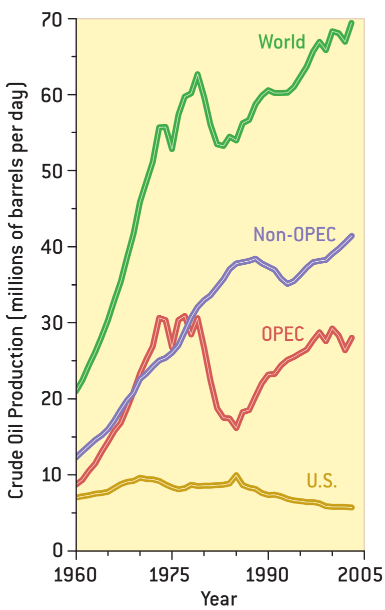
THE FOSSIL FUEL AGE WILL END, BUT FEW AGREE ON WHEN **BY RODGER DOYLE**

To some geologists, the world is heading toward an oil crisis of historic proportions. The crisis will come, they say, not when the wells go dry, but when world oil production reaches a peak and begins to decline. At that time, prices are likely to rise precipitously unless demand, which has been growing year by year, also declines.

There is, however, little agreement on when the peak production will occur. For example, the Energy Information Administration (EIA) of the U.S. Department of Energy has made several projections, with the shortfall happening at the earliest in 2021 and at the latest in 2112. Others—such as geologist Colin Campbell, chair of the Association for the Study of Peak Oil and Gas in Uppsala, Sweden—suggest the peak may occur as early as 2005; geophysicist Kenneth Deffeyes of Princeton University says the peak will definitely be next year. Economist Morris Adelman of the Massachusetts Institute of Technology insists that "for the next 25 to 50 years, the oil available to the market is for all intents and purposes infinite." The difference between oil optimists and oil pessimists is crucial, for if the pessimists are correct, there will be insufficient time for an orderly transition to alternative energy sources.

The variable estimates over the timing of the peak may exist in part because official agencies such as the EIA are under intense pressure not to throw the markets into a panic by coming out with pessimistic forecasts. But differences also arise from the lack of agreed-on data regarding oil reserves. The best known information on reserves comes from the U.S. Geological Survey, which estimates that before extraction began in the 19th century a total of 3.3 trillion barrels lay in the ground. Only 0.7 trillion barrels have been extracted, implying that the peak oil production still lies many years away.

Campbell and others assert that these estimates are far too high because countries exaggerate the amount of petroleum still in the ground. Such a revision apparently happened in the late 1980s, when six OPEC countries increased their stated reserves by huge margins, apparently to boost their export quotas, which are the basis for computing reserves. Companies also have a stake in exaggeration, as in the recent case of the Royal/Dutch Shell Group, which admitted that its "proven reserves" were 20 percent less than originally stated. Critics also point out that global discovery of new oil fields peaked in the 1960s and has been declining ever since. Oil optimists say that new techniques of discovery and retrieval will keep production high for many years to come, thus forestalling an early peak in production.



SOURCE: U.S. Energy Information Administration

The coming decline of oil could lead to a worldwide depression and exacerbate existing tensions among oil importers. China, with its sharply rising demand, vigorously competes with Japan for Siberian oil, and the U.S., Russia and Iran are all in a diplomatic tussle to control oil in Kazakhstan and Azerbaijan. Instability in Saudi Arabia could draw the U.S. deeper into military involvement in the Persian Gulf. Despite these troublesome prospects, no U.S. administration of the past two decades has put much effort into planning for a change to a new energy economy.

Rodger Doyle can be reached at rdoyle2@adelphia.net

PUMP IT OUT, PUMP IT IN

Crude oil imports and exports in 2003, in millions of barrels per day:

Leading Importers	
U.S.	11.2
Japan	5.5
Germany	2.5
China	2.0

Leading Exporters	
Persian Gulf states	18.7
Russia	5.5
Norway	3.3
Venezuela	2.2

FURTHER READING

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Association for the Study of Peak Oil and Gas: www.peakoil.net/

RODGER DOYLE

BIOCHEMISTRY

Location, Location, Location

Rather than having single, specific jobs, as long thought, enzymes can switch functions instantly depending on their place in the cell. Biochemists investigated enzymes known as desaturases in the weed *Arabidopsis*. The enzymes desaturate fat by removing hydrogen atoms from chains of fatty acids to create molecular bonds. Plant cells can tag desaturases so that they go to chloroplasts, where photosynthesis occurs. Without the tags, these desaturases instead entered the endoplasmic reticulum, where they forged bonds in different places along the fatty acid chains. Roughly 4 percent of *Arabidopsis*'s protein families possess variations in tags—substantial enough to suggest that multifunctional enzymes could help organisms adapt to changes in the environment. This property could lead to new crops with healthier, less saturated fats, according to researchers at Brookhaven National Laboratory and the University of California at Riverside, who report their findings in the July 13 *Proceedings of the National Academy of Sciences USA*. *—Charles Choi*

PALEOANTHROPOLOGY

Paleolithic Pensioners

The number of humans surviving to old age more than quadrupled about 30,000 years ago. Anthropologists looked at more than 750 fossil dental samples of hominids across millions of years, from australopithecines to Neandertals to early modern humans. Old age was defined as at least double the age at which reproductive maturity was reached, which is also the time when the third molars usually erupt—typically, in the teen years. In calculating the ratio of old-to-young hominids, Rachel Caspari of the University of Michigan at Ann Arbor and Sang-Hee Lee of the University of California at Riverside found a trend of increased longevity across the human family tree during evolution. With modern humans, older adults outnumbered younger ones for the first time. The boost in longevity may have been critical in the development of human culture, as elders passed down knowledge and helped to knit together complex societies. Their study appears in the July 13 *Proceedings of the National Academy of Sciences USA*. *—Charles Choi*

OBESITY

Cracked Caloric Counter

Artificially sweetened drinks might not help the diet, because they might make it harder for the body to know when to stop scarfing. Given a choice between flavored high- and low-calorie liquids, rats guzzle the high-calorie stuff. Susan Swithers and her colleagues at Purdue University fed rats a sugary liquid and one sweetened with zero-calorie saccharin, thereby confounding the rats' association between sweetness and calories. Ten days later, after munching a chocolaty appetizer, these rats subsequently gobbled more food than a group of control rats that had never tasted saccharin. The link between food viscosity and satiety can be disrupted, too: rats given a liquid chocolate supplement also gained more weight than rats presented with an equal-calorie puddinglike treat. The research appears in the July *International Journal of Obesity*. *—JR Minkel*

SWEET CONFUSION: Making weight loss tough?

SCALED COMPOSITES (*top*); RICHARD HAMILTON SMITH *Corbis* (*bottom*)

DATA POINTS: HIGH FLIERS

The first completely private manned spacecraft, called SpaceShipOne, successfully completed a suborbital flight on June 21. Designed by Burt Rutan of Scaled Composites and backed by billionaire Paul G. Allen, the ship is the favorite to capture the Ansari X Prize, an award of $10 million to the first firm that provides three passengers two flights within two weeks.

Approximate altitude, in kilometers, reached by:

Commercial 747 jet: 14

U2 spy plane: 23

SpaceShipOne: 100

Space shuttle: 300 to 560

International Space Station (ISS): 360

GPS satellites: 20,000

Geosynchronous satellites: 36,000

Cost of a suborbital flight through Space Adventures, a firm that offers space experiences: $102,000

Initial deposit: $6,000

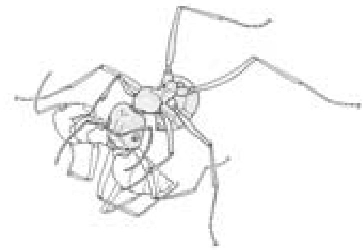
Number who have paid deposit: at least 100

Cost to go to the ISS via a Russian Soyuz ship: $20 million

SOURCES: Scaled Composites; NASA; Space Adventures

ENTOMOLOGY

No Place Like Home



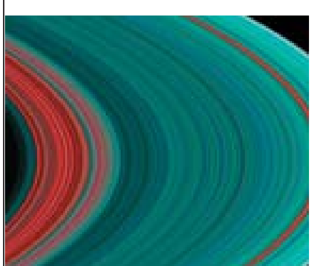
Saharan desert ants fly into rages to defend their homes, but unlike other territorial animals, they do so apparently because their onboard navigation system tells them to. When close to home, the members of *Cataglyphis fortis* employ threats, bites and poisonous acid sprays against strangers. Their aggression fades, however, when they are more than a few meters from their nests. Markus Knaden and Rüdiger Wehner of the University of Zurich first trained ants to forage at feeders 20 meters north of their nests and later abducted them the instant they reached the feeders. On release in a field kilometers away, the ants immediately ran 20 meters straight south to where their homes should be. Ants that completed this homeward dash proved about three times more likely to start fights than ants interrupted five meters into the run. The researchers surmise in the July 2 *Science* that a hardwired navigation system computes distance and controls the ants' will to fight. *—Charles Choi*

DESERT ANT *Cataglyphis fortis* near its home (*above*) readily goes into battle (*line drawing*).

ASTRONOMY

Ringed Up

The Cassini-Huygens spacecraft completed its serpentine, nearly seven-year journey on June 30, slipping through a gap in Saturn's rings to settle into orbit. The $3-billion international craft took detailed visible, infrared and ultraviolet images of the rings. They revealed clumps, kinks, spiral ripples and scalloped edges, which result from the gravitational tug of surrounding moons, along with unidentified material between some rings. Saturn's A ring, the middlemost one, contains more icy particles (*turquoise in photograph*) in its outer regions relative to the thinner Cassini division bordering it on the inside, which harbors fewer, possibly dirtier particles (*light red*). (The red ring three quarters of the way out is known as the Encke gap.) On July 2 Cassini passed near the south polar regions of the moon Titan. It captured haze-filtered images of dark water-ice patches, which researchers had suspected were methane lakes, and bright regions of hydrocarbon frost on the surface, along with very bright spots indicating tiny clouds. By this fall, Cassini should have made movies of Saturn's weather. *—JR Minkel*



"A" RING in ultraviolet.

PHYSICS

Full Entangled House

Entanglement—the weird quantum property in which one particle instantly knows what has happened to a distant partner particle—appears to be essential for performing steps in a quantum computation. A group from the University of Science and Technology of China has entangled five particles, one more than the previous record and the minimum needed for standard error correction. The researchers first created two entangled photon pairs, sent one photon from each pair through a beam splitter to entangle them, and then sent one of the remaining photons through a beam splitter with a fifth photon, thereby entangling all five photons. The entanglement allowed them to re-create, or "teleport," the quantum state of one photon among the five to any of three others (using the fourth as an intermediary), instead of to a predetermined one as in previous demonstrations. Although a quantum computer probably would not run entirely on photons, manipulating them is key for quantum communications. See the July 1 *Nature*. *—JR Minkel*

BRIEF POINTS

- **Natural decaf: A type of *Coffea arabica* plant in Ethiopia lacks an enzyme for caffeine synthesis. It could lead to better-tasting caffeine-free coffee.**

  Nature, June 24, 2004

- **At least three transplant recipients have died from rabies contracted from the lungs, kidneys and liver from an Arkansas donor who was bitten by a bat. Rabies treatment was needed for at least 174 others who may have been exposed through the victims.**

  Morbidity and Mortality Weekly, July 9, 2004; www.cdc.gov

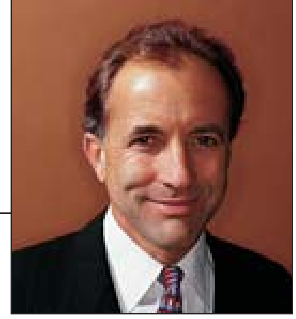
- **People with major depressive disorder have about one third more neurons than average in a region of the thalamus that regulates emotion, suggesting that anatomical abnormalities underlie the condition.**

  American Journal of Psychiatry, July 1, 2004

- **Adding a pinch of iron to an alloy whose temperature is governed by a magnetic field boosts the alloy's cooling capacity by 15 to 30 percent, pushing magnetic refrigeration a step closer to practicality.**

  Nature, June 24, 2004

EVA WEBER (*top, line drawing*); RÜDIGER WEHNER (*top, photograph*); NASA/JPL/UNIVERSITY OF COLORADO (*bottom*)


BRAD HINES

Mustangs, Monists and Meaning

The dualist belief that body and soul are separate entities is natural, intuitive and with us from infancy. It is also very probably wrong   By MICHAEL SHERMER

When I was 17 in 1971, I purchased my dream car—a 1966 Ford Mustang—blue with a white vinyl roof, bucket seats and a powerful eight-cylinder 289-cubic-inch engine that could peg the speedometer at 140 miles per hour. As testosterone-overloaded young men are wont to do, however, over the course of the next 15 years I systematically wrecked and replaced nearly every part of that car, to the extent that by the time I sold it in 1986 there was hardly an original piece remaining. Nevertheless, I turned a tidy profit because my "1966" Mustang was now a collector's classic. Even though the physical components were not original, the essence of its being—its "Mustangness"—was that model's complete form. My Mustang's essence—its "soul"—was more than a pile of parts; it was a pattern of information arranged in a particular way.

The analogy applies to humans and souls. The actual atoms and molecules that make up my brain and body today are not the same ones that I was born with on September 8, 1954, a half-century ago this month. Still, I am "Michael Shermer," the sum of the information coded in my DNA and neural memories. My friends and family do not treat me any differently from moment to moment, even though atoms and molecules are cycling in and out of my body and brain, because these people assume that the basic pattern remains unchanged. My soul is a pattern of information.

Dualists hold that body and soul are separate entities and that the soul will continue beyond the existence of the physical body. Monists contend that body and soul are the same and that the death of the body—the disintegration of DNA and neurons that store my personal information—spells the end of the soul. Until a technology is developed to preserve our patterns with a more durable medium than the electric meat of our carbon-based protein (silicon chips is one suggestion), when we die our patterns die with us.

The principal barrier to a general acceptance of the monist position is that it is counterintuitive. As Yale University psychologist Paul Bloom argues in his intriguing book, *Descartes' Baby* (Basic Books, 2004), we are natural-born dualists. Children and adults alike speak of "my body," as if "my" and "body" are dissimilar. In one of many experiments Bloom recounts, for example, young children are told a story about a mouse that gets munched by an alligator. The children agree that the mouse's body is dead—it does not need to go to the bathroom, it can't hear, and its brain no longer works. Yet they insist that the mouse is still hungry, is concerned about the alligator, and wants to go home. "This is the foundation for the more articulated view of the afterlife you usually find in older children and adults," Bloom explains. "Once children learn that the brain is involved in thinking, they don't take it as showing that the brain is the source of mental life; they don't become materialists. Rather they interpret 'thinking' in a narrow sense and conclude that the brain is a cognitive prosthesis, something added to the soul to enhance its computing power."

The reason dualism is intuitive is that the brain does not perceive itself.

The reason dualism is intuitive is that the brain does not perceive itself and so ascribes mental activity to a separate source. Hallucinations of preternatural beings (ghosts, angels, aliens) are sensed as real entities, out-of-body and near-death experiences are perceived as external events, and the pattern of information that is our memories, personality and "self" is sensed as a soul.

Is scientific monism in conflict with religious dualism? Yes, it is. Either the soul survives death or it does not, and there is no scientific evidence that it does. Does monism extirpate all meaning in life? I think not. If this is all there is, then every moment, every relationship and every person counts—and counts more if there is no tomorrow than if there is. Through no divine design or cosmic plan, we have inherited the mantle of life's caretaker on the earth, the only home we have ever known. The realization that we exist together for a narrow slice of time and a limited fraction of space elevates us all to a higher plane of humanity and humility, a passing moment on the proscenium of the cosmos. SA

Michael Shermer is publisher of Skeptic *(www.skeptic.com) and author of* The Science of Good and Evil.

Superhot among the Ultracool

With atoms near absolute zero, Deborah S. Jin created a Fermi condensate—opening a new realm in physics that might lead to room-temperature superconductivity By MARGUERITE HOLLOWAY

The small room is dominated by a long metal table littered with lasers, mirrors, metal coils, glass cells and hundreds of tubes. A video screen captures the demonstration of the moment: a white blob in a halo of gray on black. This fuzzy image represents chilled potassium atoms, and although it doesn't look like much, it is the heart of Deborah S. Jin's remarkable work in quantum physics.

DEBORAH S. JIN: USING A COOL HAND

- Chilled potassium 40 atoms to 50 billionths of a degree above absolute zero to observe the mysteries of quantum behavior.
- Won a MacArthur "genius" award in 2003.
- Her approach has proved influential: "Frankly, most of the interesting science is coming out of groups following in her footsteps," says Nobel laureate Eric A. Cornell, who had the foresight to hire Jin for his JILA lab.

Jin, a fellow at JILA (a collaboration between the National Institute of Standards and Technology and the University of Colorado at Boulder), has pushed potassium atoms into behaving strangely. She has cooled them just shy of absolute zero (–459 degrees Fahrenheit) and observed their funky quantum doings, leading the way into an unexplored realm that holds implications for superconductivity—the creation of resistance-less electrical flow.

Jin's field took off in 1995 after two of her now colleagues produced a Bose-Einstein condensate (BEC), a gas cooled to less than 100 billionths of a degree above zero. In this form, thousands or millions of atoms enter an identical quantum state and act like a single gargantuan atom. The technique, however, worked only for bosons, one of the two families of elementary particles—including photons and atoms with an even number of protons, neutrons and electrons.

Getting fermions, the other family of particles, to act in quantum concert was an even more daunting undertaking. Fermions are the basic building blocks of ordinary matter and include electrons, protons and neutrons individually, as well as atoms with an odd number of those constituents. Unlike bosons, fermions are misanthropes; the Pauli exclusion principle prohibits them from existing in the same quantum state. Then Jin took them in hand.

Jin arrived at JILA to work as a postdoc in Eric A. Cornell's lab just months after he and Carl E. Wieman created the first BEC. Within two years, she had been hired by JILA, where she was especially happy to get an appointment because her husband, John L. Bohn, a theoretical atomic physicist with whom she collaborates, also works there. Within four years, Jin had produced a degenerate Fermi gas, the initial step in creating a fermionic condensate. Last December she made the first Fermi condensate, which may indicate how to achieve room-temperature superconductivity.

"She brings a really quite amazing sense of focus to

ANDY CROSS *Denver Post*

the field," says Cornell, who won the 2001 Nobel Prize in Physics with Wieman and Wolfgang Ketterle of the Massachusetts Institute of Technology. "She has a very good instinct for understanding what is really the key problem and the key question and zooming in and addressing them very directly."

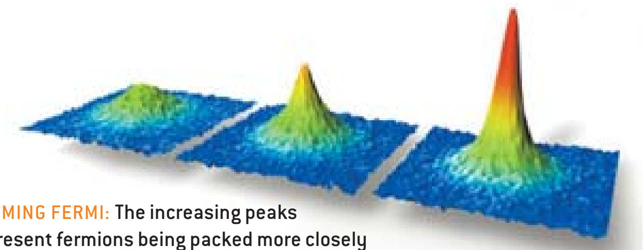
Jin's accomplishments are particularly remarkable because she was not trained in the area of physics in which she has excelled: she had neither the technical expertise needed for BEC work nor the background. "I have to say, Eric was really brave," recalls the 35-year-old Jin. "I didn't use lasers. I didn't use optics. I didn't come from atomic physics."

The daughter of physicists, Jin says she was not steeped in physics but rather in a way of thinking: "Scientists have a certain bias, a certain way of looking at things, and that sort of permeated everything more than actually talking about science." She recalls that her first research experience turned her off biological science—that and dissection. In high school, Jin worked on an agricultural engineering project at the University of Florida identifying uncapped water wells, which would have been fine, she notes, if not for the cow studies also going on there. "They were doing things like—I just find this ridiculous—dripping water on cows and then blowing fans on them to cool them off," she laughs. "I was just not properly impressed."

In 1986 Jin entered Princeton University and started taking physics, which initially didn't excite her. But a summer NASA internship, helping out with sample-collecting space probes, changed her mind: "Seeing scientists design something ... and then it would go and get built, that aspect made physics much more appealing." Jin went on to doctoral work in superconductivity with Thomas F. Rosenbaum at the University of Chicago. "She has incredible intellectual integrity," Rosenbaum remarks. "If you would say something she didn't think was quite right, she was quite forceful about probing why you were maintaining that view. She was nice enough not to call me an idiot when I was wrong." It is true that even in casual conversation Jin is thoughtful about every question, precise about every image, gentle yet firm in clarifying the details and implications of her experiments.

Shortly after arriving at JILA, Jin was effectively put in charge of Cornell's lab and began to figure out how to produce BECs consistently, no small feat then. To cool atoms to near absolute zero, physicists rely on systems of lasers and magnetic fields to trap atoms. Hotter atoms must be expelled from the trap, thereby removing energy; such cooling must continue until a condensate forms. Once Jin mastered BECs, she set out on the fermionic frontier.

In 1999 Jin and her then graduate student Brian DeMarco made a degenerate Fermi gas, which means they persuaded fermions to stack up in the lowest quantum states, one per state. Jin's approach was different from that of most other competing labs. Those researchers chose to work with lithium, which has a natural interaction that is strongly attractive—a property that should make a Fermi condensate more likely to form. But they needed to use two isotopes of lithium to do the cooling, and each one required its own set of lasers. Jin figured she could use one type of atom—the fermion potassium 40—and put it in two spin states. (An atom's spin relates to its behavior in magnetic fields.) If they had different spins, fermions could collide and exchange energy, and Jin could shoo away the higher-energy ones until only very cool fermions remained. "She was the first to work on potassium, and that turned out to be a shortcut," Ketterle says. Jin's technique required fewer lasers and a simpler setup. "It was really technologically much easier," Jin confides.



FORMING FERMI: The increasing peaks represent fermions being packed more closely together and interacting more strongly in the creation of a condensate.

MARKUS GREINER *JILA*

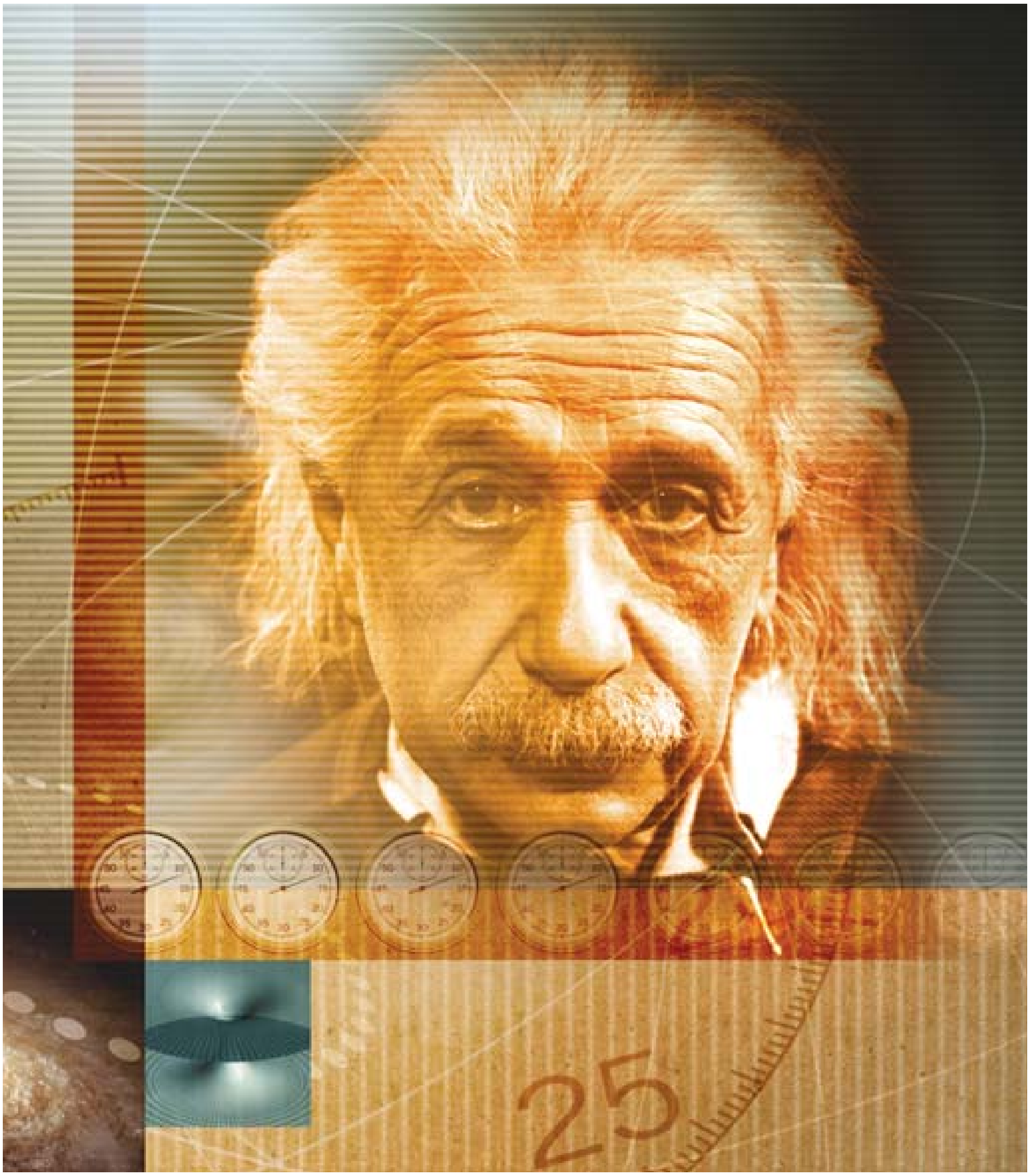
The next goal was to get fermions strongly attracted to one another. Using what she describes as a "powerful magic knob," Jin fiddled with magnetic fields to induce so-called Feshbach resonances to control interactions between potassium 40 atoms, making them more or less attracted to one another. "When I started my research, these resonances hadn't been seen," Jin relates.

Working her magic last November, Jin and her current team—Markus Greiner and Cindy A. Regal—made molecules of fermions, thereby creating bosons, and then a condensate of those bosons. (Fermions have half-integer spins, whereas bosons rotate in whole-number spins; two fermions together can make a boson.) Rudolf Grimm of the University of Innsbruck in Austria did the same with lithium, publishing just ahead of Jin.

Jin's group then grabbed the grail at the very end of the year. She showed that her fermions did not exist as molecules—that is, they had not become chemically bound together. Rather they existed as strongly interacting pairs, much as the electrons in superconductivity do. "But the difficulty with the Fermi condensate was how to see it," she states. Indeed, her results were initially questioned. Now, Ketterle notes, "there is no doubt she has entered a very rich and interesting region."

Jin is clearly thrilled about the theoretical and experimental unknowns. "We are in a regime that is not well described by BEC or the theory of superconductivity," she says. The pairing of the fermions was strong enough, Jin adds, so that "I think it tells you that it is possible to have room-temperature superconductors." Although the competition is fierce and travel often takes Jin away from her young daughter, she revels in the quantum world: "It is not intuitive. Things happen that you don't expect." Just what she likes. SA

THE PATENT



TOM DRAPER DESIGN; EINSTEIN PHOTOGRAPH BY PHILIPPE HALSMAN, © 1947 PHILIPPE HALSMAN ESTATE

CLERK'S LEGACY

In 1905 the musings of a functionary in the Swiss patent office changed the world forever. His intellectual bequest remains for a new generation of physicists vying to concoct a theory of everything

By Gary Stix

Albert Einstein looms over 20th-century physics as its defining, emblematic figure. His work altered forever the way we view the natural world. "Newton, please forgive me," Einstein begged as relativity theory wholly obliterated the absolutes of time and space that the reigning arbiter of all things physical had embraced more than two centuries earlier.

With little more to show than a rejected doctoral thesis from a few years before, this 26-year-old patent clerk, who practiced physics in his spare time and on the sly at work, declared brashly that the physicists of his day were "out of [their] depth" and went on to prove it. Besides special and general relativity, his work helped to launch quantum mechanics and modern statistical mechanics. Chemistry and biotechnology owe a debt to studies by Einstein that supplied evidence of the existence of molecules and the ways they behave.

What is even more amazing is that he purveyed many of these insights through a series of papers that appeared during a single miraculous year, 1905. No other comparably fertile period for individual scientific accomplishment can be found except during 1665 and 1666, the original *annus mirabilis,* when Isaac Newton, confined to his country home to escape the plague, started to lay the basis for the calculus, his law of gravitation and his theory of colors. The international physics community has set aside 2005 as the World Year of Physics as a tribute to Einstein's centennial.

Scientists in many realms of physics and engineering spent the 20th century testing, realizing and applying the ideas falling out of Einstein's work. As everybody knows, Einstein's $E = mc^2$ formula was a key to the atomic bomb—and all the history that sprang from it. Einstein's explanation of the photoelectric effect underpinned technologies ranging from photodiodes to television camera tubes [see "Everyday Einstein," by Philip Yam, on page 50]. A hundred years later technologists are still finding new ways to harvest novel inventions from Einstein's theories.

One mark of genius relates to the length of time needed to fully explore, through experimentation, the implications of a new theory. In that sense, Einstein is still going strong. A recently launched space probe will examine various predictions of general relativity. But physicists are not waiting until the answers are all in before asking what comes next. Much of the most exciting work in physics now has the more ambitious aim of going beyond Einstein—of transcending his ideas and achieving a task akin to the one to which he devoted the last 30 years of his life, right to his deathbed, without success.

It is clear that general relativity and particle physics form an incomplete description of physics, because the latter is fundamentally quantum-mechanical, and general relativity and the quantum go together like oil and water. Despite decades of effort, Einstein was never able to find a theoretical framework for uniting relativity and electromagnetism. He had hoped to formulate a physics based on certitudes, not the probabilities and acausal realities of quantum mechanics—just the things that had turned him away from a field he helped to found. A current generation of scientists is laboring on their own theories of everything, armed with a much more complete description of fundamental physical forces than Einstein used, while approaching the challenge without a preexisting bias against quantum mechanics. The rewards for succeeding in this endeavor? For the physicist who prevails, they might include immortality of the kind attached to the names Einstein and Newton. For the rest of us, they may provide a glimpse into nature and new technologies as incomprehensible to us now as black holes and quantum computers would have been 100 years ago.

To go beyond Einstein, one must first understand the totality of his accomplishments. In the spring of 1905 the young "patent slave," as Einstein called himself, sent a letter to his friend Conrad Habicht to tell him that he had some "inconsequential babble," a reference to a series of papers that he was going to send him. The only one of the bunch he called "very revolutionary" did not deal with relativity, but it did gain him the 1921 Nobel Prize, awarded in 1922. "On a Heuristic Point of View Concerning the Production and Transformation of Light," completed in March, expropriates and extends Max Planck's idea of quanta—that energy from hot objects can be emitted or absorbed only in certain discrete bundles.

In the paper, one of five major offerings during 1905, Einstein applied the concept of quanta to explain the photoelectric effect, how a piece of metal charged with static electricity would discharge electrons when exposed to light. He suggested that the beam of light is made up of particles, later known as photons, thus contradicting the prevailing notion that light was only wavelike. The paper, published in June in *Annalen der Physik,* paved the way for the acceptance of the dual nature of light as both particle and wave, which became a foundation of quantum mechanics. The photoelectric effect went on to become the basis for various technologies.

At that time, Einstein still had not yet received a doctorate. The University of Zurich had rejected a thesis he had submitted in 1901—an unexceptional work on the kinetic theory of gases. Einstein had all but discarded the idea of undergoing what he called the "comedy" of getting his advanced degree. But he decided to try again in 1905. According to his sister, Maja, he first submitted his paper on special relativity, but the university found it a "little uncanny." He then picked "A New Determination of Molecular Dimensions," which he finished on April 30 and which was accepted in July. It was reportedly inspired by a conversation over tea with his best friend, Michele Besso, in which Einstein mused about relating the viscosity of the liquid to the size of the dissolved sugar molecules. By considering a collection of such molecules, Einstein derived a mathematical term that measured the speed of diffusion. It was then possible to elicit the size of the sugar molecules by contemplating the diffusion coefficient and the viscosity of the solution.

A few days after completing this article, Einstein finished a related paper that was also intended to provide a guarantee of "the existence of atoms of definite size"—atoms were a still controversial idea in some circles. "On the Motion of Small Particles Suspended in Liquids at Rest Required by the Molecular-Kinetic Theory of Heat," published in July in *Annalen,* supplied a prediction of the number and mass of molecules in a given volume of liquid—and how these molecules would flit around. The erratic movements were known as Brownian motion, after the observation by Robert Brown in the early 19th century of the irregular zigs and zags of particles inside pollen grains in water. Einstein suggested that the movements of the water molecules would be so great that they would jostle suspended particles, a dance that could be

Chronology of an Extraordinary Life

Earliest known photograph of Albert Einstein

1879 — **Born** in Ulm, Germany. The town's motto: "The people of Ulm are mathematicians"

1895 — At age 16, writes **his first scientific essay,** "On the Investigation of the State of the Ether in a Magnetic Field"

1897 — **Meets engineer Michele Besso,** who will be a lifelong friend and a sounding board for Einstein's ideas

1900 — **Graduates** from Zurich Polytechnic

1901 — **Becomes Swiss citizen**

1902 — **Father, Hermann, dies**

1902 — **Daughter, Lieserl, born** out of wedlock to him and Mileva Marič. Her eventual fate is unknown; she may have died or been given up for adoption. **Starts work** at the patent office in Bern

1903 — **Marries** Mileva Marič

1904 — **Son Hans Albert born** (d. 1973)

1905 — Completes writing of seminal papers published in *Annalen der Physik,* a prominent German physics journal, during his **"miraculous year"**

"On a Heuristic Point of View Concerning the Production and Transformation of Light" deals with **light quanta and the photoelectric effect**

"On the Motion of Small Particles Suspended in Liquids at Rest Required by the Molecular-Kinetic Theory of Heat" advances ideas about **Brownian motion and the existence of molecules;** the latter topic was also explored in his doctoral dissertation that year

"On the Electrodynamics of Moving Bodies" introduces the **special theory of relativity** and a new way of understanding the relation between space and time

"Does the Inertia of a Body Depend on Its Energy Content?" builds on the special relativity paper, to show that **mass and energy** are interchangeable

3. *Zur Elektrodynamik bewegter Körper;*
von A. Einstein.

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter

Detail from a reprint of Einstein's "On the Electrodynamics of Moving Bodies" witnessed under a microscope. This paper, an important contribution to modern statistical mechanics, derived methods that can be used to simulate the behavior of airborne pollutants or the ways in which the stock market fluctuates [see "Atomic Spin-offs for the 21st Century," by W. Wayt Gibbs, on page 56].

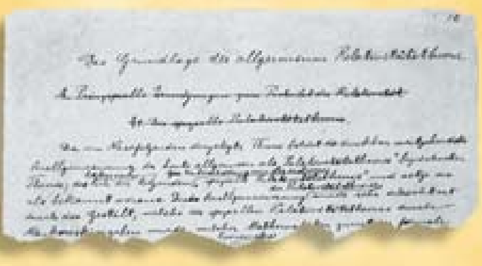
The next paper, completed in late June, was entitled "On the Electrodynamics of Moving Bodies." Relativity predated Einstein by hundreds of years. In 1632 Galileo suggested that all physical laws are the same regardless of your state of motion, as long as the velocity at which you cruise along does not change: viewed from the deck of a steadily moving ship, a rock dropped from the mast falls straight down, the same as it would if the ship were at rest. That relativity principle held for the laws of mechanics put forward by Newton in the mid-17th century. But this tidiness was upset in the late 19th century with the emergence of electromagnetism. Because the equations of James Clerk Maxwell showed that electromagnetic radiation moves through space in waves, physicists assumed that it coursed through a medium, the ether, the same way that sound waves do through air. Maxwell demonstrated that light and other electromagnetic waves race along at 300 million meters per second in a vacuum relative to the frame of reference of someone at rest in the ether. In an ether world, however, relativity would not hold for light. As soon as you budge from a state of rest, the speed of light would not measure 300 million meters per second anymore. Experimentalists, however, could never find the expected differences for moving objects. The speed of light always remained the same.

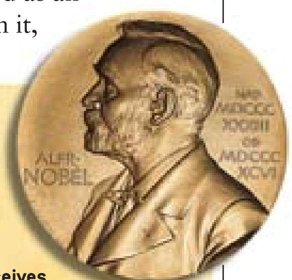
It was this inability to reconcile electromagnetism and the rest of physics that Einstein addressed. A scientist with a deep sense of aesthetics, he could not abide that the relativity principle did not account for electromagnetism as it did for Newtonian mechanics. The 1905 paper on special relativity, published in September of that year, reaffirms the principle for all of physics by applying it to electromagnetism and also establishes that the speed of light is a constant. While resolving the relativity paradox, the paper presented a new one, which strains our commonsense intuition of how things work: the speed of light remains the same whether someone is sitting in a rocking chair on the front porch or zooming along steadily in a futuristic spacecraft approaching light speed.

This constancy for light wreaked havoc with our idea of time and space as unchanging absolutes. Velocity boils down to distance divided by time. For light speed to remain unchanging on its side of the equation, both distance (length) and time had to be altered on the other when an observer in one frame of reference (the rocking chair) is watching someone move in another (astronauts in a spacecraft). Specifically, the man in a rocking chair will perceive time passing more slowly for the astronauts overhead. To him, the spacecraft will also shorten in the direction of motion.

If the rocking-chair man could somehow measure the mass of the astronauts as the spacecraft coursed along, he would also notice that they had gained mass since before its liftoff. The fifth and last paper of Einstein's miraculous year, published in November in *Annalen,* served as an addendum to his special relativity opus. In it,

- **1907** Has **"the happiest thought of my life"**—that gravity and acceleration are indistinguishable in a local frame of reference—allowing him to develop the theory of general relativity
- **1909** Appointed **Extraordinary Professor of Theoretical Physics** at the University of Zurich
- **1910** **Son Eduard born** (d. 1965)
- **1914** Appointed **professor at University of Berlin** and member of Prussian Academy of Sciences
- **1914** **Separates from Mileva;** she returns to Zurich with their sons
- **1916** Publishes **"The Foundations of the General Theory of Relativity"**
- **1917** Wrote paper that lay the foundation for stimulated emission of light **(the laser)**
- **1919** Learns via telegram that two British expeditions to observe the solar eclipse provide **evidence for his prediction in the general theory of relativity** that the gravitational field of the sun bends starlight
- **1919** **Divorces** Mileva and **marries** cousin Elsa Löwenthal (née Einstein), with whom he is living in Berlin
- **1920** **Mother, Pauline, dies**
- **1921** **Receives 1921 Nobel Prize in Physics** "for his services to theoretical physics and especially for his discovery of the law of the photoelectric effect"
- **1921** During his first visit to the U.S., Einstein is **treated like a hero** and a great scientist
- **1922** **Becomes member** of League of Nations Committee on Intellectual Cooperation
- **1922** Publishes his **first work on unified field theory;** will spend most of the rest of his life on an unsuccessful quest for a theory that unites all the laws of physics


Detail from manuscript of "The Foundations of the General Theory of Relativity"




Mileva and her two sons, Eduard (*left*) and Hans Albert


Einstein in New York motorcade

© HEBREW UNIVERSITY OF JERUSALEM (*1916 manuscript*); BROWN BROTHERS (*motorcade*); AP PHOTO (*Nobel medal*) he stated that the "mass of a body is a measure of its energy content," a concept that Einstein rephrased in 1907 as the most famous scientific equation of all time. $E = mc^2$ also applies to kinetic energy, the energy of motion. The faster the spaceship goes relative to the man in the rocking chair, the greater its kinetic energy and the greater its mass, making it increasingly difficult to accelerate. As the ship approaches the speed of light, the increments of energy needed to go faster are so large that additional acceleration becomes more and more onerous, one reason that a faster-than-light rocket ship remains only within the realm of science fiction.

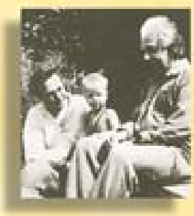
After 1905, the best was yet to come. As an intellectual achievement, the general theory of relativity, published in 1916, outshines anything that Einstein (or any physicist except maybe Newton) had done before or since then [see "Einstein and Newton: Genius Compared," by Alan Lightman, on page 108]. Mathematician Henri Poincaré almost beat Einstein to special relativity but refused to take the final but vital step of discarding the ether. The special theory had reconciled disparities in Newtonian mechanics and Maxwellian electromagnetism, but only for bodies in uniform motion, those traveling at constant speeds in straight lines. A general relativity theory was needed for the real world in which bodies change speed and direction—in other words, it would have to take into account the effects of acceleration, including that most universal of accelerations, gravity. Newton saw gravity as a force acting instantaneously over long distances, but Einstein reimagined it as an intrinsic property of space and time. A star or any massive body curves Einstein's space and time around it. Then planets move along the curved pathways in the spacetime continuum.

"The idea that mass warps spacetime and that warped spacetime tells mass how to move is pure genius," says Michael Shara, chair of the department of astrophysics at the American Museum of Natural History and curator of a recent exhibit on Einstein. "Physicists would eventually have discovered general relativistic effects on the basis of satellite and pulsar measurements but probably not until late in the 20th century. Even then, Einstein's elegant geometrical description of gravity might not have been fully replicated."

Soon after his general relativity paper, a 1919 experiment observed the sun's gravitational field deflecting rays of starlight passing through it during a solar eclipse, a prediction of the general theory. The evidence for general relativity made Einstein an instant media star, even though many in the crowds that thronged to see him would be hard-pressed to explain what the scientist had achieved. Apocryphally, Einstein was quoted as saying that only 12 people in the world understood relativity. Even if he really said it, the tiny number is a bit of an exaggeration. A devoted pack of Einstein aficionados emerged immediately. *Scientific American* even sponsored a contest, drawing hundreds of entrants for a $5,000 prize for the most understandable explanation of relativity. Einstein joked that he was the only one in his circle of friends not to participate. "I don't believe I could do it," he quipped. (See "A Century of Einstein," by Daniel C. Schlenoff, on page 102.)

From 1916 to 1925, Einstein made new contributions to quantum theory, including the work on stimulated emission of radiation that eventually resulted in the laser. But he be-

THE NEW YORK TIMES (*with Hubble*)



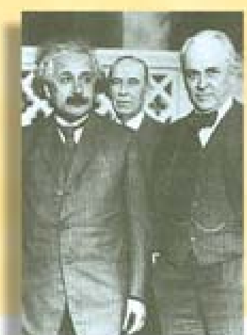
Einstein with son Hans Albert and grandson, Bernhard

1925 Publishes his prediction of **Bose-Einstein condensation**

1928 **Collapses** and is confined to bed for four months

1930 **First grandchild born,** son of Hans Albert. Eduard develops schizophrenia

1931 Meets with Edwin Hubble, who has just used the Doppler shift to prove that the universe is expanding, and Hubble convinces him of the existence of a big bang. Because of Hubble's theories, Einstein rejects his earlier idea of a **cosmological constant,** a mathematical term he had invented to model the universe as static



With Edwin Hubble (*right*)

1932 Fearing events in Germany and the rise of Hitler, Einstein and Elsa **depart for the California Institute of Technology,** intending to return to their home in Caputh the next year

Home in Princeton, N.J.

1933 Arrives at Princeton, N.J., to work at the new **Institute for Advanced Study**

His home in Caputh is **searched by Nazis,** who find nothing; Einstein's stepdaughter had arranged for his personal papers to be transferred secretly

1935 Paper written with **Boris Podolsky and Nathan Rosen** provides a critique of quantum mechanics

Sails to Bermuda to apply for an immigrant visa to America; it is the last time he leaves the U.S.

1936 Second wife, **Elsa, dies** of a heart and kidney disorder at age 60

1939 At the behest of Leo Szilard, among others, **signs letter to President Franklin D. Roosevelt** that recommends that the U.S. undertake research into nuclear weapons. Despite popular belief, this letter and his equation $E = mc^2$ are his only major contributions to the American effort to develop the atomic bomb came disenchanted with quantum mechanics as it embraced statistical probabilities instead of causal explanations to delineate what was happening in the world of subatomic particles. For the latter part of his life, until his death in 1955, Einstein concentrated on a unified field theory, which would not only reveal gravitational and electromagnetic fields as two aspects of the same thing but also explain the existence of elementary particles and constants such as the electron's charge or the speed of light.

These labors proved to be a dead end—in part because Einstein rejected the new turn that quantum physics had taken and in part because two fundamental nuclear forces (the strong and the weak) were not well understood until years after his death. "Even devoted admirers of Einstein would not dispute that the progress of physics would not have suffered unduly if the indisputably greatest scientist among them had spent the final three decades of his life—roughly from 1926 on—sailing," noted Albrecht Fölsing in a 1993 biography, referring to one of Einstein's hobbies. Others are more charitable. The physicist may simply have been ahead of his time: "The ongoing quest for a theory of everything is Einstein's most significant legacy to science," observes Ze'ev Rosenkranz, former curator of the Einstein papers.

That search still serves as the main focus of a prominent sector of the theoretical physics community. Physicists continue to marshal sophisticated mathematics to explain all the forces of nature. They have even picked up on the labors of Theodor Kaluza and Oskar Klein, extending the two men's thinking about a five-dimensional universe, a proposal that intrigued Einstein in his own search for a unified theory [see "The String Theory Landscape," by Raphael Bousso and Joseph Polchinski, on page 78]. Separately, the ongoing search for violations of relativity may provide one of the best routes to experimental hints about how to meld quantum mechanics and gravity into a single seamless theory [see "The Search for Relativity Violations," by Alan Kostelecký, on page 92]. And the revival of Einstein's cosmological constant, a form of energy that creates a repulsive force, remains at the forefront of the cosmology that is trying to find the keys to "dark energy" [see "A Cosmic Conundrum," by Lawrence M. Krauss and Michael S. Turner, on page 70].

If his search for a unified theory was premature, Einstein experienced more success in later life by using his fame to advocate causes about which he felt passionately. He had difficulty understanding why the rest of the world was so fascinated by relativity. It described the physical world and had nothing to do with subjective psychological viewpoints of time and space purveyed by cultural relativists. "I never understood," he commented, "why the theory of relativity with its concepts and problems so far removed from practical life should for so long have met with a lively, or indeed passionate, resonance among broad circles of the public."

His renown, though, did let him speak out on pacifism, world government, and the need to counter the Nazis' efforts to develop a nuclear bomb. The same longing that took him from the theory of relativity—a joining of Newtonian mechanics and Maxwellian electromagnetism—to an all-encompassing field theory carried over into the rest of his life. "As in his science, Einstein also *lived* under the compulsion to unify—in his politics, in his social ideals, even in his everyday behavior," acknowledges Gerald Holton, a preeminent Einstein scholar at Harvard University.

If Einstein were suddenly to return through some magical post-mortem warping of time and space, he might be less than wowed by the worldwide celebrations of his Year of Miracles. More interested in ideas than the media circuit, he might well divert from commemorative Year of Physics ceremonies in Jerusalem, Zurich, Berlin or Princeton to consult about the latest efforts to detect the gravity waves postulated by general relativity. And he might then go on to palaver with scientists about results from NASA's Gravity Probe B, which may provide evidence for frame dragging, the relativistic prediction that a rotating massive body, such as Earth, lugs space and time with it.

Certainly he would be intrigued by the revival of his long-discarded cosmological constant as a means of helping to explain why the expansion of the universe is accelerating. He might express fascination at a distance for work on superstrings, branes, M-theory and loop quantum gravity, all attempts to merge quantum mechanics with the gravity packaged in his general relativity. He would undoubtedly be pleased to see that physics is pushing beyond his mark, impelled by the desire he shared to elicit a coherent worldview that explains things starting at the level of subatom and working up to an integral cosmos. SA

U.S. naturalization certificate

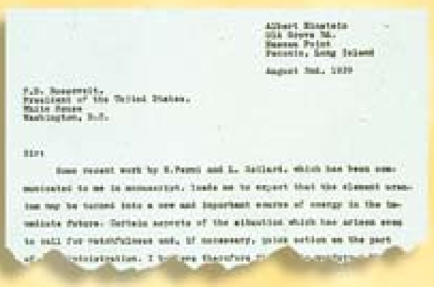
Becomes an **American citizen** but retains Swiss citizenship — 1940

First wife, **Mileva, dies** in Zurich after suffering a stroke — 1948

Declines offer to become **second president of Israel,** although he says he is very moved by the invitation — 1952

Writes his last signed letter, to longtime friend Bertrand Russell, agreeing to add his name to a manifesto calling for all nations to renounce nuclear weapons — 1955

Dies in a hospital as a result of a ruptured aorta. His ashes are scattered at a secret location, possibly the Delaware River — 1955


Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island
August 2nd, 1939

F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore [illegible]

Letter to President Roosevelt

TIMELINE COMPILED BY BETSY QUERNA

© HEBREW UNIVERSITY OF JERUSALEM (*naturalization certificate and 1939 letter to FDR*)

Finding your way out of the woods with GPS? Hanging a picture frame with a laser level? Making photocopies? Better thank Einstein

By Philip Yam

EVERYDAY EINSTEIN

To provincial Manhattanites, Queens County is known only as the place where New York City keeps its airports and where the Mets play baseball. One Saturday afternoon, when I didn't have a flight to catch and the Mets were out of town, I ventured to the northeast part of Queens—specifically, to the College Point neighborhood. There, in a strip mall stretching along a congested 20th Avenue, I went to look for Albert Einstein.

Not surprisingly, Einstein's ideas are essential in many kinds of scientific research, enabling physicists to accelerate particles to near light speed and permitting astronomers to measure and model celestial phenomena. But Einstein's contributions over his life also extend deeply into our everyday encounters with technology. His descriptions of how light can act as particles, how atoms can emit radiation, and how velocity and gravity affect clocks are all important to making common devices work today.

At the College Point mall, my first interaction with Einstein happened as I entered the giant discount store Target. The doors swung open after a photocell—an "electric eye"—spied my approach. The sensor, made from a semiconductor sandwiched between two electrodes, responds to light. As the intensity of light varies—by the breaking of a light beam, say, or a decrease in general illumination—the amount of current generated by the sensor changes. Coupled to appropriate circuitry, it can trigger the doors to open.

Such sensors represent an application of the photoelectric effect, in which light falling on metal sends electrons flying off it. Einstein did not discover the phenomenon, which was first noticed in France in 1839. He did, however, correctly explain it while puzzling out the calculations of German physicist Max Planck. Based on observations, Planck in 1900 figured that a heated body releases light of a given frequency, or color, in discrete amounts called quanta. Planck derived his now famous constant, h, to make the equations describing this so-called blackbody radiation work out.

OVERVIEW

- Einstein's theories enable several kinds of consumer technology to work.
- The photoelectric effect forms the basis of solar cells and electronic light detectors.
- The stimulated emission of radiation is the foundation of lasers.
- Relativity provides the needed corrections for GPS.

ANTHONY MARINO

EINSTEIN FOR SALE: The physicist's influence extends to solar-powered devices, GPS units, digital cameras, and lasers in DVD players, levels and cat toys.

But Einstein theorized that h was more than a mathematical patch. He postulated that light, rather than flowing as a continuous wave of energy, travels in packets. With his 1905 analysis, along with subsequent papers, Einstein showed that light can behave as a stream of particles; when it does, it knocks electrons out of the metal in the way a cue ball breaks a billiard rack.

Einstein also explained a baffling feature of the photoelectric effect. Although the intensity of light sent more electrons shooting off the metal, the velocity of the liberated electrons remained the same no matter how dim or bright the light was. The only way to change the velocity of the electrons was to use a different color of light. To account for the observation, Einstein figured that the energy of each light particle, or photon, depends on its frequency multiplied by h. Subsequent experiments confirmed Einstein's predictions, and for his explanation of the photoelectric effect, Einstein won the 1921 Nobel Prize in Physics.

The photoelectric effect today underlies instruments that turn on the streetlights at dusk, regulate the density of toner in photocopy machines and govern the exposure times of cameras—in fact, it is involved in just about any electronic device that controls or responds to lighting. Photoelectric devices are even used in Breathalyzers—the photocell picks up a color change appearing after a test gas has reacted with alcohol. The effect also led to the invention of photomultipliers, which consist of evacuated glass tubes containing a series of metal steps. The steps cough up successively more electrons after an initial metal target is struck by photons. In this way, a weak light signal is amplified. Photomultipliers channel light in astronomical detectors and television cameras.

The most visible application of the photoelectric effect is in solar, or photovoltaic, cells. Pioneered in the 1950s, solar cells convert 15 to 30 percent of the incident light into electricity and power calculators, watches, environmentally conscious homes, orbiting satellites and Martian rovers.

Stimulated Thinking

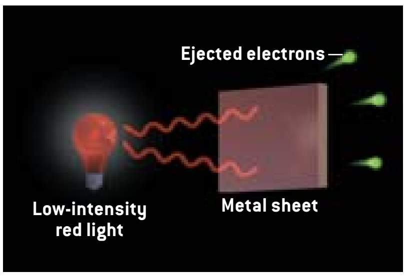
BACK AT THE MALL, I see that against the walls lining Target's electronics section, just beyond the 30 checkout registers, are stacks of DVD and portable CD players, some costing as little as $12.99. The registers and players all use some kind of photocell, but what is more interesting from an Einsteinian perspective is the red beam of coherent light they shoot. The now ubiquitous laser owes its existence to a theoretical framework erected by Einstein in 1917.

With his paper "On the Quantum Theory of Radiation," Einstein continued to explore light and matter. In par-

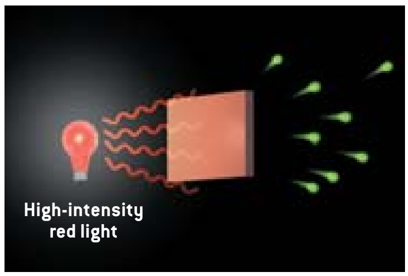
THE PHOTOELECTRIC EFFECT

Making Waves and Particles

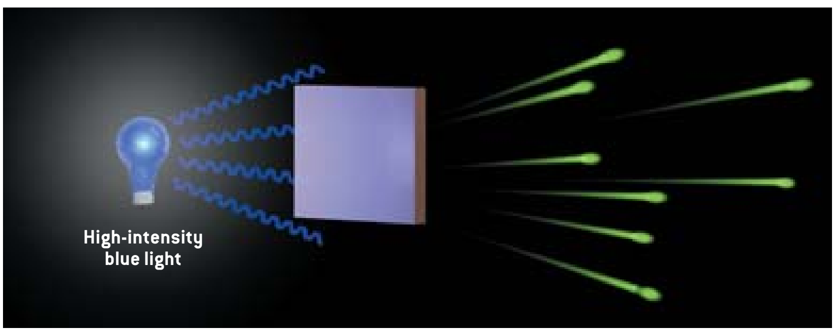
The photoelectric effect, exploited in sensors, solar cells and other electronic light detectors, refers to the ability of light to dislodge electrons from a metal surface. One aspect of the effect is that the speed of ejected electrons depends on the color of the light, not its intensity. Classical physics, which describes light as a wave, cannot explain this feature. By deducing that light could also act as a discrete bundle of energy—that is, a particle—Einstein accounted for the observation.



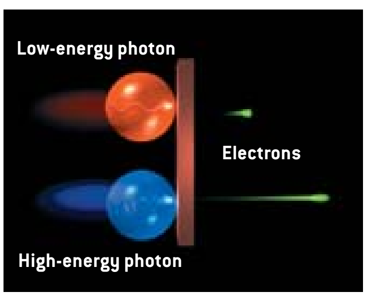
1 Red light sends electrons flying off a piece of metal. In the classical view, light is a continuous wave whose energy is spread out over the wave.



2 Increasing the brightness ejects more electrons. Classical physics also suggests that ejected electrons should move faster with more waves to ride—but they don't.



3 Changing the light to blue results in much speedier electrons. The reason is that light can behave not just as continuous waves but also as discrete bundles of energy called photons. A blue photon packs more energy than a red photon and essentially acts as a billiard ball with greater momentum, thereby hitting an electron harder (*right*). The particle view of light also explains why greater intensity increases the number of ejected electrons—with more photons impinging the metal, more electrons are likely to be struck.



ALFRED T. KAMAJIAN

The idea of correcting for relativity was not obvious to the original GPS designers.

ticular, he realized that atoms can become excited—that is, jump to a higher energy level—if they absorb light. They spontaneously emit light to return to a lower level.

In addition to absorption and spontaneous emission, Einstein deduced that a third kind of interaction must exist, one in which a photon could induce an excited atom to emit another photon. These two photons in turn could stimulate two other atoms to emit photons, yielding four photons. Those four photons could lead to eight more, and so on.

The trick to creating a coherent beam would be establishing a "population inversion"—having more atoms excited than not excited—and finding a way to allow the photons emitted to accumulate into an intense beam. That wouldn't happen until 1954, when Charles H. Townes of Columbia University and his colleagues devised the laser's predecessor, the "maser" (*m*icrowave *a*mplification through *s*timulated *e*mission of *r*adiation).

In retrospect, "it is a wonder that invention of the laser took so long," Townes wrote in his 1999 memoir, *How the Laser Happened*. "[The] laser could have happened 30 years earlier than it did." One possible reason: although Einstein's equations state that stimulated emission produces additional photons, they do not explicitly indicate that it produces exact copies, identical not just in frequency but also in phase. Light sources such as the sun and tungsten filaments produce plenty of photons of the same frequency, but they are out of step—they produce the optical version of random noise. Get all the photons to be coherent—to play the same note at the same time—and the result will be a singular roar rather than a dull hiss.

Einstein "never considered coherence," surmised Townes, now at the University of California at Berkeley. But "I feel sure that if asked, Einstein would have quickly concluded there must be coherence and that if one had enough atoms in an appropriate upper state, one would get net amplification."

Even if some physicists recognized that the photons would be coherent, Einstein's calculations showed that stimulated emission would rarely occur. "It's an incredibly small effect that Einstein predicted, so I don't think people appreciated the significance," says Carlos R. Stroud, a quantum optics physicist at the University of Rochester. Or, as Stroud's colleague Emil Wolf puts it: "Einstein was years and years ahead of everyone else."

In the decades after the 1917 paper, sporadic references to creating stimulated emission appeared, but none of the ideas were pursued. The key ingredient to making amplified radiation, Townes realized in the early 1950s, was a resonant cavity. In lasers—invented a few years after the maser—the cavity is simply the space contained by two mirrors, so that the light bounces back and forth, building up in intensity until a beam emerges from one of the mirrors (which is partially transmitting).

Armed with the basics, engineers found they could make lasers from many substances—including Jell-O infused with fluorescent dye and even tonic water. Widespread use of lasers came about thanks to the semiconductor industry and to the design of light-emitting diodes. Indeed, stimulated emission occurs in an astonishing array of products. Besides DVD players, levels and pointers, lasers are behind ring gyroscopes in aircraft, commercial cutting tools, medical instruments and communications signals through fiber optics. Lasers have become indispensable in science, earning Nobel prizes for several investigators who used them to study chemical reactions and to manipulate microscopic objects, to name two. Masers act as accurate clocks for the U.S. Naval Observatory and amplify faint radio signals in astronomy studies.

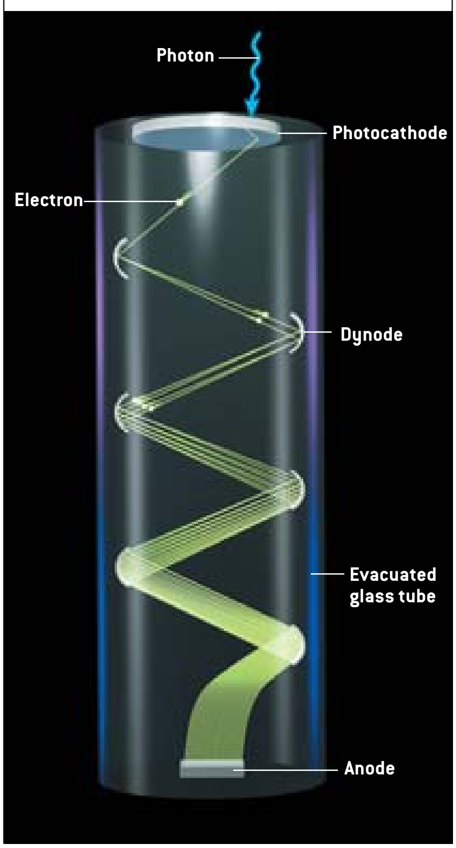
GPS Ticks

MY NEXT STOP inside Target was the outdoor sports section, but unable to find my quarry, I backtracked to the electronics department. "Do you have GPS devices?" I asked at the

PHOTOMULTIPLIERS

Light Work

The photomultiplier tube, essential in video cameras, exploits the photoelectric effect to convert illumination into electrical impulses. A photon hits a metal called a photocathode, which ejects an electron. Magnetic fields from surrounding coils (*not shown*) guide the electron to another kind of metal, called a dynode, which when struck by an electron emits additional electrons. Successively positioned dynodes thereby boost the number of electrons, which reach the anode and produce a signal.



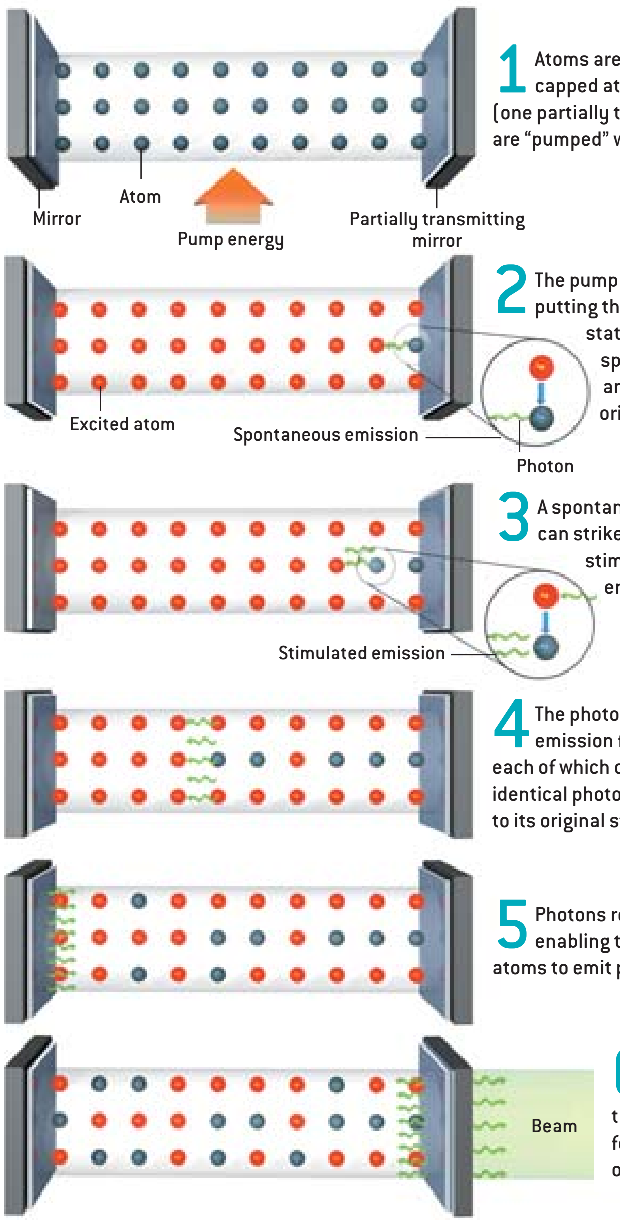
ALFRED T. KAMAJIAN

Lasers can be made from many substances—including **Jell-O infused with fluorescent dye** and even tonic water.

STIMULATED EMISSION

The Brightest Lights

The laser (and its microwave cousin, the maser) results from the stimulated emission of photons (radiation) by excited atoms. Einstein predicted the existence of the process in 1917, and today lasers form the basis of many consumer products, including pointers, levels and DVD players.



ALFRED T. KAMAJIAN

counter. "Not no more," came the reply.

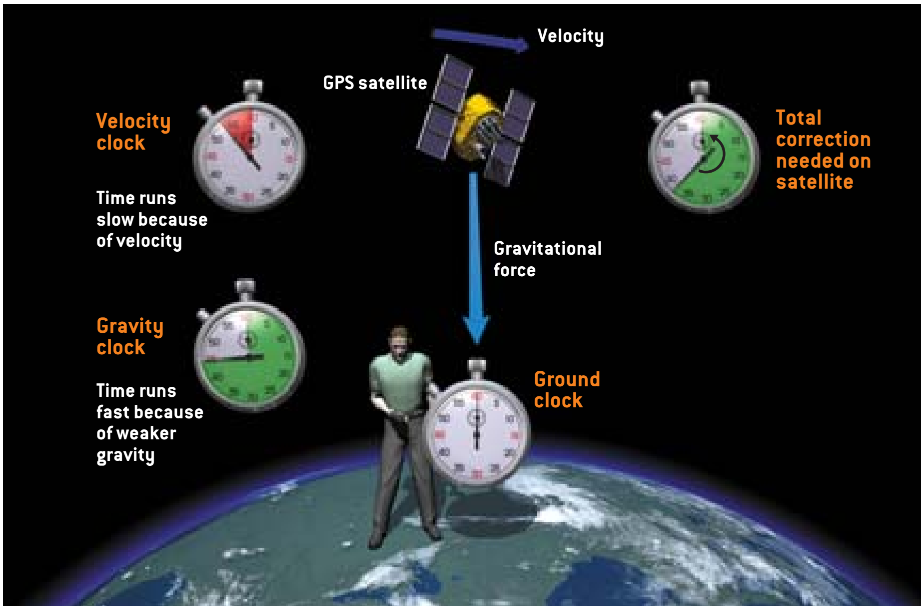
The Circuit City next door, however, offered several models, a few less than $200. These handheld instruments provide latitude, longitude and altitude by picking up timing signals from Global Positioning System satellites. Accurate distance measurements require accurate timepieces, which is why each of the 24 GPS satellites carries an atomic clock [see "Retooling the Global Positioning System," by Per Enge; SCIENTIFIC AMERICAN, May].

Today most store-bought GPS receivers can pin down your position to within about 15 meters. Accuracy of less than 30 meters, notes physicist Neil Ashby of the University of Colorado at Boulder, assuredly means that a GPS receiver incorporates relativity. "If you didn't take relativity into account, then the clocks up there would not be in sync with the clocks down here," elaborates Clifford M. Will, a physicist at Washington University. Relativity states that fast-moving objects age more slowly than stationary ones. Each GPS satellite zips along at about 14,000 kilometers per hour, meaning that its onboard atomic clock lags the pace of clocks on the earth by about seven microseconds per day, Will calculates.

Gravity, however, exerts a greater relativistic effect on timing. At an average of 20,000 kilometers up, the GPS satellites experience one fourth of the gravitational pull they would on the ground. As a result, onboard clocks run faster by 45 microseconds per day. An overall offset of 38 microseconds thus has to be figured into GPS. "If you didn't have frequency offset in satellites, then an 11-kilometer-per-day error would build up," Ashby explains. (The effects are actually more complicated because the satellites follow an eccentric orbit, traveling closer to the earth in some

Time and Time Again

Global Positioning System requires relativistic corrections. Because of the velocity of GPS satellites, onboard clocks run about seven microseconds slower per day than ground clocks. The weaker gravitational pull on the satellites adds another relativistic effect, making clocks run 45 microseconds faster per day. Hence, a correction factor must be calculated that effectively turns back onboard clocks by 38 microseconds per day to yield accurate GPS data. Relativistic errors cancel out in GPS receivers enabled with the wide-area augmentation system (WAAS), because the units rely on additional signals from ground locations.



instances and farther away at others.)

The idea of correcting for relativity was not obvious to the original GPS designers, mostly military engineers, back in the 1970s. "It was controversial," recalls Ashby, who served as a consultant. "Some people believed you had to account for it; some didn't." So divided were the designers that the first GPS satellite was launched without the frequency offset but had a switch to turn on the offset just in case. It quickly became apparent that the switch had to be on, Ashby says.

Newer GPS methods are less dependent on correcting for relativistic effects, at least for positional data. In differential GPS, which requires receivers at known ground locations in addition to the handheld unit, the offset errors effectively cancel out. (The approach is called the wide-area augmentation system, or WAAS.) But those who use GPS to keep track of time, such as radio astronomers, still need Einstein by their side.

Einstein as Inventor

EINSTEIN DID HAVE one type of invention that, alas, can't be found at the mall I visited—or at any mall, for that matter. His dabbling in appliance making may not have produced any durable consumer goods, but the related mechanisms that he patented are in use elsewhere. With fellow physicist Leo Szilard, Einstein came up with refrigerator designs in the 1920s. The machines relied on electromagnetic pumps that did not leak (cooling gases back then were toxic). The invention of safer refrigerants quickly rendered the leakless pump obsolete, and Einstein's fridge never appeared in appliance showrooms. The pump, however, survives as a means to move sodium to cool a type of nuclear reactor called a fast breeder [see "The Einstein-Szilard Refrigerators," by Gene Dannen; SCIENTIFIC AMERICAN, January 1997].

Of course, the inventor's yen did not propel Einstein, who was primarily driven by the desire to understand nature. He left the technological consequences of his reasoning to others. The same could be said of $E = mc^2$, a relation that emerged from his 1905 relativity paper. "Before that, people had not considered that matter was in any way convertible to energy," Stroud remarks. Given its seductive simplicity—multiply a tiny bit of mass with the speed of light squared to get a lot of energy—there had to be ways to see it in action. "I suspect it got a lot of people thinking about it," Will surmises.

Certainly, in making the fission bomb, the Manhattan Project scientists were motivated by imperatives more pressing than confirming that E really does equal mc^2. It is one of Einstein's technological legacies that still might radically change the world—and assuredly one never to be sold at a shopping mall. SA

Philip Yam is news editor.

MORE TO EXPLORE

How the Laser Happened: Adventures of a Scientist. Charles H. Townes. Oxford University Press, 1999.

Relativity and the Global Positioning System. Neil Ashby in *Physics Today,* Vol. 55, No. 5, pages 41–47; May 2002.

Einstein on the Photoelectric Effect. David Cassidy. **www.aip.org/history/einstein/essay-photoelectric.htm**

ALFRED T. KAMAJIAN


Spintronics
Bose-Einstein Condensate
Brownian Motion

THREE OF EINSTEIN'S THEORIES are particularly inspiring to 21st-century engineers. Researchers are making novel devices that exploit Brownian motion, the curious jitter of microscopic particles that Einstein first correctly explained. The nascent field of "spintronics" is exploiting the theory of special relativity. And labs around the world are designing sensors that use Bose-Einstein condensates, a bizarre state of matter predicted by the master 80 years ago.

A new generation of technologies aims to put Einstein's theories to work in computers, hospitals—even submarines

By W. Wayt Gibbs

ATOMIC SPIN-OFFS FOR THE 21ST CENTURY

In 1905 Albert Einstein was 26 and struggling to finish his doctoral dissertation on the size of molecules. To pay the bills, he worked at the Swiss patent office, analyzing the inventions of others. You would think his day job would have inspired Einstein to contemplate practical uses for the theories he was developing in his spare time. Yet he showed little inkling that year, as he published five of the most remarkable papers of his extraordinary career, that the new views of matter, energy and time he was urging would eventually inspire novel kinds of machines to advance human industry and health.

It isn't that Einstein disdained engineering. It just wasn't his strong suit: his own inventions, including a refrigerator with no mechanical moving parts and a leak-proof pump, never advanced to mass production. No matter; over the course of the 20th century, others built an impressive range of technologies [see "Everyday Einstein," by Philip Yam, on page 50] on Einstein's radical notions that light comes in individual packets, that those photons always obey a universal speed limit *c*, and that energy and matter can be interconverted: $E = mc^2$, in mathematical shorthand.

In the 21st century, engineers have begun to exploit those famous principles in new ways, perhaps most notably in designs for radically innovative computers. They are also finding practical applications for some of Einstein's lesser-known theories. Nanotechnologists, for example, are making devices that could speed up DNA analysis by harnessing the random motion of molecules, a phenomenon first correctly explained by Einstein in 1905. And laboratories around the world are creating exotic forms of matter that Einstein envisioned in 1925 in one of his classic "thought experiments." These coherent swarms of ultracold atoms—the matter cousins to laser beams—could find use in portable atomic clocks, superprecise gyroscopes for navigation, and gravity sensors for mapping mineral lodes and oil fields.

This article examines three of the newest and most exciting Einsteinian spin-offs emerging from research labs; more such innovations will certainly follow in the years and decades to come. Although nearly a century has passed since the master physicist began fashioning better mathematical tools to describe the universe, there seems no end to the useful gadgets that clever inventors can make with them.

OVERVIEW

- Einstein's abstract ideas are still inspiring new technologies. His theory of special relativity, for example, is a key ingredient in fast and efficient microchips that manipulate the spin of electrons.
- His insight into molecular motion has led to so-called Brownian ratchets that quickly sort DNA or separate solids from water.
- And his prediction that ultracold atoms "condense" into a laserlike state proved true. This phenomenon could soon yield supersensitive gravity detectors and superstable gyroscopes.

DAVID EMMITE PHOTOGRAPHY

Taking Relativity for a Spin

THE ONLY COMPUTER that Einstein used to work out his special theory of relativity in 1905 was the one inside his skull. In many ways, that biochemical machine was far more capable than any electronic computer. Certainly no semiconductor microprocessor yet built can rival the density and energy efficiency of the human brain, which packs roughly a million billion processing elements into a one-kilogram package that uses less power and generates less heat than a Pentium 4 microprocessor.

Indeed, heat and energy consumption today stand as the most formidable obstacles to the semiconductor industry as it seeks to produce ever more powerful microchips at the same unit cost. Within the next 20 years, the advance of digital silicon processors as we know them will hit fundamental economic and physical limits. Chipmakers will have little choice but to move to designs that exploit different principles of physics—those of special relativity, for example.

On its face, that seems an odd combination. Special relativity is all about high-velocity motion. In the theory, Einstein discards the concepts of absolute time and absolute rest. The only constant, he asserts, is *c*, the speed at which light travels through empty space. That law has strange consequences for any object as it accelerates (relative to the observer). The object's length shortens, for example, and it seems to experience time more slowly than the observer does. If the object moves through a static electric field, it perceives the field as partially magnetic. These so-called relativistic effects are all minuscule, however, unless the object accelerates to a significant fraction of *c*, which is about 300 million meters per second.

Relativistic chips could go beyond binary logic, packing more data into each bit.

Even "mobile" computers don't move very fast by that standard. But the electrons inside them do. And earlier this year a group of physicists led by David D. Awschalom of the University of California at Santa Barbara demonstrated a way to exploit relativity to make the fast-moving electrons in semiconductors perform impressive new tricks.

The work is at an early stage, roughly analogous to the construction of the first semiconductor logic gate some 40 years ago. But if engineers can figure out how to integrate millions of relativistic gates on a small silicon chip—and Awschalom is working with research groups at Intel and Hewlett-Packard to do just that—the result could be processors that run much faster than current models do, while consuming far less power and radiating far less heat.

Even more dramatically, relativistic chips could employ logic that is more sophisticated than the binary operations all computers now use. In principle, these new machines could even modify the way they are wired, adapting almost instantaneously into a circuit customized for the task at hand. Imagine a cell phone, for example, that can reconfigure its transceiver to use any network in the world and that at the push of a button can reprogram its processor to translate speech from one language to another.

Chips such as these could most likely be made in existing microprocessor factories. The secret ingredient is not some new material, but modern physics—behaviors described by the theories of relativity and quantum mechanics.

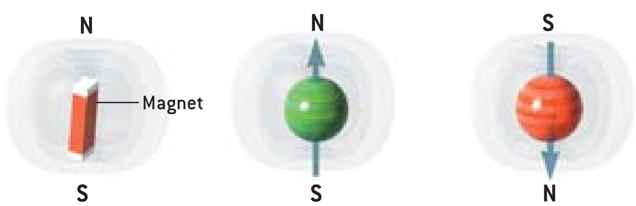
The Magnetic Attraction

CONVENTIONAL SEMICONDUCTOR microchips operate based on "classical" 19th-century theories of electromagnetism. Silicon wafers are zapped with ions, which form tiny islands with either an excess or a dearth of electrons. Voltages, applied to microscopic electrodes built up around these islands, push and pull electrons in and out of these regions, opening and closing the logic gates and regulating the flow of electric current through them.

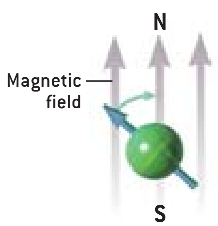
ELECTRON SPINS

Magnetic Magic

The electron has a quantum property, called spin, that makes it behave almost as if it were a magnet twirling about the axis connecting its north and south poles. Electrons (*spheres*) can have spins oriented in different directions.



A magnetic field causes an electron to swivel like the needle of a compass to line up with the field (*below left*). But the spin axis also precesses like a wobbling top (*below right*).



When the magnetic field is removed, the electron stops precessing and locks the orientation of its spin.

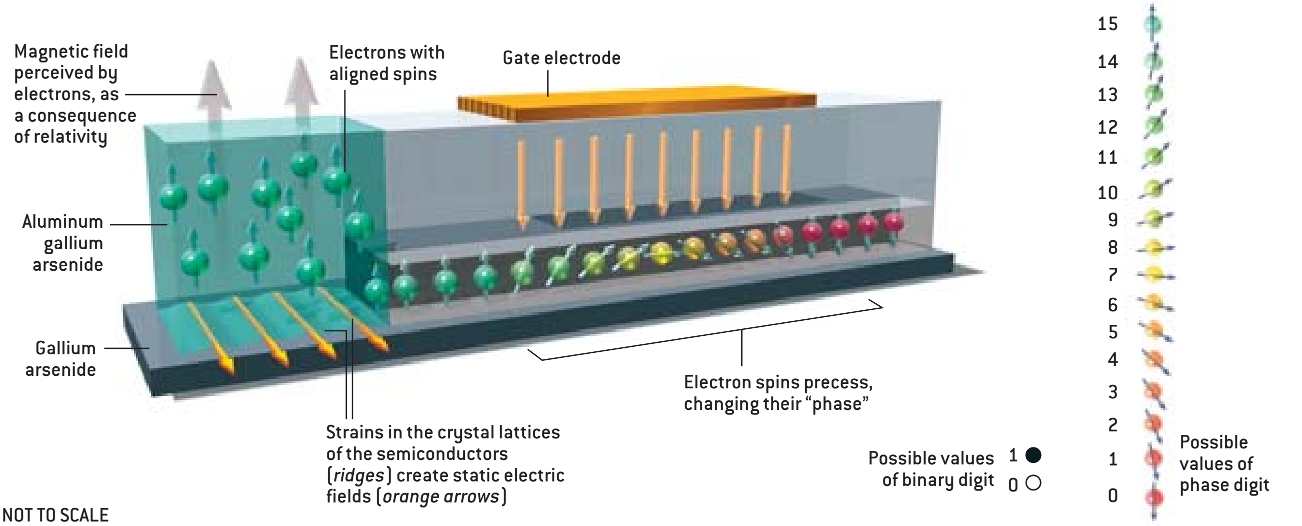
ALFRED T. KAMAJIAN

Computing beyond Binary

Special relativity suggests a new design for microchips that relies on the spin of electrons. These microchips could be made in existing fabrication plants. As electrons zip through the device, relativity makes static electric fields on the chip appear partially magnetic. The electrons align their spin axes in response to the magnetic forces.

A signal turns on a gate electrode, creating an electric field. The fast-moving electrons see this field as partly magnetic, and it causes their spin axes to precess. The gate then switches off, locking the electron spins in a new direction, or phase.

By varying the speed of the electrons and the strength of the electric field at the gate, a relativistic microchip might create spintronic "phits" (phase digits) that can take a much wider range of values than just the 0 or 1 of electronic bits.



Shoving large numbers of electrons around is imprecise—some shoot out in random directions, wasting energy—and it creates lots of collisions, which produce heat. For more than a decade now, physicists have been experimenting with a subtler alternative: using magnetic forces, rather than electric fields, to manipulate the electrons.

This can work, explains physicist Michael E. Flatté of the University of Iowa, because "an electron acts as if it carries around with it a little bar magnet." Magnets have north and south poles, and just as the earth spins around the axis that connects its poles, an electron, too, has a magnetic orientation, a quantum property that physicists call "spin." The particles don't actually rotate, but they do behave like little gyroscopes. Apply magnetic force to an electron, and its poles will precess—the axis itself rotates in a circle. Remove the field, and the electron holds its spin steady [*see box on opposite page*]. "By using this effect to precess the spin from pointing up to pointing down, you can change the bit of information carried by that electron from a 1 to a 0," Flatté says.

Whereas electronics move information around by changing the number and energy of electrons in a circuit, the nascent field of spintronics encodes data in the orientation of electrons and performs logical operations by twisting their spins this way and that [see "Spintronics," by David D. Awschalom, Michael E. Flatté and Nitin Samarth; Scientific American, June 2002]. This year Motorola began mass-producing spintronic memory chips, called MRAM (for magnetic RAM). Unlike conventional computer memories, the MRAM chips do not lose their data if power is interrupted; the electron spins simply hold their position until power returns.

Spintronic devices are easy on batteries, because spin-flipping operations consume very little power and the chips can shut off between operations. Changing an electron's spin adds virtually no kinetic energy to the particle, so the circuits produce almost no heat. And the process is exceedingly fast: experimental devices have turned electrons on their heads in a few picoseconds (trillionths of a second).

Until recently, however, all spintronic devices have required ferromagnetic metals, which do not mesh well with current microchip production techniques. "It's difficult to imagine how you could build little magnets at millions of places on a chip and control each one individually—not impossible, but difficult," Awschalom says. "It would be much nicer to use the trillions of dollars' worth of electronics gating technology that already exists and to use electric fields, not magnetic fields, to play with spins."

From Bits to Phits

ENTER EINSTEIN and his curious notion that an electric field can look distinctly magnetic to a high-speed electron. In work published this past January, Awschalom's group showed that layering two semiconductors of slightly different composition on top of one another strains the chip in

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ways that set up an internal electric field. The field has high and low spots that act like a corral to herd electrons as they pass through the semiconductor. "And because of relativity, that electric field looks like a partially magnetic field to the passing electrons," he notes. The electrons' spins start to precess like wobbly gyroscopes.

"We can control the electrons in two ways," Awschalom continues. "One way is to change the voltage, which affects the speed at which the electrons travel. The faster they move, the larger the effective magnetic field seems to them" and the faster their spins precess. The second trick exploits the fact that the strain varies with direction. "We can also operate on electrons by carefully designing the shape and direction of the wire that sets their path," he says.

In the January paper, the group described using pulses of laser light to align the orientation of incoming electrons—thus creating the spintronic bits—as well as to measure their spins. "The next step is to create them, move them around and detect them all in one electric device. That's a substantial step, but we've done that now," Awschalom reports. "The device uses the same small voltages currently used in CMOS computer chips. Electrons instantaneously polarize their spins when they hit the strained part of the semiconductor. We can then flip their spins back and forth coherently" by turning gate electrodes on or off.

"Coherently" is the key word here, because it raises the intriguing possibility of spintronic chips that go beyond bits—the binary digits 0 and 1—to "phits," or phase digits, which can take on a wider range of values. The phase of an electron is simply the direction in which its spin points. Think of it as the needle of a compass: if a microchip can distinguish groups of electrons with north-, south-, east- and west-pointing spins, then each phit could be a 0 or a 1—or a 2 or a 3.

"The more precisely you can read the phase, the more dramatically you can increase the density of data storage," Awschalom points out. "Whether it increases by a factor of 50 or by 10,000 depends on how precisely you can read that angle." Thanks to decades of work on magnetic resonance imaging, which detects the spins of atomic nuclei, "we do know how to read these angles very precisely," he notes.

Even so, "a complete, working spin transistor has not yet been demonstrated," Flatté cautions. Transistors are indispensable because they amplify signals, allowing them to pass intact through a long series of gates in a microprocessor. But although spintronic versions do not yet exist, they are clearly coming, and researchers are eagerly drawing up plans for what to do with them.

Last year Reinhold Koch and his colleagues at the Paul Drude Institute for Solid State Electronics in Berlin published a design for a spintronic logic element that can change its function under software control. One moment it could operate as a Boolean AND gate, and a few nanoseconds later it could transform into an OR gate, a NOR (not OR) gate or a NAND (not AND) gate.

Computers that rewire themselves on the fly could be powerful indeed. Koch recently designed a full adder—the commonest kind of computer logic component—from just four spinlogic elements, instead of the 16 electronic transistors usually required. The spintronic version would use about 85 percent less power and 75 percent less space yet run just as fast as today's state-of-the-art silicon designs.

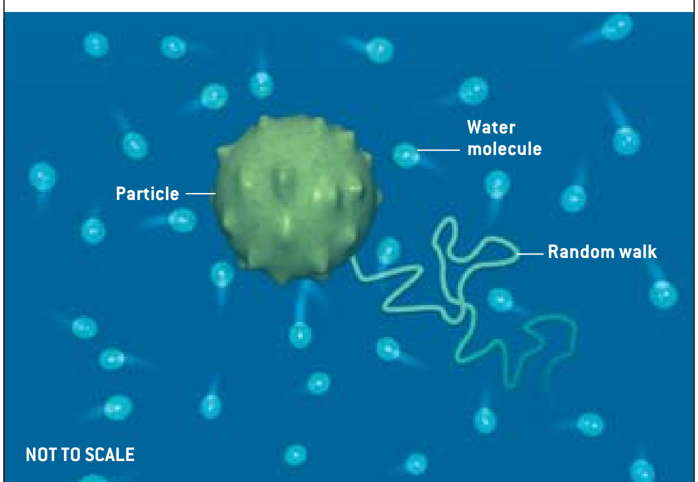
Engineers are still far from mastering relativity as a design tool for spintronic microcircuits. But Einsteinian technology could open an entirely new avenue for the computer industry just as the current road is filling with obstacles. "One interesting aspect to the physics here," Awschalom says, "is that the smaller the device, the better it works."

The Einsteinian pachinko machine reliably separated the two viral genomes.

MOLECULES IN MOTION

Buffeted by Chaos

In 1827 botanist Robert Brown put a drop of water under his microscope and saw minuscule particles dancing around inside grains of pollen as though they were alive. It wasn't until 1905 that Einstein deduced that bombardment by water molecules is what sends the particle on its random walk. Although the molecules are too small to see, they are fast and numerous enough to nudge a bacterium-size object when they strike it. Over time, the particle zigzags erratically.



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A Random Walk to Work

EINSTEIN IS MOST FAMOUS for his ideas about big things: the speed of light, the fate of the universe, the nature of time. But in 1905 submicroscopic molecules also gripped his attention. In his doctoral dissertation that year, he improved on previous estimates of their size. And in a paper published in *Annalen der Physik,* he worked out the mathematical laws governing "Brownian motion," a microscopic phenomenon that had puzzled scientists from the time that botanist Robert Brown drew attention to it in 1827.

Brown had noticed that tiny particles, such as those inside pollen grains, move haphazardly [*see box on opposite page*]. The easiest explanation was that these particles were alive, but Brown showed that even finely powdered rock skitters when suspended in water. By the turn of the 20th century, some theorists were hypothesizing that electrical forces shove the matter around, whereas others favored evaporation, convection, the effects of light, or other explanations.

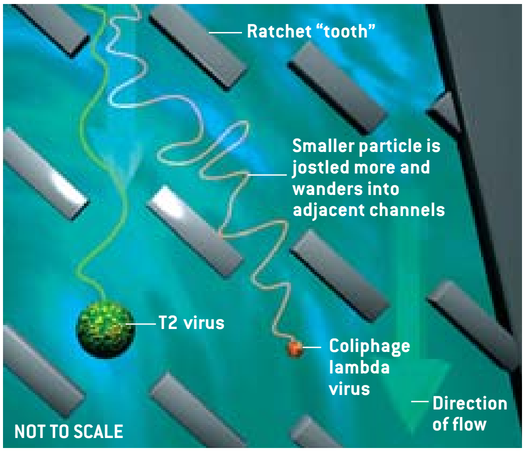
Einstein suggested that a particle drifting in liquid staggers around mainly because molecules are colliding with it from every direction. In fact, he noted, the phenomenon is strong evidence for the (then controversial) theory that heat is merely the random motion of molecules. In his paper, Einstein derived some of the basic math behind Brownian motion.

That branch of mathematics turned out to be surprisingly useful for analyzing stock markets, for predicting how substances diffuse through liquids or gases, and most recently for designing so-called Brownian ratchets. These devices exploit the fact that Brownian motion displaces small particles farther than it does big ones. Using microscopic variations on the sawtooth gear in a winch, Brownian ratchets convert the random jitter of particles into useful work, such as sorting viruses by size or removing contaminants from water.

Last year engineers constructed two such devices using techniques much like those used to make microchips. James C. Sturm and his co-workers at Princeton University built a Brownian ratchet that looks a bit like a thumbnail-size pachinko machine. They etched a channel into a silica wafer but left standing in the channel evenly spaced columns of pillars. The pillars are just six microns wide and three microns tall. They are canted 45 degrees and spaced so that as liquid streams through the channel, any suspended particles skitter into them and deflect to the right. The smaller the particle, the more it skitters and the farther to the right it wanders.

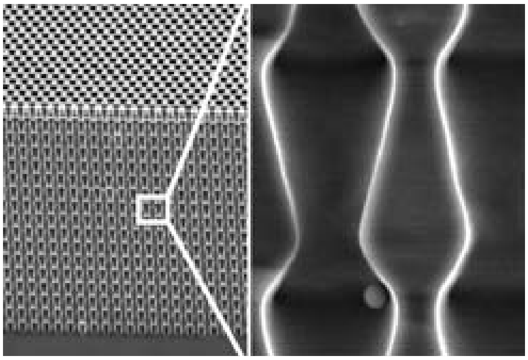
BROWNIAN RATCHETS

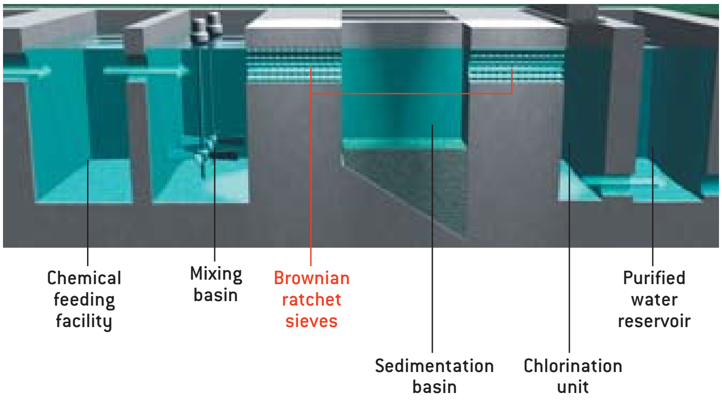
Better Sieves and Sorters



Brownian motion bumps suspended particles in random directions. In Brownian ratchets, asymmetric obstacles guide that random walk to certain paths. One design resembles a tiny pachinko pinball machine. As fluid—perhaps plasma from a drop of blood—flows down the channel, small particles such as viruses bump into angled pillars that act like the teeth of a ratchet gear (*left*). The viruses would end up sorted by size at the bottom of the device, where one species could be distinguished from another.

German engineers have made a different kind of Brownian ratchet by etching thousands of channels into a silicon wafer (*below left*). Water contaminated with soot, biological material or other particulates can be sloshed back and forth through the pores. The jostling pollutants bang into the bottlenecks, which guide them forward, and eventually they all migrate to one side of the wafer. In principle, water-purification plants (*below right*) could insert many such Brownian sieves into their pipelines.





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In tests published last December, Sturm ran a mixture of water and DNA from two different kinds of viruses through the ratchet. It reliably separated the heavier viral genome from the lighter one. Using this Einsteinian technology could cut the time needed to separate large DNA fragments by two thirds over current methods and might be cheaper and more portable to boot.

Sven Matthias and Frank Müller have built a Brownian ratchet of a different kind at the Max Planck Institute of Microstructure Physics in Weinberg, Germany. This one looks rather like a sponge: thousands of parallel channels perforate a thin wafer of silicon. Each hole widens and narrows in a series of bottlenecks.

Matthias and Müller stuck their ratchet in the middle of a tight-fitting dish full of water and microscopic plastic beads. The bottom of the dish moved up and down, sloshing the water back and forth through the ratchet. As the beads drifted through the channels, their Brownian motion pushed them against the bottlenecks, preventing them from drifting out again. Gradually, nearly all the beads migrated through the ratchet and into the upper part of the dish, leaving clean water below. Because the ratchet can be scaled to large sizes, it offers a new way to separate solid pollutants—such as soot, viruses or cell fragments—from a continuous stream of fluid.

Prospecting with Atomic Blobs

EINSTEIN STRUGGLED with the strangeness of the quantum rules that govern the atomic realm. The starring role those laws give to chance and uncertainty offended his instincts. Despite his unease with the philosophical ramifications of quantum physics, however, Einstein made several seminal contributions to the field.

In 1925, for example, he read a paper by Satyendra Nath Bose on photon statistics and realized that if atoms could ever be chilled to within a hair's breadth of absolute zero and jammed together, something uncanny would happen. Quantum effects would force the atoms to condense temporarily into a kind of superatom. The phalanx of atoms would march in lockstep, much the way that photons fly in formation inside a laser beam.

Lasers have turned out to be very handy devices, and there is good reason to expect that "atom lasers" would be quite useful as well. But the Bose-Einstein condensate (as the blob of ultracold atoms became known) remained just a curious prediction for more than 70 years. In June 1995 Eric A. Cornell and Carl E. Weiman of JILA in Boulder, Colo., finally coaxed 2,000 rubidium atoms to merge just as Einstein had foreseen. Six years later they and Wolfgang Ketterle of the Massachusetts Institute of Technology shared a Nobel Prize for the achievement.

Today Cornell and his students at JILA are putting the final touches on a chip that can guide condensates over its surface. It splits and recombines the atomic blobs in ways that can detect acceleration and rotation even more sensitively than laser-based technologies. They call it an atom interferometer.

"In the belly of the airplane, you could use one of these for measuring small changes in the strength and direction of gravity, which is a kind of acceleration," Cornell says. "Those wiggles in gravity reveal things you can't see because they are deep underground or deep underwater": anomalies such as oil fields, veins of metal ore, caves, and even subterranean bunkers and tunnels.

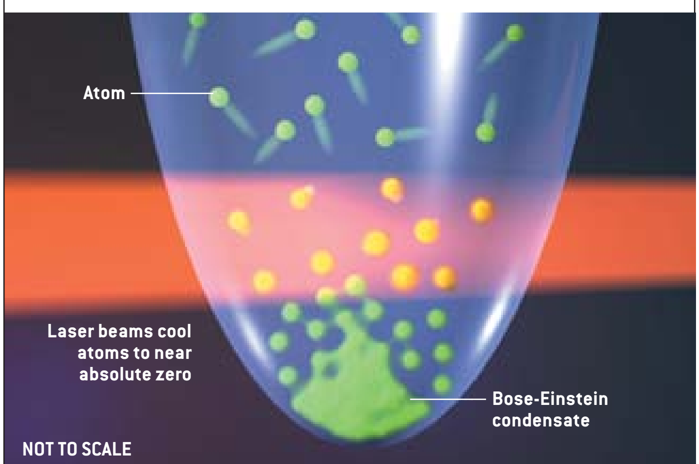
Atom interferometers could also boost the accuracy of the best rotational sensors—currently, mechanical gyroscopes—by a factor of 100 to 1,000, Cornell adds. "The reason you want really good gyroscopes is for dead reckoning. Of course, with the GPS [Global Positioning System] satellite network, hardly anyone dead reckons anymore. But one place where you do still want a good gyro is if you are in a big titanium can underwater for a long time and you aren't allowed to make any noise. Not coincidentally, the navy is paying for a lot of this work." The military is also keen on developing precision navigational systems that work even if GPS signals have been jammed.

Wiggles in gravity can reveal things hidden far underground or deep underwater.

MAKING AN ATOMIC BLOB

A New State of Matter

At a billionth of a degree above absolute zero, Bose-Einstein condensates are the coldest objects in the universe. Scientists use magnetic fields and lasers to slow and compress atoms until quantum effects synchronize their behavior. The atoms in the condensed cluster move in lockstep like a single, giant atom.



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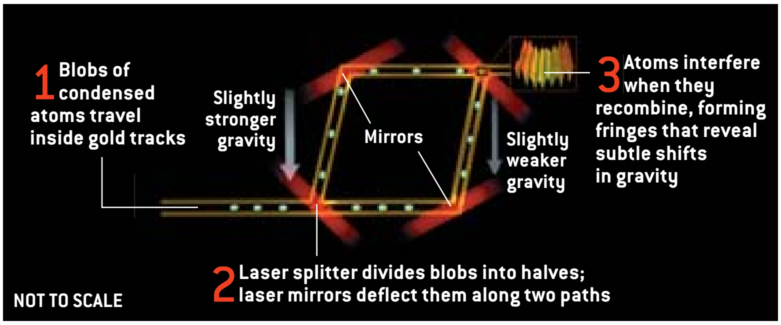
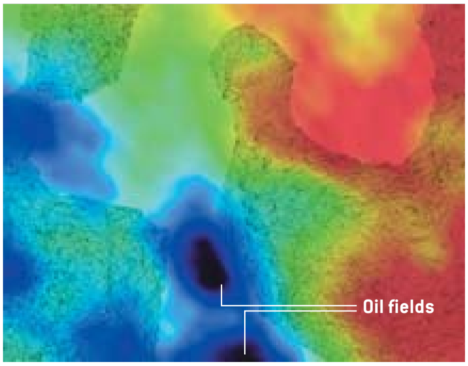
ATOM INTERFEROMETERS

Making the Invisible Visible

The laserlike properties of Bose-Einstein condensates could find work in gravity mappers and gyroscopes. The atomic blobs can split and recombine in an interferometer (*below*). Magnetic forces guide the atoms, which bounce off a splitter and "mirrors" made from standing waves of laser light. The two halves of the condensate typically remain in lockstep during their journeys, then rejoin to produce an interference pattern of fringes. But any slight difference in the paths each half follows—because of a subtle gradient in the force of gravity, say, or a rotation of the device—will shift the fringes. In the long term, atom interferometers carried by planes (*top right*) might map the gravitational signatures (*bottom right*) of deep deposits of oil or metal ore. Military craft might even use a Bose-Einstein gravity scanner to identify underground bunkers or tunnels (*not shown*).





As its name suggests, an atom interferometer brings two groups of atoms together and measures the pattern of interference that appears. Like all quantum objects, Bose-Einstein condensates behave both as waves and as particles. When a condensate is split into two, the pieces start out with the same wavelength and phase. But if they travel different paths, then one piece may be out of step with the other when the two recombine. The crests and troughs of their waves will interfere to produce a fringelike pattern, with areas containing lots of atoms separated by areas that are nearly empty.

Ketterle, Mark A. Kasevich of Stanford University and others have recently built working atom interferometers. But those devices take up most of a room, because the atomic blobs split and recombine while free-falling inside a large vacuum chamber. Cornell and his JILA colleague Dana Anderson have been fashioning more portable versions.

"By guiding the atoms, we can shrink the interferometer down onto a small chip," says Ying-Ju Wang, one of Cornell's graduate students. She is pointing to a piece of glass the size of a microscope slide. Two parallel strips of gold run across the middle of the slide like the tracks of a railroad for fleas. Electric current runs through the wires, creating magnetic fields that cancel one another out in the center between the rails. "The rubidium atoms we use like to stay in the lowest part of the magnetic field," Wang explains. "So the atoms shoot right down that channel where the field is zero."

The gold railroad comes to a Y intersection: the splitter. "Here we set up a standing wave of laser light," Wang says. "It acts like a grating to diffract half the atoms in the condensate to the left and half to the right. The blobs separate about 300 microns, and then they hit more standing waves, which act like mirrors to deflect the atoms back. Then they meet, overlap and interfere." A special kind of camera monitors the position of the fringes.

Although the business end of the interferometer fits on a palm-size slide, the entire apparatus still fills a benchtop in the lab. "A lot of things are readily scalable in our design," Cornell says. "But some aren't," such as the laser cooling system that slows atoms from room temperature down to a few billionths of a degree above absolute zero.

So an atomic gyroscope may not fit in a wristwatch or a cell phone. But before long, Bose-Einstein condensates might be flying in the noses of aircraft and floating in the bows of submarines. And if the history of lasers is any guide, future entrepreneurs will find many more uses for this new state of matter than scientists can even imagine today. SA

W. Wayt Gibbs is senior writer.

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MORE TO EXPLORE

Coherence with Atoms. M. A. Kasevich in *Science*, Vol. 298, pages 1363–1368; November 15, 2002.

Asymmetric Pores in a Silicon Membrane Acting as Massively Parallel Brownian Ratchets. S. Matthias and F. Müller in *Nature*, Vol. 424, pages 53–57; July 3, 2003.

Tilted Brownian Ratchet for DNA Analysis. L. R. Huang et al. in *Analytical Chemistry*, Vol. 75, pages 6063–6967; December 15, 2003.

Coherent Induced Spin Polarization in Strained Semiconductors. Y. Kato et al. in peer review. Online at **arXiv.org/abs/cond-mat/0403407**

What was it about the magnetism of an iron bar that could divert Einstein from perfecting his celebrated theory of general relativity? **By Peter Galison**

PERCHING ON A LAZY SUSAN (or a giant compass needle) with a gyroscope in each hand: this is the kind of thought experiment that led Einstein and W. J. de Haas to successfully explain magnetism in iron. When counterclockwise-spinning gyros are held with their axes pointing outward, their opposing angular momenta add to zero (*center*). When the holder raises the gyros upward, their angular momenta align, so they sum to a nonzero value. Because the system's total angular momentum is conserved, the lazy Susan begins to rotate to compensate. Likewise (according to the Einstein-de Haas theory, which was later revised), when the orbits of electrons around iron atoms in a magnet are aligned by an applied magnetic field, the entire magnet begins to spin.

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EINSTEIN'S COMPASS

At the beginning of 1915, Albert Einstein found himself engaging more and more in politics; he started to protest the militarism that had plunged Europe into a devastating war. That year also marked a significant change in the path of his long life in science. Collaborating with mathematician Marcel Grossman, Einstein was scrambling to learn all he could about a new kind of geometry, heretofore almost entirely unknown to physicists, that might aid him in characterizing the bending of spacetime. The stakes, he realized, were vast: Could special relativity be generalized into a theory of gravity? Could the Newtonian cosmos of distant inverse-square forces be scrapped in favor of one based on the equivalence of mass and energy with fields of curved space and time? In November 1915, after the most intense intellectual struggle of his life, Einstein was finally able to reveal general relativity to the world. His gargantuan effort was no less than a triumph of theory, reason and abstraction.

Yet from the start and through much of that eventful year, Einstein had stepped back from the Platonic reaches of tensors and coordinate transformations to focus on bench experiments involving gluing quartz fibers to mirrors and pulsing electric currents through electromagnets. As he wrote to his best friend, Michele Besso, on February 12: "The experiment will soon be finished.… A wonderful experiment, too bad you can't see it. And how devious nature is, if one wants to approach it experimentally! I've gotten a longing for experiment in my old age." Working with Hendrik Lorentz's son-in-law, W. J. de Haas, Einstein undertook an experimental challenge that had stumped some of the most adept lab hands of all time—explaining the mechanism responsible for magnetism in iron.

The basic concept was simple. An electric current traveling in a loop makes an electromagnet. Einstein wondered whether magnetized iron might not also owe its capacity for magnetization to a similar phenomenon, as André Marie Ampère and his successors had long speculated. Einstein asked whether, at the atomic or molecular level, there were many such current loops all oriented in the same direction. If so, there might be just one kind of magnetism. Said he:

> Since [Hans Christian] Oersted discovered that magnetic effects are produced not only by permanent magnets but also by electrical currents, there may have been two seemingly independent mechanisms for the generation of the magnetic field. This state of affairs itself brought the need to fuse together two essentially different field-producing causes into a single one—to search for a single cause of the production of the magnetic field. In this way, shortly after Oersted's discovery, Ampère was led to his famous hypothesis of molecular currents which established magnetic phenomena as arising from charged molecular currents. [from "Experimenteller Nachweis der Ampèreschen Molekularströme," by Einstein and de Haas, in *Deutsche Physikalische Gesellschaft,* Vol. 17, page 152; 1915]

Reducing two causations to one: here was quintessential Einstein. He had begun his work on special relativity with the assertion that the usual understanding of James Clerk Maxwell's equations must be very wrong, because it seemed as if there were two explanations for why current was produced when a wire coil approached a magnet. If the coil was moving and the magnet still, the standard story held that this was because the charge in the coil was moving (along with

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PETER GALISON is Mallinckrodt Professor of the History of Science and of Physics at Harvard University. His most recent book, *Einstein's Clocks, Poincaré's Maps: Empires of Time* (W. W. Norton, 2003), explores the idea of coordinated time at the crossroads of technology, philosophy and relativity theory. Galison is a MacArthur Fellow (1997) and winner of the Max Planck Prize (1999).

GYROSCOPIC DIRECTION FINDER, perfectly suspended so that it can rotate in any direction, will continue to point toward the same location in the heavens even as the earth spins and orbits. At any latitude away from the North Pole, however, as the earth turns, the gyro will leave the plane parallel to the ground—making it awkward to use for navigation.

the wire) and so was pulled around the loop by the magnetic field. If the magnet was moving toward the coil, then, according to the conventional view, the growing magnetic field near the coil was produced by an electric field that drove charge around the coil. Einstein's special theory of relativity accounted for both phenomena by reassessing the meaning of space, time and simultaneity.

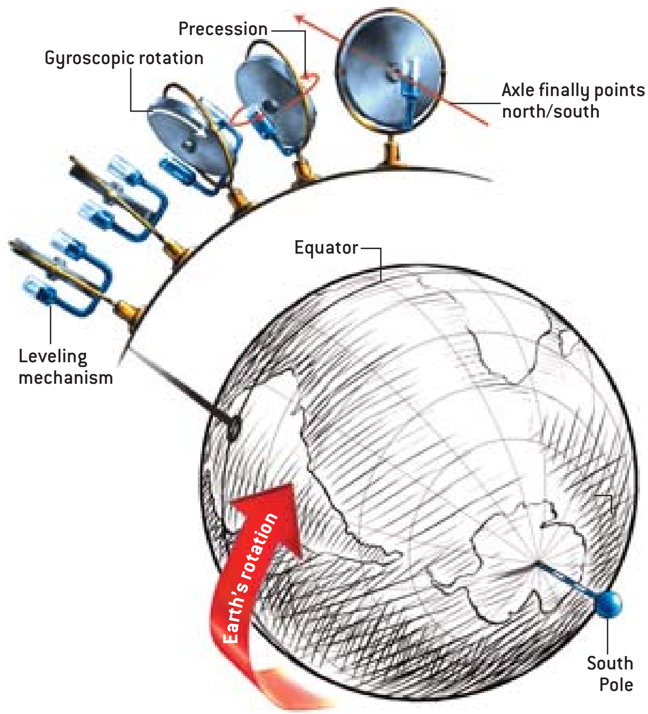
In his 1907 principle of equivalence, Einstein had objected to the previously unchallenged claim that there were two kinds of mass—gravitational mass (responsible for the weight of a lead ball) and inertial mass (the resistance of a mass, say a lead ball, to acceleration, even far out in space). Instead Einstein stated that there was just one kind of mass. There was no way to distinguish the behavior of mass pressed to the floor of an accelerating rocket ship and that of mass pulled to the floor of a stationary room in a gravitational field.

So Einstein likewise believed deeply that there was but one kind of magnetism and that it was caused by the aligned orientation of tiny magnets—current loops formed by electrons as they raced around atomic nuclei. The question was: How could one test this idea?

Suppose that you are standing on a lazy Susan with a gyroscope in each hand, each with its axis pointing away from you and spinning clockwise from your point of view. The gyroscopes' angular momenta are oriented in opposite directions, so the system's total angular momentum adds to zero. Next, say you raise your hands above your head so the gyroscopes are now both pointing up. This means their angular momenta are both aimed in the same direction, so they sum to a nonzero value. But because the angular momentum in a closed system is conserved (stays the same), you begin to rotate on the lazy Susan, in this case to counter the angular momenta of the gyros.

Einstein imagined this scenario in miniature, inside an iron bar. Suppose that an unmagnetized iron cylinder was suspended by a fine, flexible fiber [*see illustration on opposite page*] and that suddenly a strong magnetic field was applied, enough to magnetize the cylinder by orienting all the little electron orbits. If he was correct, many of the little randomly oriented electron orbits would then be aligned. Their angular momenta would suddenly add instead of canceling. And again, just as the lazy Susan did, the cylinder would rotate to compensate. This was the notion behind the experiment. In time, amazingly, Einstein and de Haas succeeded in eliciting results from the remarkably delicate apparatus they built subsequently. But from where did this concept come, and why just then in 1915, amid the worst war and his own high-stakes struggle to define general relativity?

For an answer, one must look back to the period after Einstein's graduation from the Zurich Polytechnic in 1900, years during which he found it difficult to find gainful employment. Rejection letters piled up until mid-1902, when he finally received a very welcome job offer from the Bern Patent Office. Although Einstein had battled with one teacher after another during his school years, he admired and learned much from the head of the patent office, Friedrich Haller. Einstein learned



GYROCOMPASSES use forces generated by the earth's rotation to locate north regardless of position on the globe. Early Anschütz-Kaempfe design is weighted so that gravity keeps it level. As the planet turns, the spinning gyro axle also rotates along with the surface of the earth. Because the gyro tries to hold itself level, the result is precession, an effect that moves the gyro's axle at a right angle to the applied force; the phenomenon is akin to that seen when a child's top wobbles as it slows. Precession eventually leads the axle to point north (*images left to right*).

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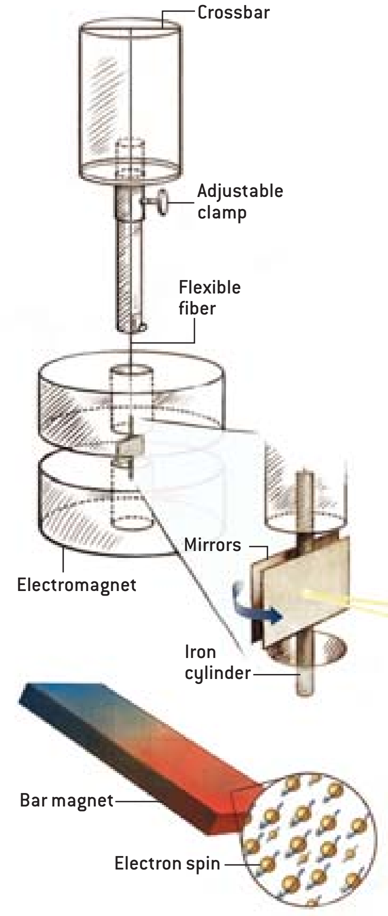
to adhere strictly to Haller's injunction to "remain critically vigilant"—to view inventors' claims with skepticism.

Einstein loved machines and corresponded with other enthusiasts about them; he even built new ones in his apartment. Over the years he patented refrigerators, invented new electrical measurement devices and advised his friends about machinery. Indeed, his father and uncle had long run an electrotechnical business and had patented their own inventions. Sadly for us, nearly all of Einstein's patent evaluations were, by law, destroyed, but a few remain—in particular, those that made their way into court proceedings. That is because Einstein soon became one of the most esteemed technical authorities in the patent office and thus a much appreciated expert witness.

Herein lies the key to understanding Einstein's fascination with magnetism. In the early 20th century the tried-and-true magnetic compass began to suffer difficulties. It worked poorly on new ships, which were becoming metallic and electrified, and functioned badly inside submarines or near the earth's poles. And the standard compass was problematic in aircraft because its directional indicator led and lagged during turns.

Two companies took up the compass problem, one headed by American inventor and industrialist Elmer A. Sperry and the other by his German archrival, Hermann Hubertus Maria Anschütz-Kaempfe. The solution was to convert powered gyroscopes into compasses. Anschütz-Kaempfe cleverly built the casing of his gyroscope so that it would precess (slowly cycle its axial orientation) in such a way that its axis lined up with the rotational axis of the earth [*see illustrations on opposite page*]. Soon afterward, Sperry produced a similar instrument. Anschütz-Kaempfe promptly sued for patent infringement. Sperry mounted the usual defense: he was merely following an older, preexisting idea.

In mid-1915 Einstein was called in to serve as an expert witness. His testimony showed, to the court's satisfaction, that the earlier gimbaled gyroscopes could not possibly have worked as compasses, because they were designed to move only within a very tight range inside their casings—a ship's slightest pitch and yaw would render them useless. Anschütz-Kaempfe won the case. Einstein went on to become sufficiently expert in gyrocompass technology to collect royalties for his work in this field for decades to come.



EXPERIMENTAL APPARATUS that Einstein and de Haas used to prove their theory explaining the magnetism of iron is shown. They suspended an unmagnetized iron cylinder by a flexible fiber and then applied a strong magnetic field. According to their theory, the cylinder would rotate because the field would align the orbits of electrons inside. Mirrors attached to the cylinder (*detail*) reflected a light beam as it turned—providing proof of their theory. It was later determined that electron spin (rotation in place), not electron orbits, produced the magnetism in iron. A bar magnet, for example, is magnetic because the spins of its electrons line up (*bottom*).

MATT COLLINS

Einstein's royalties in the science of physics proved to be even greater, however: "I was led to the demonstration of the nature of the paramagnetic atom through technical reports I had prepared on the gyromagnetic compass" [Einstein to E. Meyerson, January 27, 1930, Einstein Archives Online]. He saw that just as the earth's rotation oriented a gyrocompass, a cylinder of iron could be made to rotate by orienting all the little atomic gyroscopes inside it. The experiment turned out to be a spectacular success [*see illustration at left*]. Einstein and de Haas had demonstrated an effect so subtle that even the great James Clerk Maxwell had failed to discern it.

But this story has a twist. The two physicists showed excellent agreement between the theory (ferromagnetism caused by orbiting electrons) and their experiment. Unfortunately, their striking result soon came under attack—cautiously at first, then with growing insistence. It seemed that their measurement of magnetism per unit of angular momentum was off by a factor of two, a difference no one could adequately explain until much later, after the development of quantum mechanics and the concept of electron spin. It seems that Einstein's commitment to a particular theoretical model had cut two ways. On the one hand, it had given him real conviction about how to organize and conduct the experiment—specifically, where to look for the effect. Maxwell and others who had failed before had no feeling for the magnitude of the phenomenon. On the other hand, the theoretical model Einstein chose made it easy to accept an experimental answer when blackboard calculation and laboratory results agreed—despite the existence of many potentially interfering factors, which included such things as the effect of the earth's magnetic field and the vagaries of the fragile lab apparatus itself.

The tale reminds me of one of Einstein's wonderful sayings: "No one but a theorist believes his theory; everyone puts faith in a laboratory result but the experimenter himself." SA

MORE TO EXPLORE

A more detailed study of Einstein's patent work and experiment can be found in Galison's *How Experiments End* (University of Chicago Press, 1987).

A COSMIC CONUNDRUM

A new incarnation of Einstein's cosmological constant may point the way beyond general relativity

By Lawrence M. Krauss and Michael S. Turner

In 1917 Albert Einstein faced a confusing problem as he tried to reconcile his new theory of gravity, the general theory of relativity, with the limited understanding of the universe at the time. Like most of his contemporaries, Einstein was convinced that the universe must be static—neither expanding nor contracting—but this desired state was not consistent with his equations of gravity. In desperation, Einstein added an extra, ad hoc cosmological term to his equations to counterbalance gravity and allow for a static solution.

Twelve years later, though, American astronomer Edwin Hubble discovered that the universe was far from static. He found that remote galaxies were swiftly receding from our own at a rate that was proportional to their distance. A cosmological term was not needed to explain an expanding universe, so Einstein abandoned the concept. Russian-American physicist George Gamow declared in his autobiography that "when I was discussing cosmological problems with Einstein, he remarked that the introduction of the cosmological term was the biggest blunder he ever made in his life."

In the past six years, however, the cosmological term—now called the cosmological constant—has reemerged to play a central role in 21st-century physics. But the motivation for this resurrection is actually very different from Einstein's original thinking; the new version of the term arises from recent observations of an accelerating universe and, ironically, from the principles of quantum mechanics, the branch of physics that Einstein so famously abhorred. Many physicists now expect the cosmological term to provide the key to moving beyond Einstein's theory to a deeper understanding of space, time, and gravity and perhaps to a quantum theory that unifies gravity with the other

DON DIXON

LONELY UNIVERSE may be our ultimate fate if the cosmic expansion keeps accelerating—a phenomenon believed to be caused by the cosmological constant. The orange spheres represent the observable universe, which grows at the speed of light; the blue spheres represent an expanding patch of space. As expansion accelerates, fewer galaxy clusters are observable.

OVERVIEW

- Quantum mechanics and relativity, combined with recent evidence of an accelerating universe, have led physicists to resurrect the cosmological term that Einstein introduced and later repudiated. But this term now represents a mysterious form of energy that permeates empty space and drives an accelerated cosmic expansion.
- The efforts to explain the origin of this energy may help scientists move beyond Einstein's theory in ways that are likely to change our fundamental understanding of the universe.

fundamental forces of nature. It is too soon to say what the ultimate resolution will be, but it is likely to change our picture of the universe.

In its current incarnation, the cosmological term arises not from relativity but from quantum mechanics.

Birth of a Constant

GENERAL RELATIVITY grew out of a decade-long struggle by Einstein to follow up on his pivotal observation in 1907 that gravity and accelerated motion are equivalent. As expressed in Einstein's well-known thought experiment, the physics inside an elevator sitting at rest in a uniform gravitational field of strength g is exactly the same as the physics inside an elevator that is rocketing through empty space with a uniform acceleration of g.

Einstein was also strongly influenced by the philosophical notions of Austrian physicist Ernst Mach, who rejected the idea of an absolute frame of reference for spacetime. In Newtonian physics, inertia refers to the tendency of an object to move with constant velocity unless acted on by a force. The notion of constant velocity requires an inertial (that is, not accelerating) frame of reference. But not accelerating with respect to what? Newton postulated the existence of absolute space, an immovable frame of reference that defined all local inertial frames. Mach, though, proposed that the distribution of matter in the universe defined inertial frames, and to a large extent Einstein's general theory of relativity embodies this notion.

Einstein's theory was the first concept of gravity that offered a hope of providing a self-consistent picture of the whole universe. It allowed a description not only of how objects move through space and time but of how space and time themselves dynamically evolve. In using his new theory to try to describe the universe, Einstein sought a solution that was finite, static and adhered to Mach's principles (for instance, a finite distribution of matter trailing off into emptiness did not seem to satisfy Mach's notion of matter being necessary to define space). These three prejudices led Einstein to introduce the cosmological term to construct a static solution that was finite and yet had no boundaries—his universe curved back on itself like the surface of a balloon [*see illustration on page 74*]. Physically, the cosmological term would have been unobservable on the scale of our solar system, but it would produce a cosmic repulsion on larger scales that would counteract the gravitational attraction of distant objects.

Einstein's enthusiasm for the cosmological term began to wane quickly, however. In 1917 Dutch cosmologist Willem de Sitter demonstrated that he could produce a spacetime solution with a cosmological term even in the absence of matter—a very non-Machian result. This model was later shown to be nonstatic. In 1922 Russian physicist Alexander Friedmann constructed models of expanding and contracting universes that did not require a cosmological term. And in 1930 British astrophysicist Arthur Eddington showed that Einstein's universe was not really static: because gravity and the cosmological term were so precariously balanced, small perturbations would lead to runaway contraction or expansion. By 1931, with the expansion of the universe firmly established by Hubble, Einstein formally abandoned the cosmological term as "theoretically unsatisfactory anyway."

Hubble's discovery obviated the need for the cosmological term to counteract gravity; in an expanding universe, gravity simply slows the expansion. The question then became, Is gravity strong enough to eventually stop the expansion and cause the universe to collapse, or will the cosmos expand forever? In the Friedmann models, the answer is tied to the average density of matter: a high-density universe will collapse, whereas a low-density universe will expand eternally. The dividing point is the critical-density universe, which expands forever albeit at an ever decreasing rate. Because, in Einstein's theory, the average curvature of the universe is tied to its average density, geometry and destiny are linked. The high-density universe is positively curved like the surface of a balloon, the low-density universe is negatively curved like the surface of a saddle, and the critical-density universe is spatially flat. Thus, cosmologists came to believe that determining the universe's geometry would reveal its ultimate fate.

The Energy of Nothing

THE COSMOLOGICAL TERM was banished from cosmology for the next six decades (except for a brief reappearance as part of the steady-state universe, a theory propounded in the late 1940s but decisively ruled out in the 1960s). But perhaps the most surprising thing about the term is that even if Einstein had not introduced it in a rush of confusion following his development of general relativity, we now realize that its presence seems to be inevitable. In its current incarnation, the cosmological term arises not from relativity, which governs nature on its largest scales, but from quantum mechanics, the physics of the smallest scales.

This new concept of the cosmological term is quite different from the one Einstein introduced. His original field equation, $G_{\mu\nu} = 8\pi G T_{\mu\nu}$, relates the curvature of space, $G_{\mu\nu}$, to the distribution of matter and energy, $T_{\mu\nu}$, where G is Newton's constant characterizing the strength of gravity. When Einstein added the cosmological term, he placed it on the left-hand side of the equation, suggesting it was a property of space itself [*see box at right*]. But if one moves the cosmological term to the right-hand side, it takes on a radically new meaning, the one it has today. It now represents a bizarre new form of energy density that remains constant even as the universe expands and whose gravity is repulsive rather than attractive.

Lorentz invariance, the fundamental symmetry associated with both the special and general theories of relativity, implies that only empty space can have this kind of energy density. Put in this perspective, the cosmological term seems even more bizarre. If asked what the energy of empty space is, most people would say "nothing." That is, after all, the only intuitively sensible value.

Alas, quantum mechanics is anything but intuitive. On the very small scales where quantum effects become important, even empty space is not really empty. Instead virtual particle-antiparticle pairs pop out of the vacuum, travel for short distances and then disappear again on timescales so fleeting that one cannot observe them directly. Yet their indirect effects are very important and can be measured. For example, the virtual particles affect the spectrum of hydrogen in a calculable way that has been confirmed by measurements.

Once we accept this premise, we should be prepared to contemplate the possibility that these virtual particles might endow empty space with some nonzero energy. Quantum mechanics thus makes the consideration of Einstein's cosmological term obligatory rather than optional. It cannot be dismissed as "theoretically unsatisfactory." The problem, however, is that all calculations and estimates of the magnitude of the empty-space energy lead to absurdly large values—ranging from 55 to 120 orders of magnitude greater than the energy of all the matter and radiation in the observable universe. If the vacuum energy density were really that high, all matter in the universe would instantly fly apart.

THE COSMOLOGICAL TERM

A Change of Meaning

The heart of Einstein's general theory of relativity is the field equation, which states that the geometry of spacetime ($G_{\mu\nu}$, Einstein's curvature tensor) is determined by the distribution of matter and energy ($T_{\mu\nu}$, the stress-energy tensor), where G is Newton's constant characterizing the strength of gravity. (A tensor is a geometric or physical quantity that can be represented by an array of numbers.) In other words, matter and energy tell space how to curve.

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

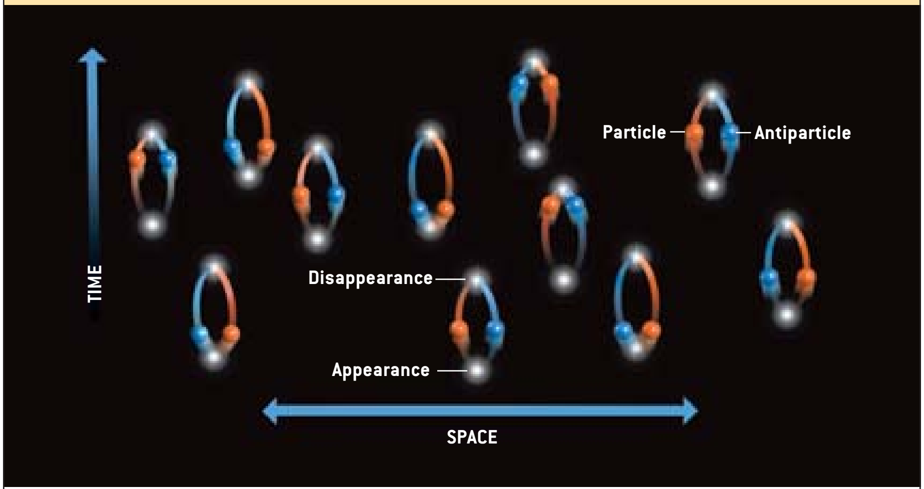
To create a model of a static universe, Einstein introduced the cosmological term Λ to counterbalance gravity's attraction on cosmic scales. He added the term (multiplied by $g_{\mu\nu}$, the spacetime metric tensor, which defines distances) to the left side of the field equation, suggesting that it was a property of space itself. But he abandoned the term once it became clear that the universe was expanding.

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

The new cosmological term now being studied by physicists is necessitated by quantum theory, which holds that empty space may possess a small energy density. This term—ρ_{VAC}, the energy density of the vacuum, multiplied by $g_{\mu\nu}$—must go on the right side of the field equation with the other forms of energy.

$$G_{\mu\nu} = 8\pi G\,(T_{\mu\nu} + \rho_{VAC}\, g_{\mu\nu})$$

Although Einstein's cosmological term and the quantum vacuum energy are mathematically equivalent, conceptually they could not be more different: the former is a property of space, the latter a form of energy that arises from virtual particle-antiparticle pairs. Quantum theory holds that these virtual particles constantly pop out of the vacuum, exist for a very brief time and then disappear (*below*).



THE AUTHORS

LAWRENCE M. KRAUSS and *MICHAEL S. TURNER* were among the first cosmologists to argue that the universe is dominated by a cosmological term that is radically different from the one introduced and then repudiated by Einstein. Their 1995 prediction of cosmic acceleration was confirmed by astronomical observations three years later. Chair of the physics department at Case Western Reserve University, Krauss has also written seven popular books, including *The Physics of Star Trek* and the soon-to-be-released *Hiding in the Mirror: The Mysterious Allure of Extra Dimensions*. Turner, who is Rauner Distinguished Service Professor at the University of Chicago, is now serving as the assistant director for mathematical and physical sciences at the National Science Foundation.

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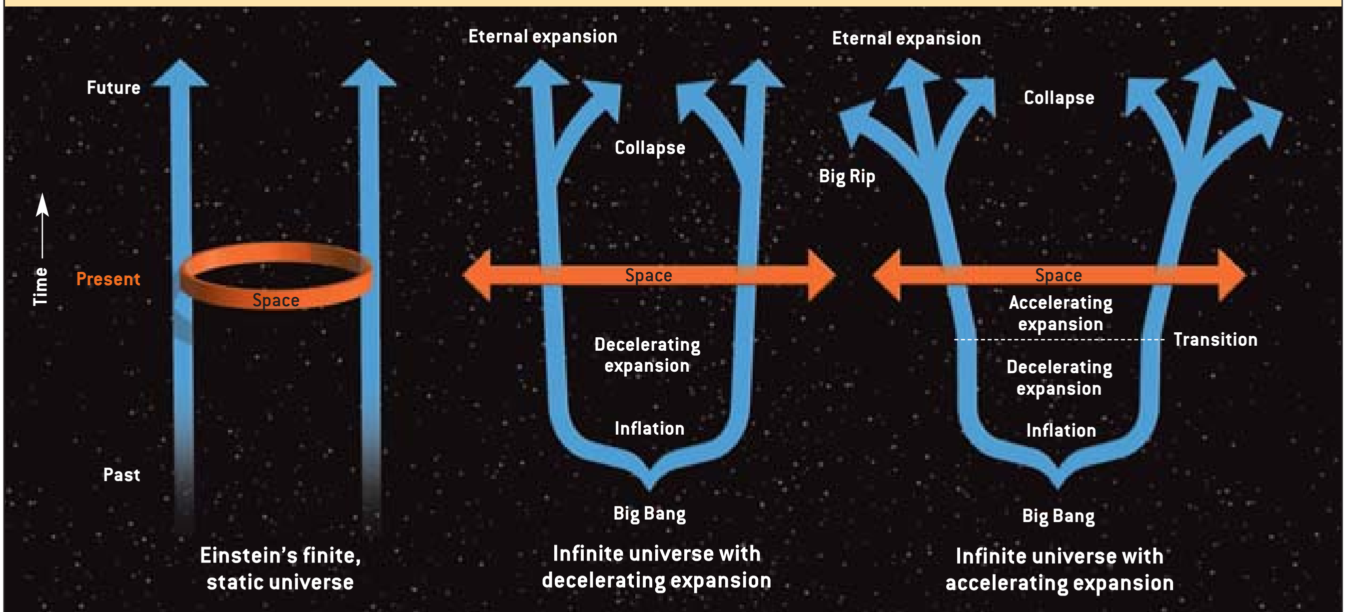
EVOLVING THEORIES

Models of the Cosmos: Then and Now

Einstein's cosmological model (*left*) was a universe finite in space but infinite in time, remaining the same fixed size for eternity. This universe has no spatial boundaries; it curves back on itself like a circle. After the discovery of cosmic expansion, cosmologists constructed a model of an infinite universe in which the rate of expansion continuously slowed because of gravity (*center*), possibly leading to collapse. In the 1980s theorists added an early phase of rapid growth called inflation, for which there is now good evidence. In the past six years observations have shown that the cosmic expansion began to accelerate about five billion years ago (*right*). The ultimate fate of the universe—continued expansion, collapse or a hyper speedup called the big rip—depends on the nature of the mysterious dark energy driving the accelerated expansion.



This problem has been a thorn in the side of theorists for at least 30 years. In principle, it should have been recognized as early as the 1930s, when calculations of the effects of virtual particles were first performed. But in all areas of physics other than those related to gravity, the absolute energy of a system is irrelevant; what matters are the energy differences between states (for example, the energy differences between an atom's ground state and its excited states). If a constant is added to all the energy values, it drops out of such calculations, making it easy to ignore. Moreover, at that time few physicists took cosmology seriously enough to worry about applying quantum theory to it.

But general relativity implies that all forms of energy, even the energy of nothing, act as a source of gravity. Russian physicist Yakov Borisovich Zel'dovich realized the significance of this problem in the late 1960s, when he made the first estimates of the energy density of the vacuum. Since that time, theorists have been trying to figure out why their calculations yield such absurdly high values. Some undiscovered mechanism, they reasoned, must cancel the great bulk of the vacuum energy, if not all of it. Indeed, they assumed that the most plausible value for the energy density is zero—even quantum nothingness should weigh nothing.

As long as theorists believed in the back of their minds that such a canceling mechanism might exist, they could place the cosmological term problem on the back burner. Although it was fascinating, it could be ignored. Nature, however, has intervened.

Back with a Vengeance

THE FIRST DEFINITIVE evidence that something was amiss came from measurements of the slowing of the expansion rate of the universe. Recall that Hubble found that the relative velocities of remote galaxies were proportional to their distance from our own galaxy. From the point of view of general relativity, this relation arises from the expansion of space itself, which should slow down over time because of gravitational attraction. And because very distant galaxies are seen as they were billions of years ago, the slowing of the expansion should lead to a curvature of the otherwise linear Hubble relation—the most distant galaxies should be receding faster than Hubble's law would predict. The trick, though, is accurately determining the distances and velocities of very remote galaxies.

Such measurements rely on finding standard candles—objects of known intrinsic luminosity that are bright enough to be seen across the universe. A breakthrough came in the 1990s with the calibration of type Ia supernovae, which are believed to be the thermonu-

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clear explosions of white dwarf stars about 1.4 times the mass of the sun. Two teams—the Supernova Cosmology Project, led by Saul Perlmutter of Lawrence Berkeley National Laboratory, and the High-z Supernova Search Team, led by Brian Schmidt of Mount Stromlo and Siding Spring Observatories—set out to measure the slowing of the expansion of the universe using this type of supernova. In early 1998 both groups made the same startling discovery: over the past five billion years, the expansion has been speeding up, not slowing down [see "Cosmological Antigravity," by Lawrence M. Krauss; SCIENTIFIC AMERICAN, January 1999]. Since then, the evidence for a cosmic speedup has gotten much stronger and has revealed not only a current accelerating phase but an earlier epoch of deceleration [see "From Slowdown to Speedup," by Adam G. Riess and Michael S. Turner; SCIENTIFIC AMERICAN, February].

The supernova data, however, are not the only evidence pointing to the existence of some new form of energy driving the cosmic expansion. Our best picture of the early universe comes from observations of the cosmic microwave background (CMB), residual radiation from the big bang that reveals features of the universe at an age of about 400,000 years. In 2000, measurements of the angular size of variations of the CMB across the sky were good enough for researchers to determine that the geometry of the universe is flat. This finding was confirmed by a CMB-observing spacecraft called the Wilkinson Microwave Anisotropy Probe and other experiments.

A spatially flat geometry requires that the universe's average density must equal the critical density. But many different measurements of all forms of matter—including cold dark matter, a putative sea of slowly moving particles that do not emit light but do exert attractive gravity—showed that matter contributes only about 30 percent of the critical density. A flat universe therefore requires some other form of smoothly distributed energy that would have no observable influence on local clustering and yet could account for 70 percent of the critical density. Vacuum energy, or something very much like it, would produce precisely the desired effect.

In addition, a third line of reasoning suggested that cosmic acceleration was the missing piece of the cosmological puzzle. For two decades, the paradigm of inflation plus cold dark matter has been the leading explanation for the structure of the universe. The theory of inflation holds that in its very first moments the universe underwent a tremendous burst of expansion that smoothed and flattened its geometry and blew up quantum fluctuations in energy density from subatomic to cosmic size. This event produced the slightly inhomogeneous distribution of matter that led to the variations seen in the CMB and to the observed structures in the universe today. The gravity of cold dark matter, which far outweighs ordinary matter, governed the formation of these structures.

By the mid-1990s, however, this paradigm was seriously challenged by observational data. The predicted level of matter clustering differed from what was being measured. Worse, the predicted age of the universe appeared to be younger than the ages of the oldest stars. In 1995 the two of us pointed out that these contradictions would disappear if vacuum energy accounted for about two thirds of the critical density. (This model was very different from Einstein's closed universe, in which the density of the cosmological term was half that of matter.) Given the checkered history of vacuum energy, our proposal was, at the very least, provocative.

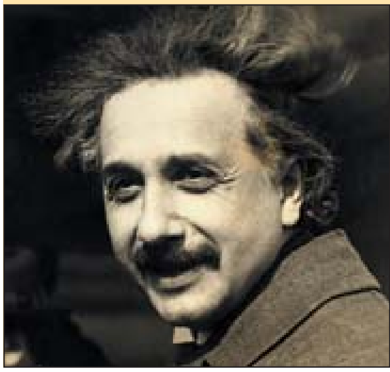
A decade later, though, everything fits together. In addition to explaining the current cosmic acceleration and the earlier period of deceleration, a resurrected cosmological term pushes the age of the universe to almost 14 billion years (comfortably above the ages of the oldest stars) and adds exactly enough energy to bring the universe to the critical density. But physicists still do not know whether this energy actually comes from the quantum vacuum. The importance of discovering the cause of cosmic acceleration has brought a whole new urgency to the efforts to quantify vacuum energy. The problem of determining the weight of nothing can no longer be put aside for future generations. And the puzzle now seems even more confounding than it did when physicists were trying to devise a theory that would cancel vacuum energy. Now theorists must explain why vacuum energy might not be zero but so small that its effects on the cosmos became relevant only a few billion years ago.

Cosmological observations may illuminate the relation between gravity and quantum mechanics at a fundamental level.

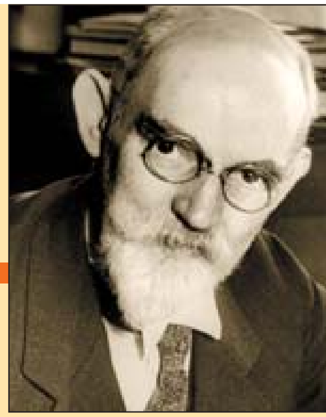
Of course, nothing could be more exciting to scientists than a puzzle of this magnitude, richness and importance. Just as Einstein was led to general relativity by considering the incompatibility of special relativity and Newton's theory of gravity, physicists today believe that Einstein's theory is incomplete because it cannot consistently incorporate the laws of quantum mechanics. But cosmological observations may illuminate the relation between gravity and quantum mechanics at a fundamental level. It was the equivalence of accelerated frames and grav-

A Checkered History

Since Einstein conceived the cosmological term almost 90 years ago, it has been repudiated, refashioned and resurrected. Here are some highlights.

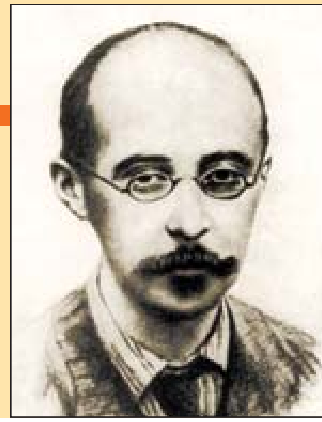


FEB. 1917: Einstein introduces the cosmological term to counteract gravity, allowing him to build a theoretical model of a static, finite universe.



MARCH 1917: Dutch cosmologist Willem de Sitter produces an alternative model with a cosmological term. This model is later shown to have accelerating expansion.

1922: Russian physicist Alexander Friedmann constructs models of expanding and contracting universes without a cosmological term.



ity that pointed the way for Einstein; perhaps another kind of acceleration, the cosmic speedup, will point the way today. And theorists have already outlined some ideas about how to proceed.

The Superworld

STRING THEORY, which is now often called M-theory, is viewed by many physicists as a promising approach to marrying quantum mechanics with gravity. One of the basic ideas underlying this theory is called supersymmetry, or SUSY. SUSY is a symmetry between particles of half-integer spin (fermions such as quarks and leptons) and those of whole-integer spin (bosons such as photons, gluons and other force carriers). In a world in which SUSY is fully manifest, a particle and its superpartner would have the same mass; for example, the supersymmetric electron (called the selectron) would be as light as the electron, and so on. In this superworld, moreover, it can be proved that quantum nothingness would weigh nothing and that the vacuum would have zero energy.

In the real world, however, we know that no selectron as light as the electron can exist because physicists would have already detected it in particle accelerators. (Theorists speculate that superpartner particles are millions of times heavier than electrons and thus cannot be found without the help of more powerful accelerators.) SUSY must therefore be a broken symmetry, which suggests that quantum nothingness might weigh something.

Physicists have produced models of broken supersymmetry yielding a vacuum energy density that is many orders of magnitude smaller than the absurdly high estimates made previously. But even this theorized density is far larger than that indicated by cosmological observations. Recently, however, researchers have recognized that M-theory appears to allow for an almost infinite number of different solutions. Although almost all these possible solutions would indeed result in a vacuum energy that is far too high, some might produce a vacuum energy as low as the value that cosmologists have observed [see "The String Theory Landscape," by Raphael Bousso and Joseph Polchinski, on page 78].

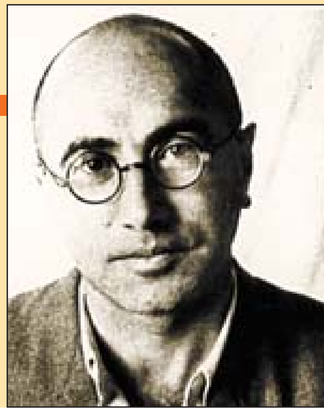
Another hallmark of string theory is the positing of additional dimensions. Current theory adds six or seven spatial dimensions, all hidden from view, to the usual three. This construct offers another approach to explaining cosmic acceleration. Georgi Dvali of New York University and his collaborators have suggested that the effect of extra dimensions may show up as an additional term in Einstein's field equation that leads to an accelerated expansion of the universe [see "Out of the Darkness," by Georgi Dvali; SCIENTIFIC AMERICAN, February]. This approach runs counter to long-held expectations: for decades, it had been assumed that the place to look for differences between general relativity and its successor theory would be at short distances, not cosmic ones. Dvali's plan flies in the face of this wisdom—if he is correct, the first harbinger of a new cosmic understanding will be at the largest distances, not the smallest.

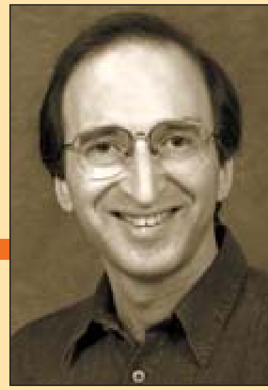
The discovery of cosmic acceleration has forever altered our thinking about the future. Destiny is no longer tied to geometry.

UNDERWOOD & UNDERWOOD/CORBIS (*Einstein*); YERKES OBSERVATORY (*de Sitter*); *SOVIET PHYSICS-USPEKHI*, COURTESY OF AIP EMILIO SEGRÈ VISUAL ARCHIVES (*Friedmann*)

1929: American astronomer Edwin Hubble discovers that the universe is expanding. Two years later Einstein abandons the cosmological term, calling it "theoretically unsatisfactory anyway."

1967: Russian physicist Yakov Borisovich Zel'dovich estimates the energy density of the quantum vacuum and finds that it would make an immense cosmological term.





1998: Two teams of supernova hunters led by Saul Perlmutter (*left*) and Brian Schmidt (*right*) report that the cosmic expansion is accelerating. A refashioned cosmological term would produce this effect. Since 1998 the evidence for cosmic acceleration has strengthened.

It is possible that the explanation of cosmic acceleration will have nothing to do with resolving the mystery of why the cosmological term is so small or how Einstein's theory can be extended to include quantum mechanics. General relativity stipulates that an object's gravity is proportional to its energy density plus three times its internal pressure. Any energy form with a large, negative pressure—which pulls inward like a rubber sheet instead of pushing outward like a ball of gas—will therefore have repulsive gravity. So cosmic acceleration may simply have revealed the existence of an unusual energy form, dubbed dark energy, that is not predicted by either quantum mechanics or string theory.

Geometry vs. Destiny

IN ANY CASE, the discovery of cosmic acceleration has forever altered our thinking about the future. Destiny is no longer tied to geometry. Once we allow for the existence of vacuum energy or something similar, anything is possible. A flat universe dominated by positive vacuum energy will expand forever at an ever increasing rate [*see illustration on page 70*], whereas one dominated by negative vacuum energy will collapse. And if the dark energy is not vacuum energy at all, then its future impact on cosmic expansion is uncertain. It is possible that, unlike a cosmological constant, the density of dark energy may rise or fall over time. If the density rises, the cosmic acceleration will increase, tearing apart galaxies, solar systems, planets and atoms, in that order, after a finite amount of time. But if the density falls, the acceleration could stop. And if the density becomes negative, the universe could collapse. The two of us have demonstrated that without knowing the detailed origin of the energy currently driving the expansion, no set of cosmological observations can pin down the ultimate fate of the universe.

To resolve this puzzle, we may need a fundamental theory that allows us to predict and categorize the gravitational impact of every single possible contribution to the energy of empty space. In other words, the physics of nothingness will determine the fate of our universe! Finding the solution may require new measurements of the cosmic expansion and of the structures that form within it to provide direction for theorists. Fortunately, many experiments are being planned, including a space telescope dedicated to observing distant supernovae and new telescopes on the ground and in space to probe dark energy through its effect on the development of large-scale structures.

Our knowledge of the physical world usually develops in an atmosphere of creative confusion. The fog of the unknown led Einstein to consider a cosmological term as a desperate solution to constructing a static, Machian universe. Today our confusion about cosmic acceleration is driving physicists to explore every avenue possible to understand the nature of the energy that is driving the speedup. The good news is that although many roads may lead to dead ends, the resolution of this profound and perplexing mystery may eventually help us unify gravity with the other forces in nature, which was Einstein's fondest hope. SA

MORE TO EXPLORE

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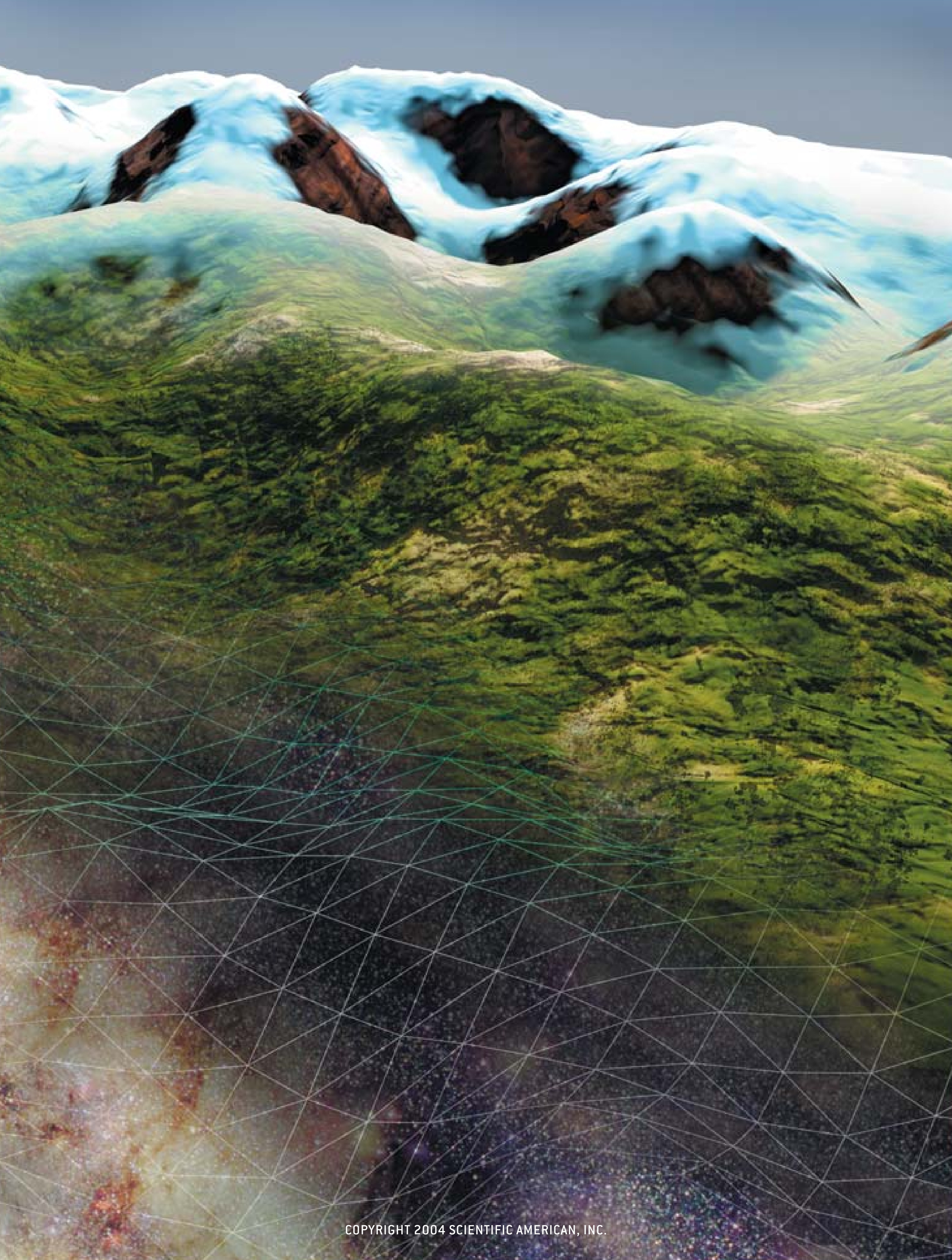


THE STRING THEORY LANDSCAPE

The theory of strings predicts that the universe might occupy one random "valley" out of a virtually infinite selection of valleys in a vast landscape of possibilities

By Raphael Bousso and Joseph Polchinski

DON FOLEY

THEORETICAL LANDSCAPE populated with an array of innumerable possible universes is predicted by string theory. The landscape has perhaps 10^{500} valleys, each one of which corresponds to a set of laws of physics that may operate in vast bubbles of space. Our visible universe would be one relatively small region within one such bubble.

OVERVIEW

- According to string theory, the laws of physics that we see operating in the world depend on how extra dimensions of space are curled up into a tiny bundle.
- A map of all possible configurations of the extra dimensions produces a "landscape" wherein each valley corresponds to a stable set of laws.
- The entire visible universe exists within a region of space that is associated with a valley of the landscape that happens to produce laws of physics suitable for the evolution of life.

According to Albert Einstein's theory of general relativity, gravity arises from the geometry of space and time, which combine to form spacetime. Any massive body leaves an imprint on the shape of spacetime, governed by an equation Einstein formulated in 1915. The earth's mass, for example, makes time pass slightly more rapidly for an apple near the top of a tree than for a physicist working in its shade. When the apple falls, it is actually responding to this warping of time. The curvature of spacetime keeps the earth in its orbit around the sun and drives distant galaxies ever farther apart. This surprising and beautiful idea has been confirmed by many precision experiments.

Given the success of replacing the gravitational force with the dynamics of space and time, why not seek a geometric explanation for the other forces of nature and even for the spectrum of elementary particles? Indeed, this quest occupied Einstein for much of his life. He was particularly attracted to work by German Theodor Kaluza and Swede Oskar Klein, which proposed that whereas gravity reflects the shape of the four familiar spacetime dimensions, electromagnetism arises from the geometry of an additional fifth dimension that is too small to see directly (at least so far). Einstein's search for a unified theory is often remembered as a failure. In fact, it was premature: physicists first had to understand the nuclear forces and the crucial role of quantum field theory in describing physics—an understanding that was only achieved in the 1970s.

The search for a unified theory is a central activity in theoretical physics today, and just as Einstein foresaw, geometric concepts play a key role. The Kaluza-Klein idea has been resurrected and extended as a feature of string theory, a promising framework for the unification of quantum mechanics, general relativity and particle physics. In both the Kaluza-Klein conjecture and string theory, the laws of physics that we see are controlled by the shape and size of additional microscopic dimensions. What determines this shape? Recent experimental and theoretical developments suggest a striking and controversial answer that greatly alters our picture of the universe.

String theory's equations imply that **six extra dimensions exist** that are too small to have yet been detected.

Kaluza-Klein Theory and Strings

KALUZA AND KLEIN put forth their concept of a fifth dimension in the early part of the 20th century, when scientists knew of two forces—electromagnetism and gravity. Both fall off inversely proportional to the square of the distance from their source, so it was tempting to speculate that they were connected in some way. Kaluza and Klein noticed that Einstein's geometric theory of gravity might provide this connection if an additional spatial dimension existed, making spacetime five-dimensional.

This idea is not as wild as it seems. If the extra spatial dimension is curled up into a small enough circle, it will have eluded our best microscopes—that is, the most powerful particle accelerators [*see box on opposite page*]. Moreover, we already know from general relativity that space is flexible. The three dimensions that we see are expanding and were once much smaller, so it is not such a stretch to imagine that there is another dimension that remains small today.

Although we cannot detect it directly, a small extra dimension would have important indirect effects that could be observed. General relativity would then describe the geometry of a five-dimensional spacetime. We can split this geometry into three elements: the shape of the four large spacetime dimensions, the angle between the small dimension and the others, and the circumference of the small dimension. The large spacetime behaves according to ordinary four-dimensional general relativity. At every location within it, the angle and circumference have some value, just like two fields permeating spacetime and taking on certain values at each location. Amazingly, the angle field turns out to mimic an electromagnetic field living in the four-dimensional world. That is, the equations governing its behavior are identical to those of electromagnetism. The circumference determines the relative strengths of the electromagnetic and gravitational forces. Thus, from a theory of gravity alone in five dimensions, we obtain a theory of both gravity and electromagnetism in four dimensions.

The possibility of extra dimensions has also come to play a vital role in unifying general relativity and quantum mechanics. In string theory, a leading approach to that unification, particles are in actuality one-dimensional objects, small vibrating loops or strands. The typical size of a string is near

THE AUTHORS

RAPHAEL BOUSSO and *JOSEPH POLCHINSKI*'s work together began at a workshop on string duality in Santa Barbara. It grew out of the synergy between Bousso's background in quantum gravity and inflationary cosmology and Polchinski's background in string theory. Bousso is assistant professor of physics at the University of California, Berkeley. His research includes a general formulation of the holographic principle, which relates spacetime geometry to its information content. Polchinski is a professor at the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. His contributions to string theory include the seminal idea that branes constitute a significant feature of the theory.

the Planck length, or 10^{-33} centimeter (less than a billionth of a billionth of the size of an atomic nucleus). Consequently, a string looks like a point under anything less than Planckian magnification.

For the theory's equations to be mathematically consistent, a string has to vibrate in 10 spacetime dimensions, which implies that six extra dimensions exist that are too small to have yet been detected. Along with the strings, sheets known as "branes" (derived from "membranes") of various dimensions can be immersed in spacetime. In the original Kaluza-Klein idea, the quantum wave functions of ordinary particles would fill the extra dimension—in effect, the particles themselves would be smeared across the extra dimension. Strings, in contrast, can be confined to lie on a brane. String theory also contains fluxes, or forces that can be represented by field lines, much as forces are represented in classical (nonquantum) electromagnetism.

Altogether the string picture looks more complicated than Kaluza-Klein theory, but the underlying mathematical structure is actually more unified and complete. The central theme of Kaluza-Klein theory remains: the physical laws that we see depend on the geometry of hidden extra dimensions.

Too Many Solutions?

THE KEY QUESTION IS, What determines this geometry? The answer from general relativity is that spacetime must satisfy Einstein's equations—in the words of John Wheeler of Princeton University, matter tells spacetime how to curve, and spacetime tells matter how to move. But the solution to the equations is not unique, so many different geometries are allowed. The case of five-dimensional Kaluza-Klein geometry provides a simple example of this nonuniqueness. The circumference of the small dimension can take any size at all: in the absence of matter, four large flat dimensions, plus a circle of any size, solve Einstein's equations. (Similar multiple solutions also exist when matter is present.)

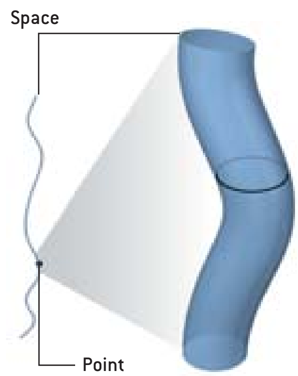
In string theory we have several extra dimensions, which results in many more adjustable parameters. One extra dimension can be wrapped up only in a circle. When more than one extra dimension exists, the bundle of extra dimensions can have many different shapes (technically, "topologies"), such as a sphere, a doughnut, two doughnuts joined together and so on. Each doughnut loop (a "handle") has a length and a circumference, resulting in a huge assortment of possible geometries for the small dimensions. In addition to the handles, further parameters correspond to the locations of branes and the different amounts of flux wound around each loop [*see box on page 83*].

Yet the vast collection of solutions are not all equal: each configuration has a potential energy, contributed by fluxes, branes and the curvature itself of the curled-up dimensions. This energy is called the vacuum energy, because it is the energy of the spacetime when the large four dimensions are completely devoid of matter or fields. The geometry of the small dimensions will try to adjust to minimize this energy, just as a ball

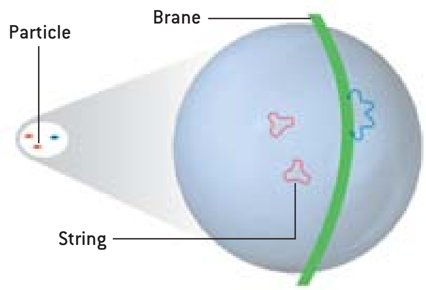
EXTRA DIMENSIONS

Strings and Tubes

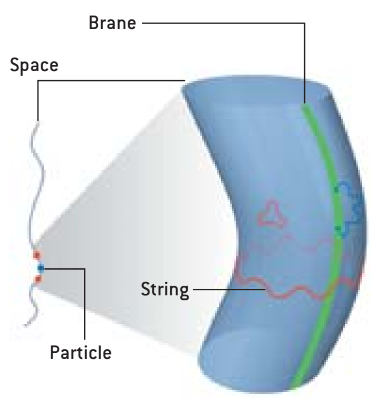
Extra spatial dimensions beyond the three we perceive are postulated by Kaluza-Klein theory and string theory. To imagine those dimensions, which are tiny, consider a space that consists of a long, very thin tube. Viewed from a distance, the tube looks like a one-dimensional line, but under high magnification, its cylindrical shape becomes apparent. Each zero-dimensional point on the line is revealed to be a one-dimensional circle of the tube. In the original Kaluza-Klein theory, every point in our familiar three-dimensional space is actually a tiny circle.



String theory predicts that what appear to be pointlike particles are actually tiny strings. In addition, it predicts the existence of membranelike objects called branes (*green*), which can come in a variety of dimensionalities. Strings that have end points (*blue*) always have their ends on a brane. Those that are closed loops (*red*) are free from that restriction.



String theory also incorporates Kaluza-Klein theory, which we again represent by showing a line of space that is actually a tube. This tube has a one-dimensional brane running through it and is populated by strings, some of which loop around the circumference of the tube one or more times. At lower magnification, the strings look like point particles, and the extra dimension, including its brane, is not apparent.



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placed on a slope will start to roll downhill to a lower position.

To understand what consequences follow from this minimization, focus first on a single parameter: the overall size of the hidden space. We can plot a curve showing how the vacuum energy changes as this parameter varies. An example is shown in the top illustration on page 85. At very small sizes, the energy is high, so the curve starts out high at the left. Then, from left to right, it dips down into three valleys, each one lower than the previous one. Finally, at the right, after climbing out of the last valley, the curve trails off down a shallow slope to a constant value. The bottom of the leftmost valley is above zero energy; the middle one is at exactly zero; and the right-hand one is below zero.

How the hidden space behaves depends on the initial conditions—where the "ball" that represents it starts on the curve. If the configuration starts out to the right of the last peak, the ball will roll off to infinity, and the size of the hidden space will increase without bound (it will cease to be hidden). Otherwise it will settle down at the bottom of one of the troughs—the size of the hidden space adjusts to minimize the energy. These three local minima differ by virtue of whether the resulting vacuum energy is positive, negative or zero. In our universe the size of the hidden dimensions is not changing with time: if it were, we would see the constants of nature changing. Thus, we must be sitting at a minimum. In particular, we seem to be sitting at a minimum with a slightly positive vacuum energy.

Because there is more than one parameter, we should actually think of this vacuum energy curve as one slice through a complex, multidimensional mountain range, which Leonard Susskind of Stanford University has described as the landscape of string theory [*see middle illustration on page 85*]. The minima of this multidimensional landscape—the bottoms of depressions where a ball could come to rest—correspond to the stable configurations of spacetime (including branes and fluxes), which are called stable vacua.

A real landscape allows only two independent directions (north-south and east-west), and this is all we can draw. But the landscape of string theory is much more complicated, with hundreds of independent directions. The landscape dimensions should not be confused with the actual spatial dimensions of the world; each axis measures not some position in physical space but some aspect of the geometry, such as the size of a handle or the position of a brane.

The landscape of string theory is far from being fully mapped out. Calculating the energy of a vacuum state is a difficult problem and usually depends on finding suitable approximations. Researchers have made steady progress recently, most notably in 2003, when Shamit Kachru, Renata Kallosh and Andrei Linde, all at Stanford, and Sandip Trivedi of the Tata Institute of Fundamental Research in Mumbai, India, found strong evidence that the landscape does have minima where a universe can get stuck.

We cannot be sure how many stable vacua there are—that is, how many points where a ball could rest. But the number could very well be enormous. Some research suggests that there are solutions with up to about 500 handles, but not many more. We can wrap different numbers of flux lines around each handle, but not too many, because they would make the space unstable, like the right part of the curve in the figure. If we suppose that each handle can have from zero to nine flux lines (10 possible values), then there would be 10^{500} possible configurations. Even if each handle could have only zero or one flux unit, there are 2^{500}, or about 10^{150}, possibilities.

As well as affecting the vacuum energy, each of the many solutions will conjure up different phenomena in the four-dimensional macroscopic world by defining which kinds of particles and forces are present and what masses and interaction strengths they have. String theory may provide us with a unique set of fundamental laws, but the laws of physics that we see in the macroscopic world will depend on the geometry of the extra dimensions.

Each solution will conjure up different phenomena in the macroscopic world by defining which kinds of particles and forces are present.

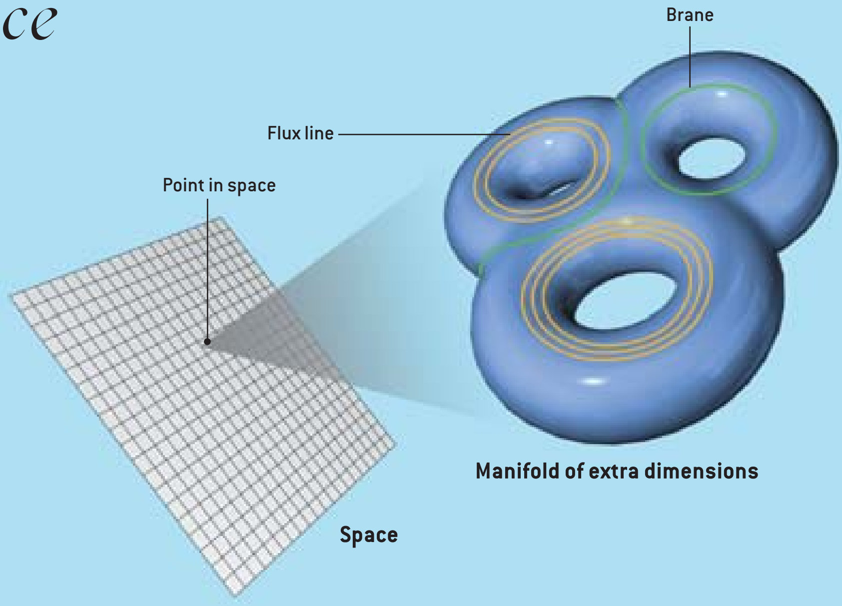
Many physicists hope that physics will ultimately explain why the universe has the specific laws that it does. But if that hope is to come true, many profound questions about the string theory landscape must be answered. Which stable vacuum describes the physical world we experience? Why has nature chosen this particular vacuum and not any other? Have all other solutions been demoted to mere mathematical possibilities, never to come true? String theory, if correct, would be the ultimate failure in democracy: richly populated with possible worlds but granting the privilege of reality to only one of its many citizens.

Instead of reducing the landscape to a single chosen vacuum, in 2000 we proposed a very different picture based on two important ideas. The first is that the world need not be stuck with one configuration of the small dimensions for good, because a rare quantum process allows the small dimensions to jump from one configuration to another. The second is that Einstein's general relativity, which is a part of string theory, implies that the universe can grow so rapidly that different configurations will coexist side by side in different subuniverses, each large enough to be unaware of the others. Thus, the mys-

VACUUM STATE

The Hidden Space

Any given solution to the equations of string theory represents a specific configuration of space and time. In particular, it specifies the arrangement of the small dimensions, along with their associated branes (*green*) and lines of force known as flux lines (*orange*). Our world has six extra dimensions, so every point of our familiar three-dimensional space hides an associated tiny six-dimensional space, or manifold—a six-dimensional analogue of the circle in the top illustration on page 81. The physics that is observed in the three large dimensions depends on the size and the structure of the manifold: how many doughnutlike "handles" it has, the length and circumference of each handle, the number and locations of its branes, and the number of flux lines wrapped around each doughnut.



tery of why our particular vacuum should be the only one to exist is eliminated. Moreover, we proposed that our idea resolves one of the greatest puzzles in nature.

A Trail through the Landscape

AS OUTLINED BEFORE, each stable vacuum is characterized by its numbers of handles, branes and flux quanta. But now we take into account that each of these elements can be created and destroyed, so that after periods of stability, the world can snap into a different configuration. In the landscape picture, the disappearance of a flux line or other change of topology is a quantum jump over a mountain ridge into a lower valley.

Consequently, as time goes on, different vacua can come into existence. Suppose that each of the 500 handles in our earlier example starts out with nine units of flux. One by one, the 4,500 flux units will decay in some sequence governed by the probabilistic predictions of quantum theory until all the energy stored in fluxes is used up. We start in a high mountain valley and leap randomly over the adjoining ridges, visiting 4,500 successively lower valleys. We are led through some varied scenery, but we pass by only a minuscule fraction of the 10^{500} possible solutions. It would seem that most vacua never get their 15 minutes of fame.

Yet we are overlooking a key part of the story: the effect of the vacuum energy on how the universe evolves. Ordinary objects such as stars and galaxies tend to slow down an expanding universe and can even cause it to recollapse. Positive vacuum energy, however, acts like antigravity: according to Einstein's equation, it causes the three dimensions that we see to grow more and more rapidly. This rapid expansion has an important and surprising effect when the hidden dimensions tunnel to a new configuration.

Remember that at every point in our three-dimensional space there sits a small six-dimensional space, which lives at some point on the landscape. When this small space jumps to a new configuration, the jump does not happen at the same instant everywhere. The tunneling first happens at one place in the three-dimensional universe, and then a bubble of the new low-energy configuration expands rapidly [*see box on page 86*]. If the three large dimensions were not expanding, this growing bubble would eventually overrun every point in the universe. But the old region is also expanding, and this expansion can easily be faster than that of the new bubble.

Everybody wins: both the old and the new regions increase in size. The new never completely obliterates the old. What makes this outcome possible is Einstein's dynamical geometry. General relativity is not a zero-sum game—the stretching of the spatial fabric allows new volume to be created for both the old and the new vacua. This trick will work as the new vacuum ages as well. When its turn comes to decay, it will not disappear altogether; rather it will sprout a growing bubble, occupied by a vacuum with yet lower energy.

Because the original configuration keeps growing, eventually it will decay again at another location, to another nearby minimum in the landscape. The process will continue infinitely many times, decays happening in all possible ways, with far separated regions losing fluxes from different handles. In this manner, every bubble will be host to many new solutions. Instead of a single sequence of flux decay, the universe thus experiences all possible sequences, resulting in a hi-

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erarchy of nested bubbles, or subuniverses. The result is very similar to the eternal inflation scenario proposed by Alan Guth of the Massachusetts Institute of Technology, Alexander Vilenkin of Tufts University, and Linde [see "The Self-Reproducing Inflationary Universe," by Andrei Linde; Scientific American, November 1994].

Our scenario is analogous to an infinite number of explorers embarking on all possible paths through every minimum in the landscape. Each explorer represents some location in the universe far away from all the others. The path taken by that explorer is the sequence of vacua experienced at his location in the universe. As long as the explorers' starting point in the landscape is high up in the glaciers, practically all the minima will be visited. In fact, each one will be reached infinitely many times by every possible path downhill from the higher minima. The cascade comes to a halt only where it drops below sea level—into negative energy. The characteristic geometry associated with negative vacuum energy does not allow the game of perpetual expansion and bubble formation to continue. Instead a localized "big crunch" occurs, much like in the interior of a black hole.

In each bubble, an observer conducting experiments at low energies (like we do) will see a specific four-dimensional universe with its own characteristic laws of physics. Information from outside our bubble cannot reach us, because the intermediate space is expanding too rapidly for light to outrun it. We see only one set of laws, those corresponding to our local vacuum, simply because we do not see very far. In our scenario, what we think of as the big bang that began our universe was no more than the most recent jump to a new string configuration in this location, which has now spread across many billions of light-years. One day (probably too far off to worry about) this part of the world may experience another such transition.

Think of the landscape of string theory as a complex, **multidimensional mountain range**, with hundreds of independent directions.

The Vacuum Energy Crisis

The picture we have described explains how all the different stable vacua of the string landscape come into existence at various locations in the universe, thus forming innumerable subuniverses. This result may solve one of the most important and long-standing problems in theoretical physics—one related to the vacuum energy. To Einstein, what we now think of as vacuum energy was an arbitrary mathematical term—a "cosmological constant"—that could be added to his equation of general relativity to make it consistent with his conviction that the universe was static [see "A Cosmic Conundrum," by Lawrence M. Krauss and Michael S. Turner, on page 70]. To obtain a static universe, he proposed that this constant takes a positive value, but he abandoned the idea after observations proved the universe to be expanding.

With the advent of quantum field theory, empty space—the vacuum—became a busy place, full of virtual particles and fields popping in and out of existence, and each particle and field carries some positive or negative energy. According to the simplest computations based on this theory, these energies should add up to a tremendous density of about 10^{94} grams per cubic centimeter, or one Planck mass per cubic Planck length. We denote that value by Λ_P. This result has been called the most famous wrong prediction in physics because experiments have long shown that the vacuum energy is definitely no greater than $10^{-120}\Lambda_P$. Theoretical physics thus stumbled into a major crisis.

Understanding the origin of this great discrepancy has been one of the central goals of theoretical physics for more than three decades, but none of the numerous proposals for a resolution has gained wide acceptance. It was frequently assumed that the vacuum energy is exactly zero—a reasonable guess for a number that is known to have at least 120 zeros after the decimal point. So the apparent task was to explain how physics could produce the value zero. Many attempts centered on the idea that the vacuum energy can adjust itself to zero, but there were no convincing explanations of how this adjustment would take place or why the end result should be anywhere near zero.

In our 2000 paper, we combined the wealth of string theory solutions and their cosmological dynamics with a 1987 insight of Steven Weinberg of the University of Texas at Austin to provide both a how and a why.

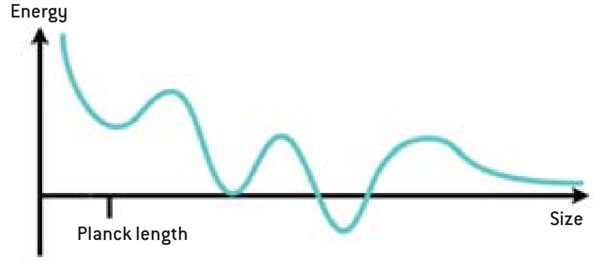
First consider the wealth of solutions. The vacuum energy is just the vertical elevation of a point in the landscape. This elevation ranges from around $+\Lambda_P$ at the glacial peaks to $-\Lambda_P$ at the bottom of the ocean. Supposing that there are 10^{500} minima, their elevations will lie randomly between these two values. If we plot all these elevations on the vertical axis, the average spacing between them will be $10^{-500}\Lambda_P$. Many, albeit a very small fraction of the total, will therefore have values between zero and $10^{-120}\Lambda_P$. This result explains *how* such small values come about.

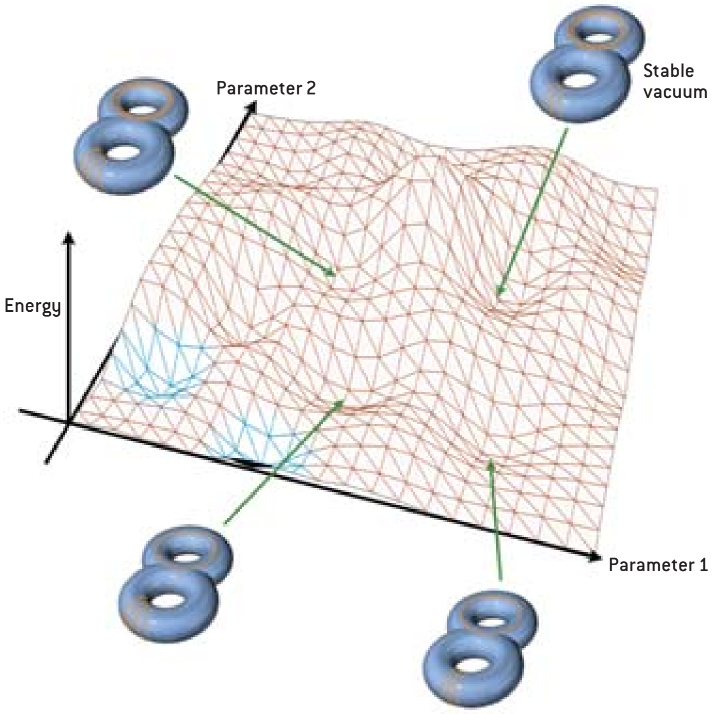
The general idea is not new. Andrei Sakharov, the late Soviet physicist and dissident, suggested as early as 1984 that the complicated geometries of hidden dimensions might produce a spectrum for vacuum energy that includes values in the ex-

STRING LANDSCAPE

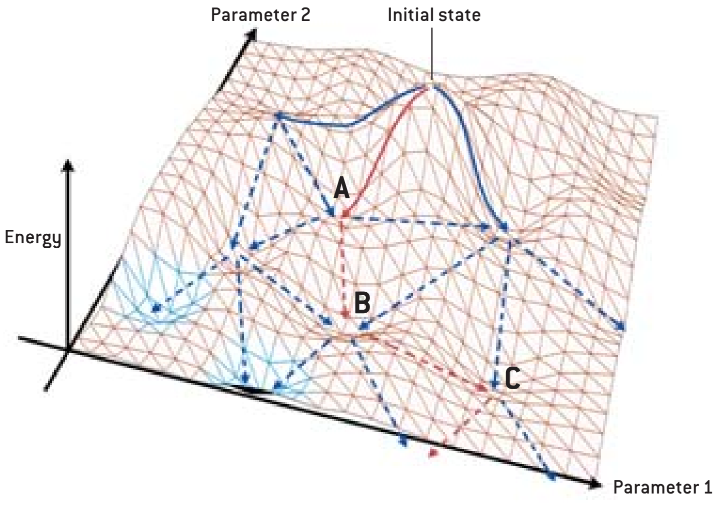
Topography of Energy

A landscape emerges when the energy of each possible string solution is plotted as a function of the parameters that define the six-dimensional manifold associated with that solution. If only one parameter is varied—say, the overall size of that manifold—the landscape forms a simple line graph. Here three particular sizes (all close to the Planck scale) have energies in the troughs, or minima, of the curve. The manifold will naturally tend to adjust its size to end up at one of the three minima, like a ball rolling around on the slope (it might also "roll off" to infinity at the right-hand end of the graph in this example).





The true string theory landscape reflects all parameters and thus would form a topography with a vast number of dimensions. We represent it by a landscape showing the variation of the energy contained in empty space when only two features change. The manifold of extra dimensions tends to end up at the bottom of a valley, which is a stable string solution, or a stable vacuum—that is, a manifold in a valley tends to stay in that state for a long while. Blue regions are below zero energy.



Quantum effects, however, allow a manifold to change state abruptly at some point—to tunnel through the intervening ridge to a nearby lower valley. The red arrows show how one region of the universe might evolve: starting out at a high mountaintop, rolling down into a nearby valley (*vacuum A*), eventually tunneling through to another, lower valley (*vacuum B*), and so on. Different regions of the universe will randomly follow different paths. The effect is like an infinite number of explorers traversing the landscape, passing through all possible valleys (*blue arrows*).

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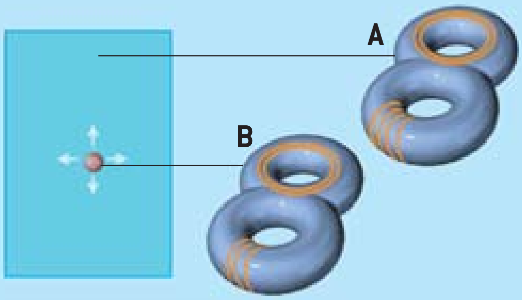
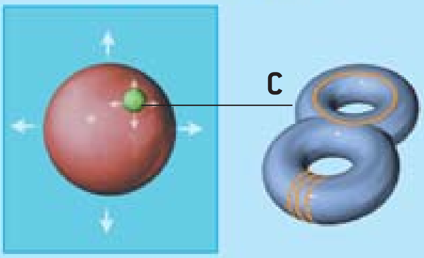
Bubbles of Reality

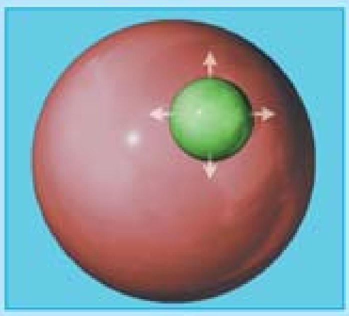
The possibility of decay from one stable vacuum to another suggests a radical new picture of our universe at the largest scales.



Tunneling from one stable vacuum to another would not occur everywhere in the universe at once. Instead it would occur at one random location, producing an expanding bubble of space (*arrows*) having the new vacuum. In this example, the blue region of space has vacuum A, whose manifold of small extra dimensions consists of a two-handled doughnut with groups of two and four flux lines wrapped around the handles. The red region, which has vacuum B, emerges when one of the four flux lines decays. Corresponding to their different manifolds, the two regions will have different kinds of particles and forces and thus different laws of physics.



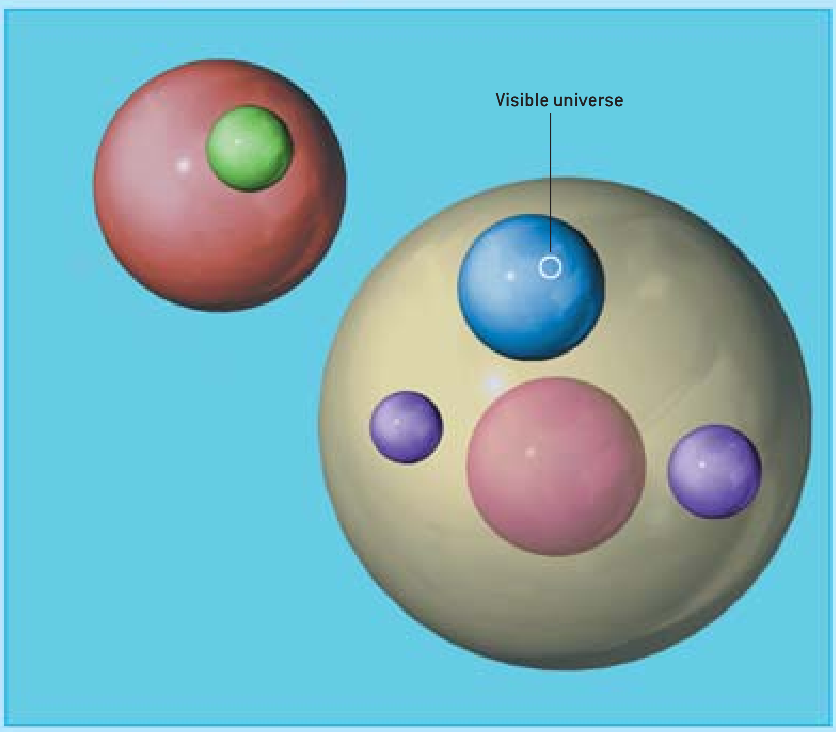
The red region grows rapidly, potentially becoming billions of light-years in diameter. Eventually another transition occurs within the red region, this time a decay of one of the two flux lines. This decay generates the green region, which has vacuum C and still another set of particles and forces.



The green region also grows rapidly, but it never catches up with the red region. Similarly, the red region never completely replaces the original blue vacuum.

Because the quantum tunneling is a random process, widely separated locations in the universe will decay through different sequences of vacua. In this way, the entire landscape is explored; every stable vacuum occurs in many different places in the universe.

The whole universe is therefore a foam of expanding bubbles within bubbles, each with its own laws of physics. Extremely few of the bubbles are suitable for the formation of complex structures such as galaxies and life. Our entire visible universe (more than 20 billion light-years in diameter) is a relatively small region within one of these bubbles.



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perimental window. Other researchers have made alternative proposals that do not seem to be realized in string theory.

We have explained how cosmology populates most of the minima, resulting in a complicated universe that contains bubbles with every imaginable value of the vacuum energy. In which of these bubbles will we find ourselves? Why should our vacuum energy be so close to zero? Here Weinberg's insight comes into play. Certainly an element of chance is involved. But many places are so inhospitable, it is no wonder we do not live there. This logic is familiar on smaller scale—you were not born in Antarctica, at the bottom of the Marianas Trench or on the airless wastes of the moon. Rather you find yourself in the tiny fraction of the solar system that is hospitable to life. Similarly, only a small fraction of the stable vacua are hospitable to life. Regions of the universe with large positive vacuum energy experience expansions so virulent that a supernova explosion would seem peaceful in comparison. Regions with large negative vacuum energy rapidly disappear in a cosmic crunch. If the vacuum energy in our bubble had been greater than $+10^{-118}\Lambda_P$ or less than $-10^{-120}\Lambda_P$, we could not have lived here, just as we do not find ourselves roasting on Venus or crushed on Jupiter. This type of reasoning is called anthropic.

Plenty of minima will be in the sweet spot, a hair's breadth above or below the water line. We live where we can, so we should not be surprised that the vacuum energy in our bubble is tiny. But neither should we expect it to be exactly zero! About 10^{380} vacua lie in the sweet spot, but at most only a tiny fraction of them will be exactly zero. If the vacua are distributed completely randomly, 90 percent of them will be somewhere in the range of 0.1 to $1.0 \times 10^{-118}\Lambda_P$. So if the landscape picture is right, a nonzero vacuum energy should be observed, most likely not much smaller than $10^{-118}\Lambda_P$.

In one of the most stunning developments in the history of experimental physics, recent observations of distant supernovae have shown that the visible universe's expansion is accelerating—the telltale sign of positive vacuum energy [see "Surveying Space-time with Supernovae," by Craig J. Hogan, Robert P. Kirshner and Nicholas B. Suntzeff; Scientific American, January 1999]. From the rate of acceleration, the value of the energy was determined to be about $10^{-120}\Lambda_P$, just small enough to have evaded detection in other experiments and large enough for the anthropic explanation to be plausible.

The landscape picture seems to resolve the vacuum energy crisis, but with some unsettling consequences. Einstein asked whether God had a choice in how the universe was made or whether its laws are completely fixed by some fundamental principle. As physicists, we might hope for the latter. The underlying laws of string theory, although they are still not completely known, appear to be completely fixed and inevitable: the mathematics does not allow any choices. But the laws that we see most directly are not the underlying laws. Rather our laws depend on the shape of the hidden dimensions, and for this the choices are many. The details of what we see in nature are not inevitable but are a consequence of the particular bubble that we find ourselves in.

Does the string landscape picture make other predictions, beyond the small but nonzero value of the vacuum energy? Answering this question will require a much greater understanding of the spectrum of vacua and is the subject of active research on several fronts. In particular, we have not yet located a specific stable vacuum that reproduces the known laws of physics in our four-dimensional spacetime. The string landscape is largely uncharted territory. Experiments could help. We might someday see the higher-dimensional physical laws directly, via strings, black holes or Kaluza-Klein particles using accelerators. Or we might even make direct astronomical observations of strings of cosmic size, which could have been produced in the big bang and then expanded along with the rest of the universe.

The picture that we have presented is far from certain. We still do not know the precise formulation of string theory—unlike general relativity, where we have a precise equation based on a well-understood underlying physical principle, the exact equations of string theory are unclear, and important physical concepts probably remain to be discovered. These may completely change or do away with the landscape of string vacua or with the cascade of bubbles that populate the landscape. On the experimental side, the existence of nonzero vacuum energy now seems an almost inevitable conclusion from observations, but cosmological data are notoriously fickle and surprises are still possible.

It is far too early to stop seeking competing explanations for the existence of vacuum energy and its very small size. But it would be equally foolish to dismiss the possibility that we have emerged in one of the gentler corners of a universe more varied than all the landscapes of planet Earth. SA

In each bubble, an observer will see **a specific four-dimensional universe** with its own characteristic laws of physics.

MORE TO EXPLORE

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The official string theory Web site is at **www.superstringtheory.com/**

Unlike nearly all his contemporaries, Albert Einstein thought quantum mechanics would give way to a classical theory. Some researchers nowadays are inclined to agree **By George Musser**

WAS EINSTEIN RIGHT?

Einstein has become such an icon that it sounds sacrilegious to suggest he was wrong. Even his notorious "biggest blunder" merely reinforces his aura of infallibility: the supposed mistake turns out to explain astronomical observations quite nicely [see "A Cosmic Conundrum," by Lawrence M. Krauss and Michael S. Turner, on page 70]. But if most laypeople are scandalized by claims that Einstein may have been wrong, most theoretical physicists would be much more startled if he had been right.

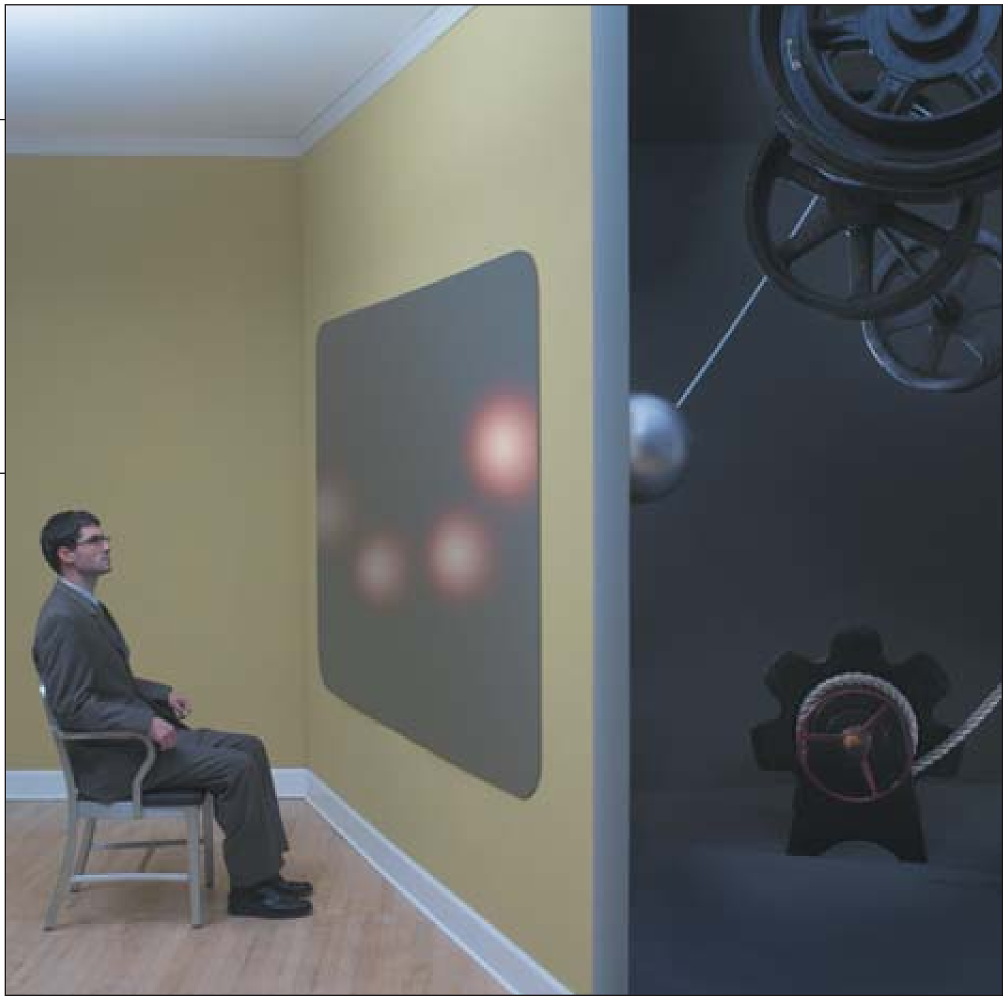
Although no one doubts the man's greatness, physicists wonder what happened to him during the quantum revolution of the 1920s and 1930s. Textbooks and biographies depict him as the quantum's deadbeat dad. In 1905 he helped to bring the basic concepts into the world, but as quantum mechanics matured, all he seemed to do was wag his finger. He made little effort to build up the theory and much to tear it down. A reactionary mysticism—embodied in his famous pronouncement, "I shall never believe that God plays dice with the world"—appeared to eclipse his scientific rationality.

Estranged from the quantum mainstream, Einstein spent his final decades in quixotic pursuit of a unified theory of physics. String theorists and others who later took up that pursuit vowed not to walk down the same road. Their assumption has been that when the general theory of relativity (which describes gravity) meets quantum mechanics (which handles everything else), it is relativity that must give way. Einstein's masterpiece, though not strictly "wrong," will ultimately be exposed as mere approximation.

Collapsing Theories

IN RECENT YEARS, though, as physicists have redoubled their efforts to grok quantum theory, a growing number have come to admire Einstein's position. "This guy saw more deeply and more quickly into the central issues of quantum mechanics than many give him credit for," says Christopher Fuchs of Bell Labs. Some even agree with Einstein that the quantum must eventually yield to a more fundamental theory. "We shouldn't just assume quantum mechanics is going to make it through unaltered," says Raphael Bousso of the University of California at Berkeley.

Those are strong words, because quantum mechanics is the most successful theoretical frame-



IS QUANTUM MECHANICS a facade? Einstein believed that behind the bizarre results apparent to us, the universe ultimately worked according to the intuitive principles of classical physics.

DAVID EMMITE PHOTOGRAPHY

work in the history of science. It has superseded all the classical theories that preceded it, except for general relativity, and most physicists think its total victory is just a matter of time. After all, relativity is riddled with holes—black holes. It predicts that stars can collapse to infinitesimal points but fails to explain what happens then. Clearly, the theory is incomplete. A natural way to overcome its limitations would be to subsume it in a quantum theory of gravity, such as string theory.

Still, something is rotten in the state of quantumland, too. As Einstein was among the first to realize, quantum mechanics, too, is incomplete. It offers no reason for why individual physical events happen, provides no way to get at objects' intrinsic properties and has no compelling conceptual foundations. Moreover, quantum theory turns the clock back to a pre-Einsteinian conception of space and time. It says, for example, that an eight-liter bucket can hold eight times as much as a one-liter bucket. That is true in everyday life, but relativity cautions that the eight-liter bucket can ultimately hold only four times as much—that is, the true capacity of buckets goes up in proportion to their surface area rather than their volume. This restriction is known as the holographic limit. When the contents of the buckets are dense enough, exceeding the limit triggers a collapse to a black hole. Black holes may thus signal the breakdown not only of relativity but also of quantum theory (not to mention buckets).

The obvious response to an incomplete theory is to try to complete it. Since the 1920s, several researchers have proposed rounding out quantum mechanics with "hidden variables." The idea is that quantum mechanics actually derives from classical mechanics rather than the other way round. Particles have definite positions and velocities and obey Newton's laws (or their relativistic extension). They appear to behave in funky quantum ways simply because we don't, or can't, see this underlying order. "In these models, the randomness of quantum mechanics is like a coin toss," says Carsten van de Bruck of the University of Sheffield in England. "It looks random, but it's not really random. You could write down a deterministic equation."

Creative Friction

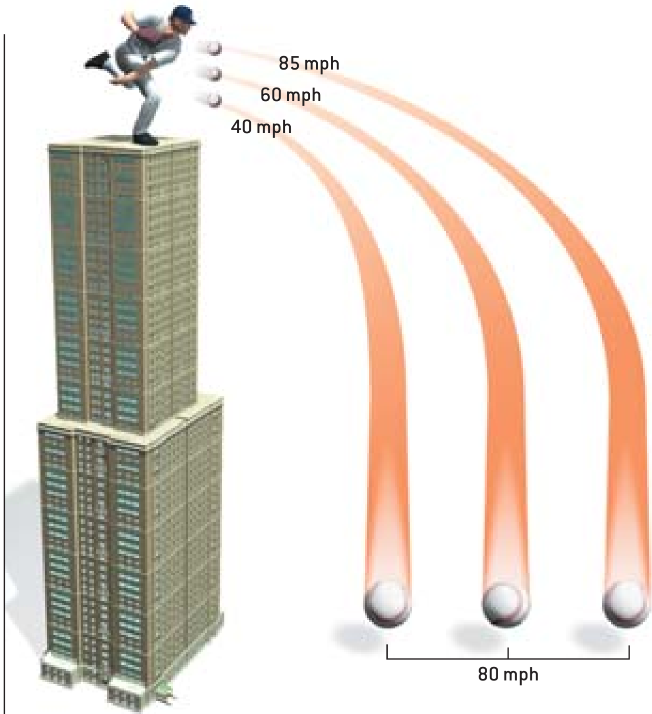
AN ANALOGY is to Brownian motion. The jiggling of dust motes looks random, but as Einstein himself demonstrated, it is caused by unseen molecules following classical laws. In fact, this analogy is tantalizingly tight. The equations of quantum mechanics bear an uncanny resemblance to those of the kinetic theory of molecules and, more generally, statistical mechanics. In some formulations, Planck's constant, the basic parameter of quantum theory, plays the mathematical role of temperature. It is as though quantum mechanics describes some kind of gas or ensemble of "molecules"—a chaotic soup of more primitive entities.

When confronted with a speculative idea such as this one, long before physicists know enough to test it empirically, they are guided by a pragmatic criterion: Is the idea intellectually fertile? String theory, for example, has spawned new physical principles as well as entire mathematical disciplines, so even if it fails experimentally, it won't have been a waste. Applying this criterion, most physicists rejected the concept of hidden variables long ago. Theories that incorporated hidden variables predicted no novel phenomena, illuminated no compelling principles and could not reproduce quantum mechanics without resorting to the very shenanigans they were supposed to avoid, such as action at a distance. Einstein himself dabbled in hidden variables before deciding they were "cheap." He concluded that quantum theory could not be completed by grafting on classical elements; it had to emerge from a thoroughgoing rethinking of fundamental physics.

Over the past five years, though, hidden variables have come back from the dead, thanks largely to Gerard 't Hooft of the University of Utrecht in the Netherlands, a Nobel laureate quantum mechanician known for toying with radical hypotheses. He argues that the salient difference between quantum and classical mechanics is information loss. A classical system contains more information than a quantum one does, because classical variables can take on any value, whereas quantum ones are discrete. So for a classical system to give rise to a quantum one, it must lose information. And that can happen naturally because of friction or other dissipative forces.

If you throw two pennies off the Empire State Building at different speeds, air friction causes them to approach the same terminal velocity. A person standing on the sidewalk below can scarcely tell the precise velocity at which you threw the pennies; that information is a hidden variable. In this situation and many others, a wide range of starting conditions lead to the same long-term behavior, known as an attractor. Attractors are discrete—just like quantum states. The laws they obey derive from, but differ from, Newton's laws. In fact, 't Hooft asserts, the derived laws are none other than quantum mechanics. Therefore, nature could be classical at its most detailed level yet look quantum-mechanical because of dissipation. "You'd have quantum mechanics as a low-energy limit of some fundamental theory," says Massimo Blasone of the University of Salerno in Italy.

Fleshing out this idea, Blasone and his colleagues have shown that a quantum linear harmonic oscillator, the quantized version of a simple pendulum, can emerge from a pair of friction-plagued classical oscillators. Each oscillator continues to obey classical laws, but their joint behavior comes to follow quantum rules. Berndt Müller of Duke University and his associates have demonstrated that a classical system operating in five dimensions can morph into a quantum one when observed in only four dimensions. Quantum weirdness reflects the rich web of interconnections that the extra dimension (a hidden variable) allows. As for the source of the friction that turns classical systems into quantum ones, van de Bruck thinks it may have to do with gravity.



FRICTION AND INFORMATION LOSS offer one explanation for quantum mechanics in classical terms. Because of air friction, balls falling from a skyscraper all reach the same terminal velocity. To an observer on the ground, any differences in the balls' initial velocities are lost. Similarly, if the universe is affected by some unknown type of friction, quantum mechanics may reflect the fact that outcomes of events collapse to discrete values rather than filling the full range of possibilities.

BRYAN CHRISTIE DESIGN

A Stitch in Time

A SEPARATE APPROACH to hidden variables also relies on dimensional tomfoolery—but in this case occurring in time. Various physicists and philosophers have mused that quantum mechanics seems odd because we assume that only the past affects the present. What if the future did, too? Then the probabilistic qualities of quantum theory could merely reflect our own ignorance of what is to come. This notion has been honed over the past decade by Mark Hadley of the University of Warwick in England. He points out that in general relativity, the future exists as surely as the past does, so it would be quite natural for both to affect the present. "The observation that will be carried out in the future is one of the hidden variables," Hadley says.

Going further, he claims that the basic logic of quantum mechanics flows as a matter of course out of Einstein's theory. He has also resurrected an idea that Einstein worked on in the 1930s: elementary particles are not objects sitting in spacetime but rather parts of spacetime itself, not lint clinging to the fabric but small knots in the fabric. This idea fell into disfavor because, among other things, it could not explain the special rotational symmetries of quantum particles, but Hadley claims to have overcome that problem.

So what do we make of 't Hooft's and Hadley's approaches? They have two advantages over past attempts at hidden variables. First, the connection between the observed quantum reality and the deeper classical one is tough to visualize. Physicists like that: a fundamental theory *should* be tough. The concept should be elegant enough to write on a T-shirt yet subtle enough that no one could claim to understand its implications fully. Second, both approaches predict novel phenomena that experimenters can look for. For instance, van de Bruck suggests that strong gravitational fields could change the laws of quantum mechanics.

Intriguingly, similar ideas crop up in mainstream theories. In string theory, a quantum system can be mathematically equivalent, or "dual," to a classical one. Some of these dualities involve statistical-mechanical systems akin to those that Müller and his colleagues studied. Few, if any, string theorists would go so far as to say that the quantum system literally is a classical one, but Brian Greene of Columbia University says that investigating these dualities could pinpoint what differentiates the two—and therefore what principles underlie quantum theory. As for the idea that the quantum can emerge from relativity, Bousso recently derived the most famous formula of quantum mechanics, the Heisenberg uncertainty principle, from the holographic limit.

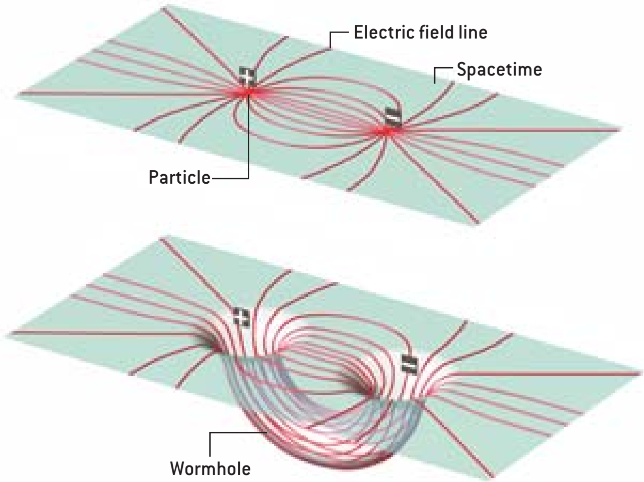
All that said, most physicists still regard hidden variables as a long shot. Quantum mechanics is such a rain forest of a theory, filled with indescribably weird animals and endlessly explorable backwaters, that seeking to reduce it to classical physics seems like trying to grow the Amazon from a rock garden. Instead of presuming to reconstruct the theory from scratch, why not take it apart and find out what makes it tick? That is the approach of Fuchs and others in the mainstream of studying the foundations of quantum mechanics.

They have discovered that much of the theory is subjective: it does not describe the objective properties of a physical system but rather the state of knowledge of the observer who probes it. Einstein reached much the same conclusion when he critiqued the concept of quantum entanglement—the "spooky" connection between two far-flung particles. What looks like a physical connection is actually an intertwining of the observer's knowledge about the two particles. After all, if there really were a connection, engineers should be able to use it to send faster-than-light signals, and they can't. Similarly, physicists had long assumed that measuring a quantum system causes it to "collapse" from a range of possibilities into a single actuality. Fuchs argues that it is just our uncertainty about the system that collapses.

The trick is to strip away the subjective aspects of the theory to expose the objective reality. Uncertainty about a quantum system is very different from uncertainty about a classical one, and this difference is a clue to what is really going on. Consider Schrödinger's famous cat. Classically, the cat is either alive or dead; uncertainty means that you don't know until you look. Quantum-mechanically, the cat is neither alive nor dead; when you look, you force it to be one or the other, with a 50–50 chance. That struck Einstein as arbitrary. Hidden variables would eliminate that arbitrariness.

Or would they? The classical universe is really no less arbitrary than the quantum one. The difference is where the arbitrariness comes in. In classical physics, it goes back to the dawn of time; once the universe was created, it played itself out as a set piece. In quantum mechanics, the universe makes things up as it goes along, partly through the intervention of observers. Fuchs calls this idea the "sexual interpretation of quantum mechanics." He has written: "There is no one way the world is because the world is still in creation, still being hammered out." The same thing can clearly be said of our understanding of quantum reality. SA

George Musser exists in a quantum superposition of staff writer and staff editor.



SPACETIME KNOTS, also known as wormholes, offer another way to derive quantum mechanics from a classical theory. Electrically charged particles, rather than being material objects where electromagnetic field lines originate (*top*), could be illusions caused by a wormhole (*bottom*).

BRYAN CHRISTIE DESIGN

MORE TO EXPLORE

The Logic of Quantum Mechanics Derived from Classical General Relativity. Mark J. Hadley in *Foundations of Physics Letters,* Vol. 10, No. 1, pages 43–60; February 1997. **arXiv.org/abs/quant-ph/9706018**

Quantum Gravity as a Dissipative Deterministic System. Gerard 't Hooft in *Classical and Quantum Gravity,* Vol. 16, No. 10, pages 3263–3279; October 1999. **gr-qc/9903084**

On Gravity, Holography and the Quantum. Carsten van de Bruck. Revised January 20, 2000. **gr-qc/0001048**

Dissipation and Quantization. Massimo Blasone, Petr Jizba and Giuseppe Vitiello in *Physics Letters A,* Vol. 287, Nos. 3–4, pages 205–210; August 27, 2001. **hep-th/0007138**

Chaotic Quantization of Classical Gauge Fields. T. S. Biró, S. G. Matinyan and B. Müller in *Foundations of Physics Letters,* Vol. 14, No. 5, pages 471–485; October 2001. **hep-th/0105279**

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Quantum Mechanics as Quantum Information (and Only a Little More). Christopher A. Fuchs. **quant-ph/0205039**

VIOLATIONS OF RELATIVITY could be manifest in the ticking rates of mirror-image, antimatter clocks and the stretching of matter along specific directions.

THE SEARCH FOR RELATIVITY VIOLATIONS

To uncover evidence for an ultimate theory, scientists are looking for infractions of Einstein's once sacrosanct physical principle

By Alan Kostelecký

Relativity lies at the heart of the most fundamental theories of physics. Formulated by Albert Einstein in 1905, relativity is built on the key idea that physical laws take the same form for any inertial observer—that is, for an observer oriented in any direction and moving at any constant speed. The theory predicts an assortment of well-known effects: among them, constancy of the speed of light for all observers, slowing of moving clocks, length contraction of moving objects, and equivalence of mass and energy ($E = mc^2$). These effects have been confirmed in highly sensitive experiments, and relativity is now a basic, everyday tool of experimental physics: particle colliders take advantage of the increase in mass and lifetime of fast particles; experiments with radioactive isotopes depend on the conversion of mass into energy. Even consumer electronics is affected—the Global Positioning System must allow for time dilation, which alters the rates of clocks on its orbiting satellites.

In recent years, however, motivated by attempts to combine all the known forces and particles into one ultimate unified theory, some physicists have been investigating the possibility that relativity's postulates provide only an approximation of nature's workings. The hope is that small relativity violations might offer the first experimental signals of the long-sought ultimate theory.

The unchanging quality, or invariance, of physical laws for different observers represents a symmetry of space and time (spacetime), called Lorentz symmetry after Dutch theoretical physicist Hendrik Antoon Lorentz, who studied it beginning in the 1890s. A perfect sphere illustrates an ordinary symmetry, what is known as symmetry under rotations: no matter how you turn it, the sphere looks the same. Lorentz symmetry is not based on objects looking the same but expresses instead the sameness of the laws of physics under rotations and also under boosts, which are changes of velocity. An observer sees the same

OVERVIEW

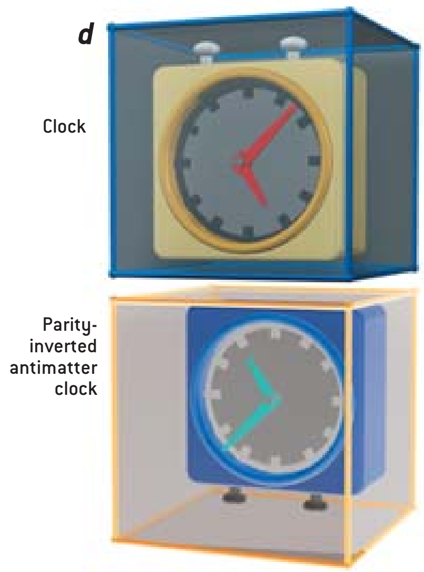
- Although special relativity is among the most fundamental and well verified of all physical theories, tiny violations of it could be predicted by theories that unify quantum mechanics, gravity and the other forces of nature.
- Numerous experiments are under way to uncover such effects, but so far none have proved sensitive enough to succeed.

DAVID EMMITE PHOTOGRAPHY

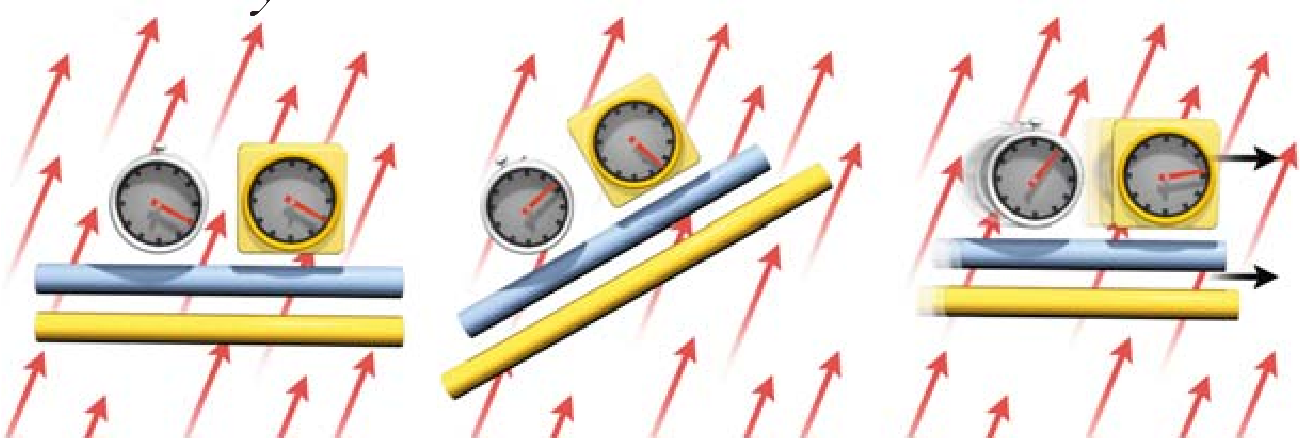
SPACETIME SYMMETRY

Relativity Obeyed

Lorentz symmetry is a fundamental property of the natural world that is of supreme importance for physics. It has two components: rotational symmetry and boost symmetry. Imagine that we have two rods made of dissimilar materials but having identical lengths when placed side by side and two clocks operating by different mechanisms that keep identical time (*a*). Rotational symmetry states that if one rod and one clock are rotated relative to the others, the rods nonetheless retain identical lengths and the clocks remain in sync (*b*). Boost symmetry considers what happens when one rod and one clock are "boosted" so that they move at a constant velocity relative to the other two, which here remain at rest. Boost symmetry predicts that the moving rod will be shorter and that the moving clock will run slower by amounts that depend in a precise way on the relative velocity (*c*). When space and time are combined to form spacetime, boost symmetry actually has almost identical mathematical form to rotational symmetry. A closely related symmetry is CPT symmetry, where the letters stand for charge conjugation, parity inversion and time reversal. This predicts that if a clock is replaced by its antimatter equivalent (charge reversal), which is also inverted (parity) and running backward in time, the two will keep identical time (*d*).
A mathematical theorem demonstrates that for a quantum field theory, CPT symmetry must hold whenever Lorentz symmetry is obeyed.



Relativity Violated



Broken Lorentz symmetry can be represented by a field of vectors throughout spacetime. Particles and forces have interactions with this vector field (*arrows*) similar to the interaction of charged particles with an electric field (which is also a vector field). As a result, unlike the Lorentz symmetric case, all directions and all velocities are no longer equivalent. Two dissimilar rods that have equal lengths at one orientation relative to the vector field (*left*) may shrink or expand at another orientation (*center*). Similarly, two dissimilar clocks that are synchronized at the first orientation may run slow or fast at the second orientation. In addition, dissimilar rods and clocks that are boosted (*right*) may undergo different length contractions and time dilations depending on their materials and the direction and magnitude of the boost.

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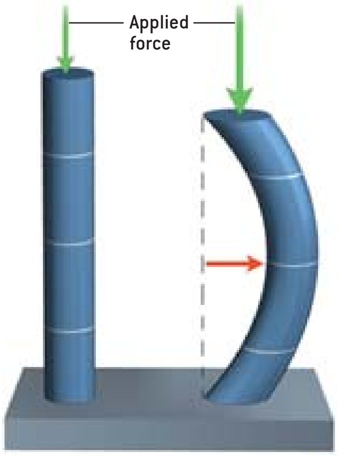
laws of physics at play, no matter what her orientation (rotation) and no matter what her velocity (boost). When Lorentz symmetry holds, spacetime is isotropic in the sense that all directions and all uniform motions are equivalent, so none are singled out as being special.

The Lorentz symmetry of spacetime forms the core of relativity. The details of how boosts work produce all the well-known relativistic effects. Before Einstein's 1905 paper, equations relating to these effects had been developed by several other researchers, including Lorentz, but they typically interpreted the equations as describing physical changes in objects—for example, bond lengths between atoms becoming shorter to generate length contraction. Einstein's great contributions included combining all the pieces and realizing that the lengths and clock rates are intimately linked. The notions of space and time merge into a single concept: spacetime.

Lorentz symmetry is a key element in the very foundations of our best description of the fundamental particles and forces. When combined with the principles of quantum mechanics, Lorentz symmetry produces a framework called relativistic quantum field theory. In this framework, every particle or force is described by a field that permeates spacetime and has the appropriate Lorentz symmetry. Particles such as electrons or photons exist as localized excitations, or quanta, in the relevant field. The Standard Model of particle physics, which describes all known particles and all known nongravitational forces (the electromagnetic, weak and strong forces), is a relativistic quantum field theory. The requirements of Lorentz symmetry strongly constrain how the fields in this theory can behave and interact. Many interactions that one could write down as plausible-looking terms to be added to the theory's equations are excluded because they violate Lorentz symmetry.

The Standard Model does not include the gravitational interaction. Our best description of gravity, Einstein's general relativity, is also founded on Lorentz symmetry. (The term "general" means that gravity is included, whereas "special" relativity excludes it.) In general relativity, the laws of physics at any given location are the same for all observer orientations and velocities, as before, but the effects of gravity make comparisons between experiments at different locations more complicated. General relativity is a classical theory (that is, nonquantum), and no one knows how to combine it with the basic Standard Model in a completely satisfactory way. The two can be partially combined, however, into a theory called "the Standard Model with gravity," which describes all particles and all four forces.



SPONTANEOUS SYMMETRY BREAKING occurs when a completely symmetric set of conditions or underlying equations gives rise to an asymmetric result. For example, consider a cylindrical stick with a force applied vertically (*left*). The system is completely symmetrical with respect to rotations around the axis of the stick. If a large enough force is applied, however, the system becomes unstable and the stick will bend in some direction (*right*). The symmetry breaking can be represented by a vector, or an arrow (*red*), that indicates the direction and magnitude of the bending. Lorentz violation involves the emergence of such vector quantities throughout spacetime.

Unification and the Planck Scale

TOGETHER THIS MELDING of the Standard Model and general relativity is astonishingly successful in describing nature. It describes all established fundamental phenomena and experimental results, and no confirmed experimental evidence for physics beyond it exists [see "The Dawn of Physics beyond the Standard Model," by Gordon Kane; SCIENTIFIC AMERICAN, June 2003]. Nevertheless, many physicists deem the combination unsatisfactory. One source of difficulty is that although quantum physics and gravity each have an elegant formulation, they seem mathematically incompatible in their present form. In situations where both gravity and quantum physics are important, such as the classic experiment in which cold neutrons rise against the earth's gravitational field, the gravity is incorporated into the quantum description as an externally applied force. That characterization models the experiment extremely well, but it is unsatisfactory as a fundamental and consistent description. It is like describing how a person can lift a heavy object, with the bones' mechanical strength and other properties accurately modeled and explained down to the molecular level, but with the muscles depicted as black-box machines that can supply a specified range of forces.

For these reasons and others, many theoretical physicists believe that it must be possible to formulate an ultimate theory—a complete and unified description of nature that consistently combines quantum physics and gravity. One of the first physicists to work on the idea of a unified theory was Einstein himself, who tackled this problem during the last part of his life. His goal was to find a theory that would describe not only gravity but also electromagnetism. Alas, he had tackled the problem too early. We now believe that electromagnetism is closely related to the strong and weak forces. (The strong force acts between quarks, which make up particles such as protons and neutrons, whereas the weak force is responsible for some kinds of radioactivity and the decay of the neutron.) It was only with experimental facts uncovered after Einstein's death that the strong and weak forces became characterized

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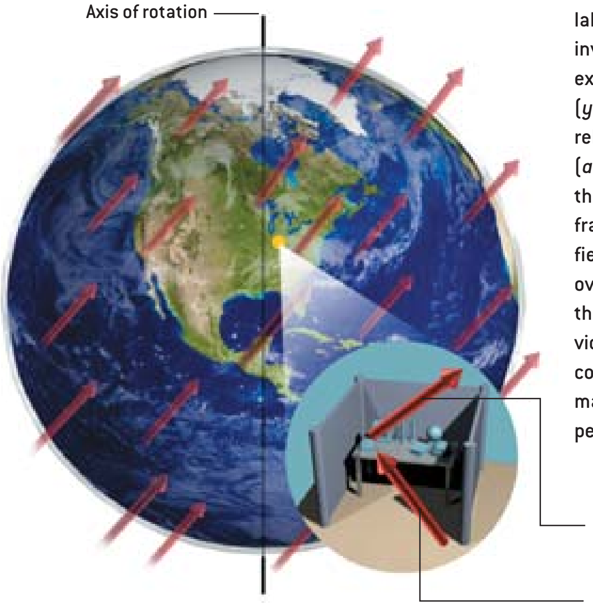

EARTH'S ROTATION will turn a laboratory, such as this one involved in a hypothetical experiment at Indiana University (*yellow dot*), relative to any relativity-violating vector field (*arrows*) that is present throughout spacetime. In the lab frame of reference, the vector field will seem to change direction over the course of a day, enabling the experiment to detect Lorentz violations. For example, a comparison of two dissimilar masses in the lab may see small periodic variations in their masses.

well enough for them to be understood separately, let alone in combination with electromagnetism and gravity.

One promising and comprehensive approach to this ultimate theory is string theory, which is based on the idea that all particles and forces can be described in terms of one-dimensional objects ("strings"), along with membranes of two dimensions and higher that are called branes [see "The String Theory Landscape," by Raphael Bousso and Joseph Polchinski, on page 78]. Another approach, known as loop quantum gravity, seeks a consistent quantum interpretation of general relativity and predicts that space is a patchwork of discrete pieces (quanta) of volume and area [see "Atoms of Space and Time," by Lee Smolin; SCIENTIFIC AMERICAN, January].

Whatever the eventual form of the ultimate theory, quantum physics and gravity are expected to become inextricably intertwined at a fundamental length scale of about 10^{-35} meter, which is called the Planck length, after 19th-century German physicist Max Planck. The Planck length is far too small to be within the direct reach of either conventional microscopes or less conventional ones such as high-energy particle colliders (which probe "merely" down to about 10^{-19} meter). So not only is it very challenging to construct a convincing ultimate theory, but it is also impractical to observe directly the new physics it must surely predict.

Despite these obstacles, a route may exist for obtaining experimental information about the unified theory at the Planck scale. Minuscule indirect effects reflecting the new physics in the unified theory may be detectable in experiments of sufficient sensitivity. An analogy is the image on a television or computer screen, which is composed of many small, bright pixels. The pixels are small compared with the distance at which the screen is viewed, so the image appears smooth to the eye. But in special situations, the pixels become evident—for example, when a newscaster is wearing a tie with narrow stripes that trigger a Moiré pattern on the screen. One class of such "Moiré patterns" from the Planck scale is relativity violations. At macroscopic distances, spacetime appears Lorentz invariant, but this symmetry may be broken at sufficiently small distances as a consequence of features of the unification of quantum physics and gravity.

The observable effects of Planck-scale relativity violations are likely to lie in the range of 10^{-34} to 10^{-17}. To gain some feeling for these numbers, consider that the thickness of a human hair is about 10^{-30} of the distance across the observable universe. Even 10^{-17} is roughly the ratio of a hair's thickness to the diameter of Neptune's orbit. The detection of relativity violations therefore requires some of the most sensitive experiments ever performed.

Another fundamental spacetime symmetry that could be violated is so-called CPT symmetry. This symmetry holds when the laws of physics are unaffected when three transfomations are all applied at once: interchange of particles and antiparticles (charge conjugation, C), reflection in a mirror (parity inversion, P) and reversal of time (T). The Standard Model obeys CPT symmetry, but theories with relativity violations may break it.

Spontaneous Violations

HOW MIGHT RELATIVITY violations emerge in the ultimate theory? One natural and elegant mechanism is called spontaneous Lorentz violation. It has similarities to the spontaneous breaking of other kinds of symmetry, which occurs whenever the underlying physical laws are symmetrical but the actual system is not. To illustrate the general idea of spontaneous symmetry breaking, consider a slender cylindrical stick, placed vertically with one end on the floor [*see illustration on preceding page*]. Imagine applying a force vertically downward on the stick. This situation is completely symmetrical under rotations around the axis of the stick: the stick is cylindrical, and the force is vertical. So the basic physical equations for this situation are symmetrical under rotation. But if sufficient force is applied, the stick will bend in some particular direction, which spontaneously breaks the rotational symmetry.

THE AUTHOR

ALAN KOSTELECKÝ is professor of theoretical physics at Indiana University. His publications span a broad range of topics in particle physics, gravitation, string theory, mathematical physics and atomic physics. His research on Lorentz and CPT symmetry triggered the recent flood of interest in relativity violations and has led to many new experimental tests.

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In the case of relativity violations, the equations describing the stick and the applied force are replaced by the equations of the ultimate theory. In place of the stick are the quantum fields of matter and forces. The natural background strength of such fields is usually zero. In certain situations, however, the background fields acquire a nonzero strength. Imagine that this happened for the electric field. Because the electric field has a direction (technically, it is a vector), every location in space will have a special direction singled out by the direction of the electric field. A charged particle will accelerate in that direction. Rotational symmetry is broken (and so is boost symmetry). The same reasoning applies for any nonzero "tensor" field; a vector is a special case of a tensor.

Such spontaneous nonzero tensor fields do not arise in the Standard Model, but some fundamental theories, including string theory, contain features that are favorable for spontaneous Lorentz breaking. The idea that spontaneous Lorentz breaking and observable relativity violations could occur in string theory and field theories with gravity was originally proposed in 1989 by me and Stuart Samuel of the City College of New York. It was extended in 1991 to include spontaneous CPT violation in string theory by me and Robertus Potting of Algarve University in Portugal. Since then, various additional mechanisms have been proposed for relativity violations arising in string theory and in other approaches to quantum gravity. If spontaneous Lorentz breaking or any other mechanisms do turn out to be part of the ultimate fundamental theory, the concomitant relativity violations could provide the first experimental evidence for the theory.

Standard Model Extension

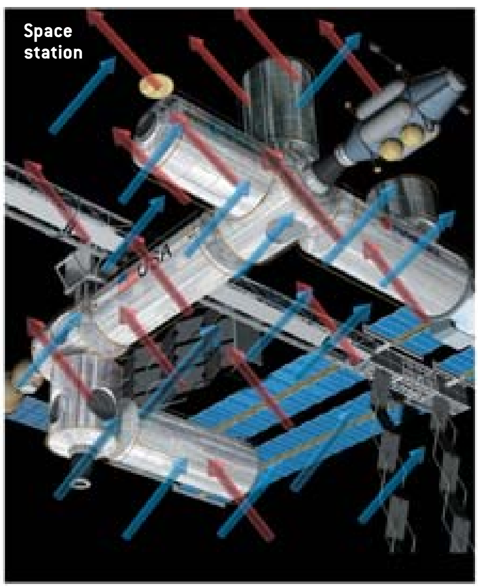
SUPPOSE THAT the fundamental theory of nature does contain Lorentz violation, perhaps with CPT violation, through some mechanism. How would this manifest itself in experiments, and how can it be related to known physics? To answer these questions, we would like to have a general theoretical framework that encompasses all possible effects and that can be applied to analyze any experiment. With such a framework, specific experimental parameters can be calculated, different experiments can be compared, and predictions can be made for the kind of effects to be expected.

Certain criteria guide our construction of this framework. First, all physical phenomena should be independent of the particular coordinate system used to map out space and time. Second, the experimental successes of the Standard Model and general relativity mean that any Lorentz and CPT violations must be small. By following these criteria and using only the known forces and particles, we are led to a set of possible terms—possible interactions—that could be added to the equations of the theory. Each term corresponds to a particular tensor field acquiring a nonzero background value. The coefficients that specify the magnitudes of these terms are unknown, and indeed many might be zero when the ultimate theory is known.

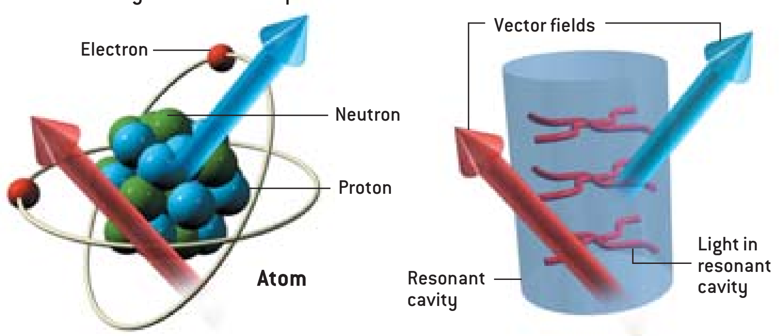
The end result is a theory called the Standard Model Extension, or SME. The beauty of this formulation is its

ORBITING LABORATORIES

Studying Space in Space



On satellites such as the space station will be experiments that seek evidence of Lorentz violations in comparisons of clocks. The illustration shows the case where there are two relativity-violating vector fields (*red* and *blue arrows*) with different interactions with particles. Depicted below is a comparison between an atomic clock (*represented by an atom*) and a clock based on light or microwaves (*wavy lines*) in a resonant cavity. The light and electrons (*red*) interact with the red vectors, whereas protons (*blue*) interact with the blue vectors. As the space station rotates, these changing interactions cause the clocks to go in and out of sync, revealing the Lorentz violation. The 92-minute rotation of the space station provides for much faster and more sensitive data taking than a stationary earth-based experiment.



DON FOLEY

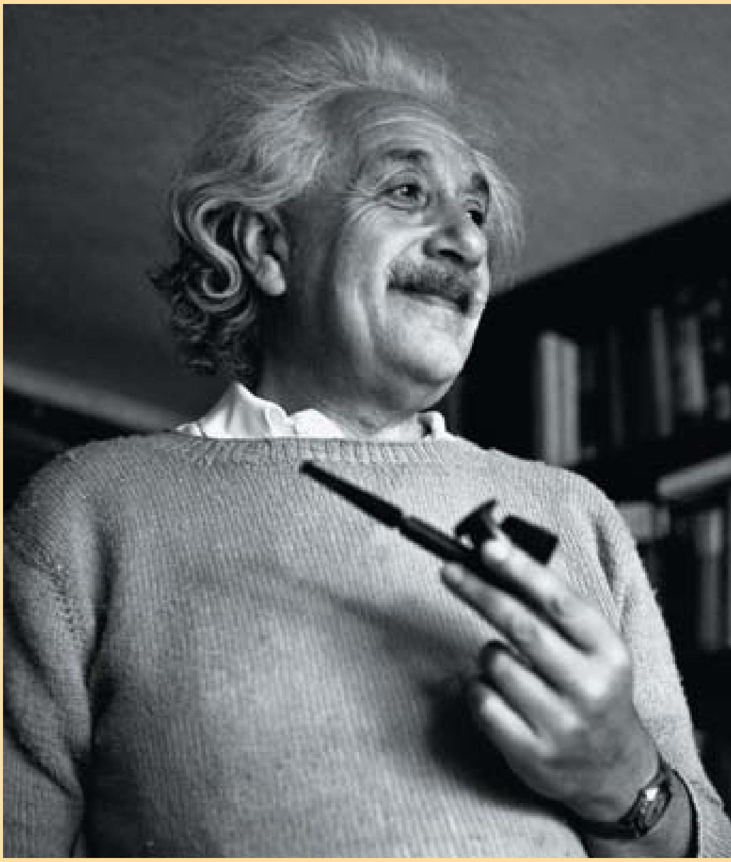
Toppling the Giant

Everyone wants to get a piece of Einstein. Two of the three most common crackpot missives received by scientists and science magazines involve Einstein: claims to have a unified theory (succeeding where Einstein failed) and claims to have proved his theories false. (The third big class of craziness: perpetual-motion machines and infinite-energy sources.) Like cannibals seeking the strength and life spirit of their victims, these misguided amateurs seem to think that by outdoing or disproving Einstein they will acquire all his prestige and acclaim. Of course, all that they disprove is their own competence with basic relativity.

But the crazies are not the only iconoclasts. Many serious and well-qualified researchers also seek to go beyond Einstein, in the way that he went beyond Galileo and Newton. The accompanying article by Alan Kostelecký describes the experimental search for departures from Einsteinian relativity. The analysis he discusses is based on a general "Standard Model Extension" in which all plausible relativity-violating terms are added to the equations of particle physics. This all-encompassing model covers every possible deviation that could trickle down to everyday physics from the high-energy pinnacle of the (as yet undiscovered) ultimate unified theory.

Yet certain putative breaches of relativity have attracted specific attention. One class of theories goes by the name "doubly special relativity," which has been studied by Giovanni Amelino-Camelia of the University of Rome since 2000 and later by Lee Smolin of the Perimeter Institute for Theoretical Physics in Ontario, João Magueijo of Imperial College London and others. Magueijo, incidentally, fits the label "iconoclast" to a T—as is apparent from his argumentative book *Faster Than the Speed of Light.*

Doubly special relativity is inspired by quantum gravity theories such as loop quantum gravity [see "Atoms of Space and Time," by Lee Smolin; SCIENTIFIC AMERICAN, January], and it imposes a second kind of "speed limit" that works in conjunction with the conventional barrier of the speed of light in a vacuum, also known as *c.* The idea is that at very short distances the smooth continuity of spacetime should break down into something more granular—like grains of sand or the



TOWERING FIGURE of Einstein provides a tempting target for physicists of all stripes. He would perhaps look with approval on these efforts to go beyond his theories.

LUCIEN AIGNER *Corbis*

generality: whatever your philosophical or physical preferences for the origin of relativity violations, the resulting effects in nature must be described by the SME, because it contains all viable modifications and generalizations of relativity that are compatible with the Standard Model and the known behavior of gravity.

To visualize the effects of Lorentz violation, it is useful to think of spacetime as having an intrinsic orientation. In the case of a vector field causing a particular term in the SME equations, the orientation coincides with the direction of the vector field. The more general case of a tensor field is similar but more complicated. By virtue of couplings to these background fields, the motions and interactions of particles acquire a directional dependence, like charged particles moving in an electric or a magnetic field. A similar visualization works for CPT violation, but in this case the effects occur because particles and antiparticles have different couplings to the background fields.

The SME predicts that the behavior of a particle can be affected by relativity violations in several ways. The particle's properties and interactions can depend on the direction it is moving (rotation violations) and on how fast it is going (boost violations). The particle may have spin, an intrinsic quantity of angular momentum, in which case the relativity-violating behavior can depend on the size and orientation of the spin. The particle can also fail to mirror its antiparticle (CPT violations). Each behavior can vary depending on the species of particle; for instance, protons might be affected more than neutrons, and electrons not at all. These effects combine to produce a plethora of interesting signals that can be sought in experiments. A number of such experiments have begun, but so far none has provided conclusive evidence for relativity violations.

Ancient Light

ONE WAY TO OBTAIN exceptional sensitivity to relativity violations is by network of a spider's web. In quantum physics, short distances and short times correspond to high momenta and high energies. Thus, at sufficiently high energy—the so-called Planck energy—a particle should "see" the graininess of spacetime. That violates relativity, which depends on spacetime being smooth down to the tiniest size scales. Reflecting this, in a doubly special theory, just as a particle cannot be accelerated beyond *c*, it cannot be boosted beyond the Planck energy.

Some of these models predict that extremely high frequency light should travel faster than lower-frequency light. Experimenters are looking for that effect in light from distant explosions called gamma-ray bursts.

But skeptics are unconvinced that these theories are well founded. Some researchers argue, for example, that the equations are physically equivalent to ordinary relativity, just dressed up in enough complexities for that to be unobvious. The proof of the pudding will have to come from a rigorous derivation of such a theory from something more fundamental, such as string theory or loop quantum gravity. Not to mention experimental evidence.

Another infraction that some have contemplated is that *c* itself has varied over the history of the universe. John W. Moffat of the University of Toronto studied models of this type in the early 1990s, and Magueijo has been a more recent champion of them. If *c* had been much greater in the very early moments of the big bang, certain effects could have propagated at an extremely fast rate, which would solve some cosmological puzzles.

If *c* varies, so, too, does the fine structure constant, alpha, which is a dimensionless number that specifies the strength of the electromagnetic interaction. Alpha can be expressed in terms of *c*, Planck's constant and the charge of the electron. Alpha can therefore also change with *c* remaining constant, which might not infringe on relativity but would be equally seismic. Such variation in alpha could occur in string theory, where the magnitude of alpha depends on the precise structure of extra tiny dimensions that are appended to the four dimensions of space and time that we know and love [see "The String Theory Landscape," by Raphael Bousso and Joseph Polchinski, on page 78].

The possibility that alpha might change was considered as long ago as 1955, by the great Russian physicist Lev Landau. Today physicists and astronomers are looking at ancient light from distant quasars for evidence that alpha was slightly different eons ago. Changing alpha would subtly alter the frequency of light emitted or absorbed by atoms and ions. Most searches for such shifts have turned up empty thus far. One exception is the results of a group led by John K. Webb of the University of New South Wales in Australia. Those researchers have used a novel method of analyzing the data to achieve finer precision and have reported evidence (albeit statistically somewhat weak) of shifts: between eight billion and 11 billion years ago, alpha appears to have been about six parts in a million feebler than it is today. Such a minute variation is hard to reconcile with the string theory explanation, which predicts long-term stability of constants such as alpha, punctuated by occasional catastrophic changes of great magnitude.

Some researchers, however, assert that the precision claimed by the new method is not correct and that the "shifts" are just statistical fluctuations. In March of this year a team of astronomers led by Patrick Petitjean of the Institute of Astrophysics of Paris and the Observatory of Paris and Raghunathan Srianand of the Inter-University Center for Astronomy and Astrophysics in Pune, India, reported using the traditional methods pushed to the limit. They concluded that as far back as 10 billion years, alpha has changed by less than 0.6 part in a million, contradicting the claims of Webb and company.

So far then, Einstein has withstood all challengers. The iconoclasts will have to keep looking for the first chink in his armor.

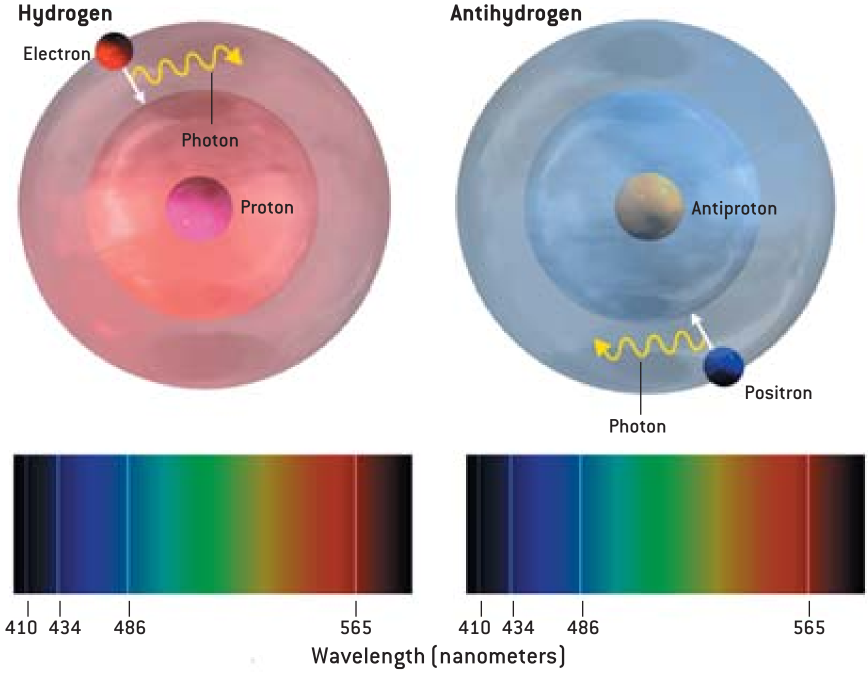
—Graham P. Collins, staff writer

studying the properties of polarized light that has traveled billions of light-years across the cosmos. Certain relativity-violating interactions in the SME will change the polarization of light as it travels through otherwise empty space. The change grows as the light travels greater distances.

In the SME, the dominant relativity violations involving light include both ones that break CPT and ones that preserve it. Those that break CPT are expected for technical theoretical reasons to be absent or negligible, and studies of cosmological data have confirmed this down to a sensitivity of 10^{-42}. About half the CPT-preserving relativity violations for light would be observable by measuring cosmological polarization: the change in polarization as the light travels would depend on the color of the light. At Indiana University, Matthew Mewes and I have searched for this effect in polarization data of infrared, visible and ultraviolet light from distant galaxies, obtaining a sensitivity of 10^{-32} on the coefficients controlling these violations.

The remaining relativity violations for light can be measured in the laboratory using modern versions of experiments similar to the classic Michelson-Morley test of relativity (named after physicist Albert Michelson and chemist Edward Morley). The original Michelson-Morley experiment sent two beams of light at right angles and verified that their relative speed is independent of direction. The most sensitive experiments nowadays use resonant cavities; for example, rotating one on a turntable and searching for changes in the resonant frequency as it rotates. John A. Lipa's group at Stanford University uses superconducting cavities to study the properties of microwave resonances. Achim Peters of Humboldt University in Berlin, Stephan Schiller of Düsseldorf University in Germany and their collaborators use laser light in sapphire crystal resonators. These experiments and similar ones by other groups have already achieved sensitivities of 10^{-15} to 10^{-11}.

Antimatter Experiments



Antimatter should behave in identical fashion to matter if a form of spacetime symmetry called CPT invariance holds. Two experiments at CERN near Geneva are testing this hypothesis using antihydrogen atoms. A hydrogen atom emits light with a characteristic color or wavelength when its electron drops from a higher energy level to a lower one (*top left*). The same process in antihydrogen (*top right*) should emit the same color light (photons are their own antiparticles, so it is still a photon that is emitted). Thus, if CPT invariance holds, antihydrogen and hydrogen should have identical emission spectra (*bottom*). The CERN experiments will actually use absorption of ultraviolet laser light (the inverse of the emission process shown here), and transitions involving microwaves, all of which should also be identical for hydrogen and antihydrogen. Any discrepancy would be a signal of CPT violation, which in turn implies Lorentz violation.

Clock-Comparison Experiments

EXCEPTIONAL SENSITIVITY to relativity violations has also been achieved in clock-comparison experiments, which search for changes in the ticking rate of a clock depending on its orientation. The typical basic "clock" is an atom in a magnetic field, and the ticking rate is the frequency of a transition between two of the atom's energy levels that depends on the strength of the magnetic field. The orientation of the clock is defined by the direction of the applied magnetic field, which is usually fixed in the laboratory and so rotates as the earth rotates. A second clock monitors the ticking rate of the first one. The second clock is often taken to be a different type of atom undergoing the same kind of transition. The ticking rates (the transition frequencies) have to be affected by different amounts for the violation to become apparent.

To date, the most sensitive experiments of this type have been performed in Ronald Walsworth's laboratory at the Harvard-Smithsonian Center for Astrophysics. These experiments have attained the remarkable sensitivity of 10^{-31} to a specific combination of SME coefficients for neutrons. Walsworth's group mixes helium and neon in a single glass bulb and turns both gases into masers (microwave lasers), a difficult technical feat. The frequencies of the two masers are compared.

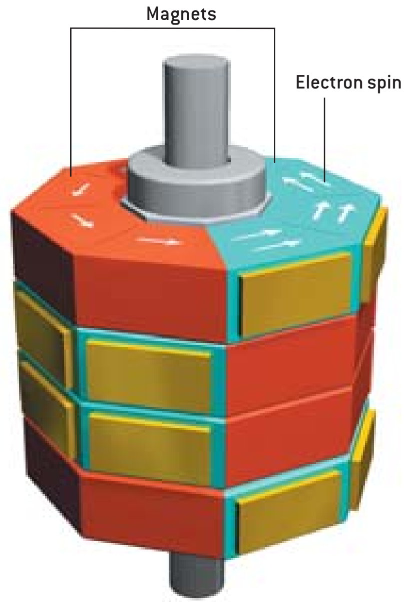
Various clock-comparison experiments with atoms as clocks have been performed at other institutions, achieving sensitivities of 10^{-27} to 10^{-23} for different types of relativity violations involving protons, neutrons and electrons. Other experiments have used (instead of atoms) individual electrons, positrons (antielectrons), negatively charged hydrogen ions and antiprotons in electromagnetic traps, and muonium (an "atom" made of an electron orbiting a positive muon particle).

Researchers have plans for several clock-comparison experiments on the International Space Station (ISS) and other satellites. These experiments would have a number of potential advantages, including easier access to all spatial directions. Typical ground-based clock-comparison experiments use the earth's rotation, but the fixed rotational axis limits sensitivity to some types of rotation violation. Because the ISS's orbital plane is inclined and precesses, all spatial directions could be sampled. Another advantage is that the ISS's orbital period of 92 minutes would allow data to be taken about 16 times as fast as a fixed earth-based experiment. (The ISS is often configured to keep the same side facing the earth, and thus it rotates every 92 minutes as well as orbiting in that time.)

Antimatter

DIRECT TESTS FOR CPT violation can be performed by comparing properties of particles and antiparticles. One of the classic CPT tests involves a type of fundamental particle called the kaon. It turns out that the weak interaction causes a kaon gradually to convert into its antiparticle, the antikaon, and then back again. These kaon oscillations are so finely balanced that even a minuscule CPT violation would change them noticeably. Several large experimental collaborations have studied the oscillations of kaons to search for CPT violation. At present, the most sensitive constraint on Lorentz and CPT violation in kaons has been achieved by the KTeV Collaboration. This experiment used the giant

DON FOLEY



SPIN-COUPLED FORCES are investigated by a University of Washington experiment involving a torsion pendulum experiment (in which the hanging pendulum bob twists back and forth on its wire). The bob (*photograph above*) consists of rings of magnets made of two different materials (*red* and *blue at right*). The field of each magnet type has the same strength but is generated by a different quantity of electron spins (*arrows*). The magnetic field forms a closed loop with very little field outside the bob, reducing spurious signals caused by magnetic interactions. The electron spins, however, are unbalanced. If there is a sufficiently large relativity-violating vector field that interacts with electron spin, it will show up in perturbations of the bob's oscillations.

Tevatron accelerator at Fermilab to create vast numbers of kaons. The results yielded two independent measurements of SME coefficients at the level of 10^{-21}.

Two experiments, ATHENA and ATRAP, both at CERN (the European laboratory for particle physics near Geneva), are under way to trap antihydrogen and compare its spectroscopic properties with those of hydrogen, which should be identical if CPT is preserved [*see box opposite page*]. Any difference uncovered would represent a CPT violation and consequently a Lorentz violation.

High-sensitivity tests of relativity have also used objects made of materials in which the spins of many electrons combine to yield a net overall spin. (Think of each electron's "spin" as being a tiny compass needle. Opposite pointing needles cancel, but parallel ones add to give a larger total spin.) Such materials are common—for example, an overall spin produces the magnetic field of a bar magnet. In searching for Lorentz violation, however, the presence of a strong magnetic field is a hindrance. To circumvent this, Eric Adelberger, Blayne Heckel and their colleagues at the University of Washington have designed and built a spin-polarized ring of material that has a net electron spin but no external magnetic field [*see illustration above*]. The ring is used as the bob in a torsion pendulum, which twists back and forth while suspended from a mounting on a rotating platform. A spin-dependent Lorentz violation would show up as a perturbation of the pendulum's oscillations that depends on the pendulum's orientation. This apparatus has been used to set the best current bounds on relativity violations involving electrons, at 10^{-29}.

It is possible that relativity violations have already been detected but have not been recognized as such. In recent years, ghostly fundamental particles called neutrinos have been shown to oscillate, which requires a modification of the minimal form of the Standard Model [see "Solving the Solar Neutrino Problem," by Arthur B. McDonald, Joshua R. Klein and David L. Wark; SCIENTIFIC AMERICAN, April 2003]. The oscillations are usually ascribed to small, previously unknown masses of neutrinos. But unusual oscillation properties for neutrinos are also predicted in the SME. Theorists have shown that the description of neutrino behavior in terms of relativity violations and the SME may be simpler than the conventional description in terms of masses. Future analyses of neutrino data could confirm this idea.

The experiments I have discussed have demonstrated that Planck-scale sensitivities are attainable with existing techniques. Although no compelling evidence for relativity violations has emerged to date, comparatively few types of relativity violations have been studied so far. The next few years will see major improvements both in the scope of relativity tests (more coefficients measured) and in their depth (improved sensitivities). If relativity violations are finally discovered, they will signal a profound change in our understanding of the universe at its most fundamental level. SA

MORE TO EXPLORE

Testing Times in Space. Steve K. Lamoreaux in *Nature,* Vol. 416, pages 803–804; April 25, 2002.

Back to the Future. Philip Ball in *Nature,* Vol. 427, pages 482–484; February 5, 2004.

Breaking Lorentz Symmetry. Robert Bluhm in *Physics World,* Vol. 17, No. 3, pages 41–46; March 2004. Available at **physicsweb.org/article/world/17/3/7**

Lorentz Invariance on Trial. Maxim Pospelov and Michael Romalis in *Physics Today,* Vol. 57, No. 7, pages 40–46; July 2004.

Alan Kostelecký's Web site on Lorentz and CPT violation is at **www.physics.indiana.edu/~kostelec/faq.html**

TED COOK *University of Washington (photograph)*; DON FOLEY *(illustration)*

Scientific American has covered Einstein's theories—and the refinements and reactions to them—ever since scientists began to grasp the import of his landmark 1905 papers. Read on for a sampling of our reports, some by leading physicists of their times

By Daniel C. Schlenoff

PORTRAIT of Albert Einstein was drawn by Ben Shahn to accompany the article that Einstein wrote for the April 1950 issue of *Scientific American*.

A CENTURY OF EINSTEIN

It took several years for Scientific American, and mainstream physics for that matter, to start mulling over the radical proposals Albert Einstein expounded in 1905. His repudiation of the intuitive understanding of the cosmos was hard to accept:

"In 1905, came a fundamental and (as the future historian will probably say) an epoch-making contribution in the shape of an unassuming and dry-looking dissertation, 'Concerning the Electro-dynamics of Moving Bodies,' by A. Einstein, a Swiss professor of physics. It appeared in the Annalen der Physik, the German counterpart of our Philosophical Magazine. It created no sensation at the time. It was hardly noticed. Yet, at the present time, you cannot open a journal devoted to physics without finding some fresh contribution to the ever-increasing literature on the subject: Einstein's Principle of Relativity. —E. E. Fournier D'Albe"

Scientific American Supplement,
November 11, 1911

"But is the 'Principle of Relativity' true? That is for experiment to decide. Its postulates have been and are now being pursued by the relentless logic of mathematics, and they must stand or fall as the deductions thus reached agree or conflict with experimental evidence. Just now, however, the 'Principle of Relativity' seems to be irresistibly fascinating to mathematicians, but equally abhorrent to that host of physicists who can no more conceive of time as a function of velocity than they can imagine space to be curved or picture for themselves a fourth dimension."

Scientific American,
June 8, 1912

Scientific American kept track of Einstein's efforts to extend the theory of relativity and of the reaction to his seminal 1916 paper:

"The principle of relativity in the strict sense has stood the test of experiment. If it long seemed doubtful, and is still so regarded by some physicists, this is because it appears irreconcilable with the electrodynamical theories of Maxwell and Lorentz. In particular, the constancy of the velocity of light, which is deduced from those theories, seems difficult to admit. Now there is one domain of fundamental importance in which our empirical knowledge is far too small to supply, even in conjunction with the principle of relativity, a firm basis for a general theory, so that the

ISSUE of *Scientific American* dated June 8, 1912, covered an early debate on the special theory of relativity.

SCIENTIFIC AMERICAN, JUNE 8, 1912

Scientific American ran a contest to solicit a cogent explanation of Einstein's complex theory.

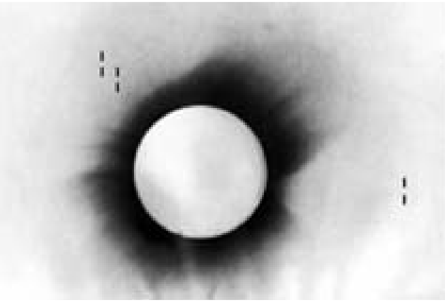
foundation must be completed by physical hypotheses. This domain is gravitation."

Scientific American Supplement,
September 19, 1914

"Whatever may be the nature of the aether, it is devoid of those material properties which could constitute it a framework of reference in space. We can perhaps best picture the aether as a four-dimensional fluid filling uniformly Minkowski's space-time continuum, not as a material three-dimensional fluid occupying space and time independently. The position we have now reached is known as the principle of relativity. In so far as it is a physical theory, it seems to be amply confirmed by numerous experiments (except in regard to gravitation). —A. S. Eddington"

Scientific American Supplement,
July 6, 1918

The theory put forward in the 1916 paper lacked experimental proof. Several astronomers, including Arthur Stanley Eddington, in charge of the University of Cambridge Observatory, used a solar eclipse of May 29, 1919, as an opportunity to test one prediction: that light rays from a star would be bent as they passed close by the gravitational field of the sun. When the prediction appeared to be proved accurate, Einstein was hailed by the science community and achieved almost an apotheosis in the public mind:



SOLAR ECLIPSE in 1919 bolstered Einstein's theory. As he predicted, the sun's mass caused light from distant stars (*marked by vertical bars*) to be deflected at the earth—by a few hundredths of a millimeter.

"The results obtained at the total solar eclipse of May 29 last were reported at a joint meeting of the Royal Society and the Royal Astronomical Society, held on November 6. The results with the 4-inch lens stationed at Sobral, North Brazil, were most satisfactory. The star-images are well defined, and their character is the same on the eclipse and check plates. The resulting shift at the limb is 1.98″, with a probable error of 0.12″. It will be seen that this result agrees very closely with Einstein's predicted value of 1.75″. It was generally acknowledged at the meeting that this agreement, combined with the explanation of the motion of the perihelion of Mercury, went far to establish his theory as an objective reality. Sir J. J. Thomson, who presided, spoke of the verification as epoch-making. —A.C.D. Crommelin"

Scientific American Supplement,
December 6, 1919

But how was the public to understand such a complex theory? *Scientific American* ran a contest to solicit a cogent, concise explanation, offering as a first prize the hefty sum of $5,000 (worth more than $50,000 in today's money). Einstein is reported to have said, "I am the only one in my entire circle of friends who is not entering.... I don't believe I could do it." Interest was keen:

"We have with us a freshly-risen scientific topic of transcendent importance—one which has occupied a place in the public prints and the public mind such as has never before been granted to any matter of abstruse scientific doctrine. It gives us the greatest pleasure to state that Mr. Eugene Higgins, an American resident of Paris and for many years a close friend of this paper, offers through the *Scientific American* a prize of Five Thousand Dollars for the best essay on the Einstein postulates."

Scientific American,
July 10, 1920

"Numerous prospective competitors for the five-thousand dollar prize have written us, asking more or less baldly where they may inform themselves upon the subject of the Einstein theories. We have no serious expectations that Mr. Higgins' money is going to be won by anybody whose knowledge of and interest in the doctrines of relativity is of such recent growth that he has to ask this question."

Scientific American,
August 28, 1920

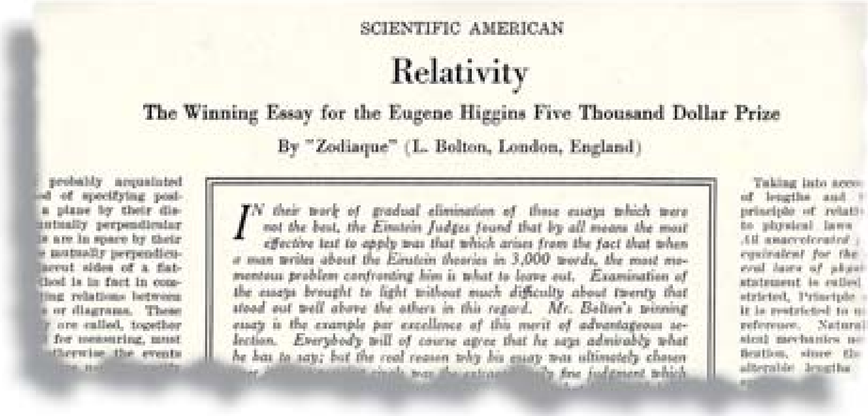
"Mr. L. Bolton, author of the winning essay [*see top illustration on opposite page*], we suppose may fairly be called unknown in a strictly scientific sense, though he is a professional man of distinction in his field. He is on the staff of the British Patent Office. It will be recalled that Einstein himself was in the Swiss Patent Office for some years."

Scientific American,
February 5, 1921

And yet, while relativity became a popular topic, the science community continued its lively debate on all its aspects:

"Whether or not the general reading public is to believe that Professor Dayton C. Miller, the physicist who during several years past has been reperforming at Cleveland and Mount

SCIENTIFIC AMERICAN, JUNE 1991; ROYAL ASTRONOMICAL SOCIETY



SCIENTIFIC AMERICAN

Relativity

The Winning Essay for the Eugene Higgins Five Thousand Dollar Prize

By "Zodiaque" (L. Bolton, London, England)

IN their work of gradual elimination of those essays which were not the best, the Einstein Judges found that by all means the most effective test to apply was that which arises from the fact that when a man writes about the Einstein theories in 3,000 words, the most momentous problem confronting him is what to leave out. Examination of the essays brought to light without much difficulty about twenty that stood out well above the others in this regard. Mr. Bolton's winning essay is the example par excellence of this merit of advantageous selection. Everybody will of course agree that he says admirably what he has to say; but the real reason why his essay was ultimately chosen

WINNING ESSAY in the Einstein contest appeared in *Scientific American*, February 5, 1921. (The full version is available at www.sciam.com/ontheweb)

Wilson the famous Michelson-Morley ether-drift experiment and obtaining with uniform consistency indications of an actual ether-drift and hence the existence of an ether, is out to 'get' the Einstein theory of relativity, which dispenses with an ether, seems to depend upon what it reads. Let a world of blind admirers and enraged detesters of a theory beat the air with super-heated syllables, Einstein serenely smokes his pipe and says 'If Professor Miller's research is confirmed, my theory falls, that's all.' And Miller, standing before his assembled peers in science, is almost apologetic about his findings, but indicates that there they are."

Scientific American,
March 1930

There was, and is, an ongoing discussion as to how great Einstein truly was:

"Not that Einstein 'needs the publicity'; but because the editors from time to time receive communications from persons who either request confirmation of his high standing in science or, as sometimes occurs, wish to have their private opinion confirmed that he is a 'faker' (as one rather excitable anti-Einsteinian repeatedly put it), attention is called to the recent tribute of the Riverside Church in New York which has chosen to include a carved figure of Einstein with those of the world's very greatest on the tympanum of the doorway of its new edifice. Einstein is the only living person thus to be honored. Another naïve question sometimes is asked: 'Is Einstein really Jewish?' Einstein is a Jew."

Scientific American,
December 1930

"Albert Einstein, whose 70th birthday this month is being noted throughout the civilized world, occupies a position unique among scientists. He has become a legend in his own lifetime. The importance of Einstein's scientific ideas does not reside merely in their great success. Equally powerful has been their psychological effect. At a crucial epoch in the history of science Einstein demonstrated that long-accepted ideas were not in any way sacred. —Banesh Hoffman"

Scientific American,
March 1949

In 1950 Einstein wrote an article for *Scientific American* on his attempts at further extensions to the theory of relativity [see "Forces of the World, Unite!" by George Musser, on page 106]:

"As for my latest theoretical work, I do not feel justified in giving a detailed account of it before a wide group of readers interested in science. That should be done only with theories which have been adequately confirmed by experience. Experience alone can decide on truth. —Albert Einstein"

Scientific American,
April 1950

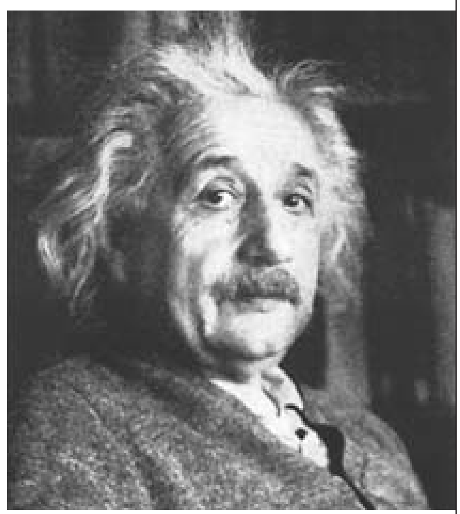
Einstein died on April 18, 1955. The leading lights of science acknowledged with gratitude their debt to him:

"With the death of Albert Einstein, a life in the service of science and humanity which was as rich and fruitful as any in the whole history of our culture has come to an end. To the whole of mankind Albert Einstein's death is a great loss, and to those of us who had the good fortune to enjoy his warm friendship it is a grief that we shall never more be able to see his gentle smile and listen to him. —Niels Bohr"

Scientific American,
June 1955

And a final word about Einstein's history, according to Einstein:

"Two weeks before the death of Albert Einstein, I sat and talked with him about the history of scientific thought. Einstein said most emphatically that he thought the worst person to document any ideas about how discoveries are made is the discoverer. Many people, he went on,



PROFESSOR EINSTEIN was photographed at home in his study for our June 1939 edition.

had asked him how he had come to think of this or how he had come to think of that. Einstein believed that the historian is likely to have a better insight into the thought processes of a scientist than the scientist himself. —I. Bernard Cohen"

Scientific American,
July 1955

Daniel C. Schlenoff edits the 50, 100 & 150 Years Ago column.

SCIENTIFIC AMERICAN, FEBRUARY 5, 1921 (*essay*); SCIENTIFIC AMERICAN, JUNE 1939; PHOTOGRAPH BY ELIZABETH MENZIES, COURTESY OF G. GOSEN RARE BOOKS (*Einstein*)

FORCES OF THE WORLD, UNITE!

In a 1950 *Scientific American* article, Einstein outlined his unified theory of physics. Too bad it was wrong **By George Musser**

When Albert Einstein started his efforts to develop a unified theory of physics in the early 1920s, it was such a hopeful enterprise. Existing theories, including both relativity and the emerging quantum mechanics, raised as many questions as they answered, so most physicists agreed on the need for a grander framework. Ideas poured forth from figures such as Hermann Weyl, Arthur Stanley Eddington and Theodor Kaluza. Although these pioneering efforts fell short of achieving unification, they introduced theorists to such fruitful concepts as gauge symmetry and extra dimensions.

Thirty years later Einstein stood alone. He had published and retracted a string of unified theories. Other scientists saw his approach as a dead end—an assessment that has been borne out by the progress of physics since his death in 1955. Whereas Einstein sought to base a unified theory on general relativity, quantum mechanics has proved the best starting point.

Toward the end of 1949, Einstein published what he called the definitive formulation of his unified theory, and the editors of *Scientific American* invited him to prepare a nontechnical account. Appearing in the April 1950 issue, it was the second-to-last article he ever wrote on science for the general public. Einstein scribbled it in longhand in German (the original survives in the Einstein Archives Online at alberteinstein.info), and the published version is a nearly unedited translation. It is a challenging read. Dry and methodical, it lacks the vivid thought experiments—trains, light beams, elevators—that animated Einstein's earlier writings, and its description of the details of the unified theory is so vague as to be nearly incomprehensible. Dennis Flanagan, the magazine's editor at the time, remarks: "The article was considerably more difficult than those we normally published, and we proposed some editorial changes to Dr. Einstein. He felt the article should be published without change."

That said, the article rewards multiple readings, especially if one thinks of it as a discussion not of science but of the philosophy of science. The abstractness of the article, though a stumbling block for the nonphysicist, is actually one of its most important features, showing how Einstein's goals had shifted over his career. His main research interest was no longer to explain observed phenomena. The general theory of relativity had taken care of gravitation, and Maxwell's equations handled the other prominent force of nature, electromagnetism. Instead Einstein was trying to unite those two theories out of an urge to solve their conceptual riddles.

Thus, the abstract structure of these theories was precisely what concerned him. In the article, he wrote:

> New theories are first of all necessary when we encounter new facts which cannot be "explained" by existing theories. But this motivation for setting up new theories is, so to speak, trivial, imposed from without. There is another, more subtle motive of no less importance. This is the striving toward unification and simplification of the premises of the theory as a whole.

Because physicists had already plucked the low-hanging fruit—they had come up with the laws that described our direct experiences—the next step was inevitably going to be harder:

> A theory has an important advantage if its basic concepts and fundamental hypotheses are "close to experience," and greater confidence in such a theory is certainly justified. There is less danger of going completely astray, particularly since it takes so much less time and effort to disprove such theories by experience. Yet more and more, as the depth of our knowledge increases, we must give up this advantage in our quest for logical simplicity and uniformity in the foundations of physical theory.

These comments remain pertinent even today. Many people have complained that string theory, in particular, has drift-

IN TRYING TO DEVELOP a unified theory, Einstein worked closely with Peter Bergmann (*left*) and Valentine Bargmann (*right*), two young German-born physicists who also had fled the Nazis and who went on to become renowned scientists in their own right. Bargmann's wife, Sonja, was the one who translated Einstein's *Scientific American* article (and many other manuscripts) into English. This picture was taken in 1940.

LUCIEN AIGNER *Corbis*

ed so far from the moorings of experiment that it has ceased to be a science. But any theory worthy of being called fundamental is going to seem remote and inaccessible, at least initially. You can't just make some observations, follow a set of rules and arrive at an explanation. You have to come up with an idea, work it through and only then figure out how to test it experimentally. In that sense, science is an art. Einstein wrote:

> The theoretical idea … does not arise apart from and independent of experience; nor can it be derived from experience by a purely logical procedure. It is produced by a creative act.

In Einstein's theories, the creative spark was the idea of symmetry. A symmetric object remains the same even if it is transformed: reflected, rotated, distorted. Mathematically, a transformation is like typing the relevant equation into a word processor and doing a search-and-replace operation. If the equation has a particular kind of symmetry, the corresponding search-and-replace operation will have no effect on it. An example is the equation for a simple hyperbola, $xy = 1$. If you replace x by y and y by x, the equation does not change. That is an abstract way of saying that the two arms of a hyperbola are mirror images.

The goal that Einstein laid out was to formulate equations that stay the same for as many different search-and-replace operations as possible. The idea is that the more symmetrical the equations are, the more phenomena they encapsulate.

In the case of special relativity, you can replace every instance of x, y, z and t—the coordinates that specify the position and time—with a certain mathematical function of x, y, z and t. Only a certain function will do; that is why it is called "special" relativity. This symmetry unites space with time. To calculate the distance between points, you cannot use the usual Pythagorean theorem containing x, y and z. You need a four-dimensional version of the theorem that also includes t.

The general theory of relativity broadens the type of search-and-replace operation you can perform. Instead of a certain operation of x, y, z and t, you can use nearly any function of these coordinates. For the equations of physics to remain the same, a force must enter into play, and this force is none other than gravitation. The distance between points is given by a more complicated rule—the "metric"—than the Pythagorean theorem. The metric can be represented by a four-by-four matrix of numbers. Because the distance from point A to point B is the same as from B to A, this matrix is symmetrical about the diagonal centerline, so it contains 10 unique numbers; the other six are repeats.

Einstein reasoned: Why stop there? Why not allow any matrix whatsoever? To the symmetric matrix (with 10 unique numbers) would be added a so-called antisymmetric matrix (another six). As it happens, Maxwell's equations can be written using an antisymmetric matrix. So it is natural to hope that this approach unites gravitation with electromagnetism.

Unfortunately, what is natural is not necessarily right. Einstein ran into trouble trying to force-fit the two matrices together. It was not a transitory problem, as he thought, but a deep mismatch. Despite the outward similarities between gravitation and electromagnetism, physicists have found that the two are profoundly dissimilar. Moreover, during the three decades over which Einstein pursued his unified theory, researchers identified new forces that did not fit into his scheme: the weak and strong nuclear forces. Electromagnetism is more closely related to those forces than it is to gravitation. Although Einstein's basic instincts about symmetry were right, he was applying them to the wrong entities. In the article, he wrote:

> I do not see any reason to assume that the heuristic significance of the principle of general relativity is restricted to gravitation and that the rest of physics can be dealt with separately.… The comparative smallness of what we know today as gravitational effects is not a conclusive reason for ignoring the principle of general relativity in theoretical investigations of a fundamental character. In other words, I do not believe that it is justifiable to ask: What would physics look like without gravitation?

The opposite turned out to be true. Quantum mechanics without gravitation explains electromagnetism, the nuclear forces and the structure of matter with exquisite precision. Gravitation has actually been the hardest piece of physics to unify with the rest; physicists still struggle with it. Rather like Einstein himself at the end of his life, it stands apart. SA

George Musser is the symmetric union of staff writer and staff editor.

The two scientific giants were alike in intellect and temperament

By Alan Lightman

EINSTEIN & NEWTON: GENIUS COMPARED

How can we measure the genius of Albert Einstein?

In many ways, the task is not possible. If we journey back through the centuries, passing such towering figures as James Clerk Maxwell, Ludwig Boltzmann, Charles Darwin, Louis Pasteur, Antoine Lavoisier, we must travel all the way to Isaac Newton before finding another human being of comparable scientific achievement. And before Newton, there might be none.

Both Einstein and Newton had intellects that carried them to every known continent of their subjects and beyond. Newton invented the calculus, formulated the laws of mechanics and motion, proposed a universal theory of gravitation. Einstein laid the foundations for the two skyscrapers of modern physics, special relativity and quantum mechanics, and created a new theory of gravity.

But beyond these particular achievements, both scientists radically changed thinking in science. Both developed worldviews. Today we refer to the "Newtonian" universe and the "Einsteinian" universe—the first being a world of absolutes, the second a world of relativities. In the Newtonian universe, time flows inexorably, always at the same rate, now and forever. Causality is as strict as a commandment of God. Without exception, every effect has a cause. The future is completely predictable from the past. In the Einsteinian universe, time is not absolute. The rate of temporal flow depends on the observer. Furthermore, according to the new quantum physics, which Einstein helped to establish despite reservations, the intrinsic uncertainties of nature at the subatomic level prevent forecasting the future from the past. Certainties must be replaced by probabilities.

These ideas are larger than scientific theories. They are philosophies, they are symphonic themes, they are different ways of being in the world.

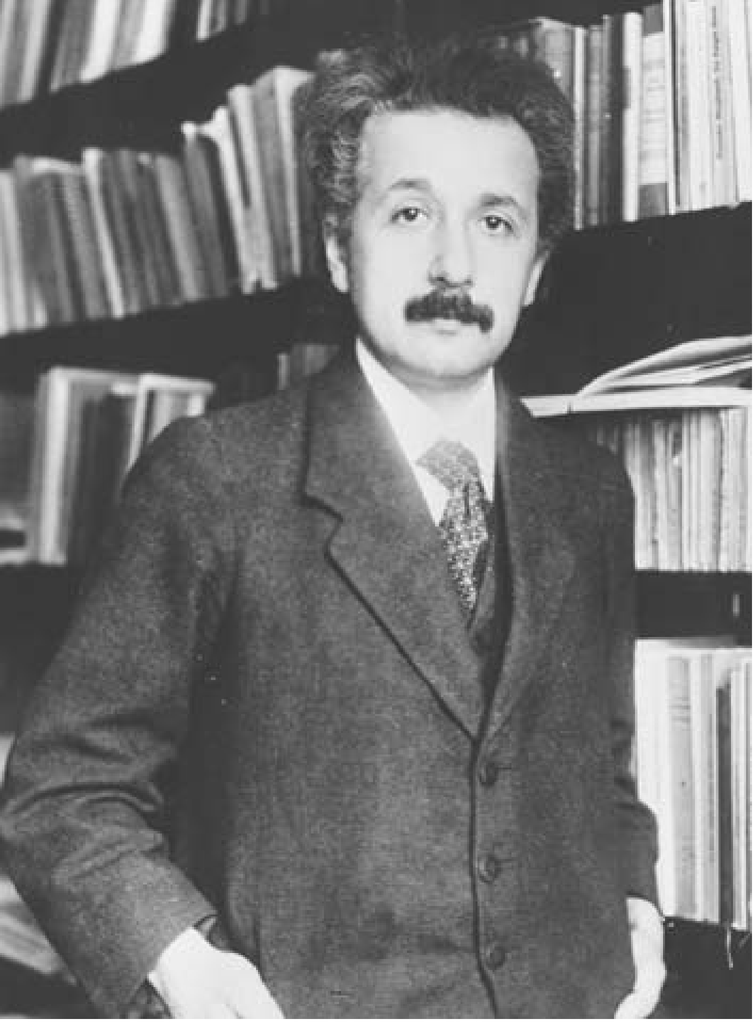
Both Newton and Einstein were principally theoretical physicists. Like many theoretical physicists, they did their greatest work in their mid-twenties. Both tried their hand at experiments. Newton, the far greater experimentalist, discovered among other things that white light is composed of a mixture of colors. Newton invented mathematics that he needed. Einstein did not, but his brilliant intuition led him to study and adopt the obscure non-Euclidean geometry of Riemann and Gauss for his geometric theory of gravity.

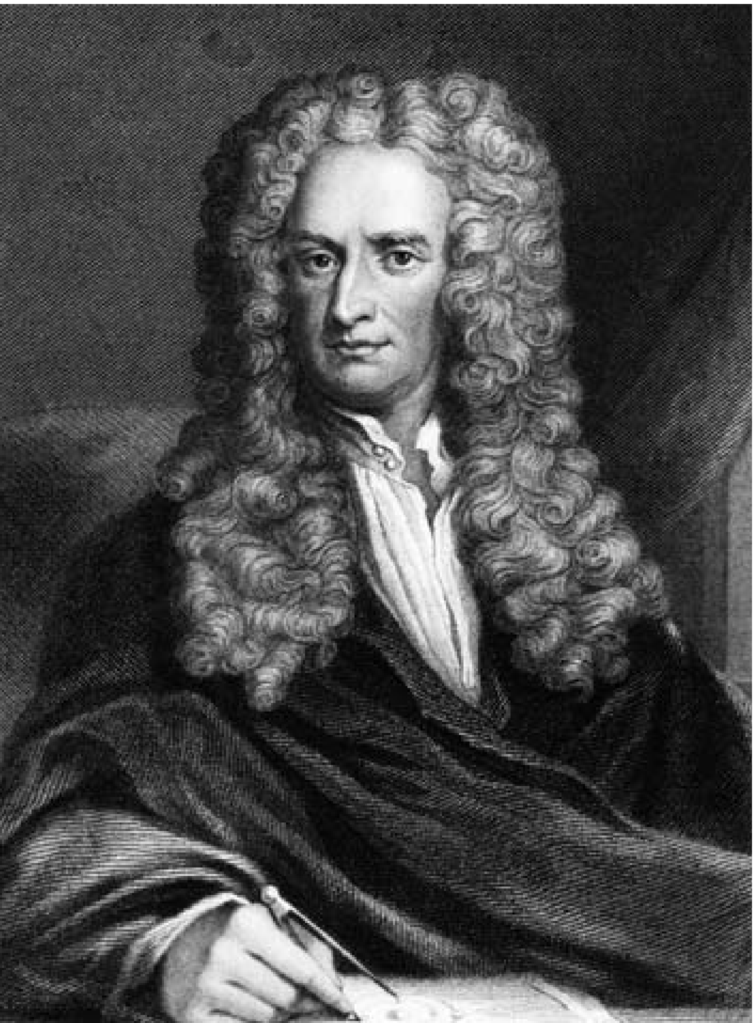
Both were artists. Both devoted themselves to simplicity, elegance and mathematical beauty. Like artists, both preferred to work in isolation. Newton sequestered himself for months at a time when he was at work on a project. Einstein never had any graduate students and rarely taught. Both were loners. Newton was the greater loner. He seems to have been practically antisocial, and, as Voltaire noted at Newton's death, "in the course of such a long life [Newton] had neither passion nor weakness; he never went near any woman." Newton even formulated a plan to preserve his celibacy: "The way to chastity," he wrote, "is not to struggle with incontinent thoughts but to avert the thoughts by some employment, or by reading, or meditating on other things."

In later life, Einstein involved himself with many social causes, such as supporting the League for Human Rights, giving numerous lectures around the world on politics and philosophy and education, helping to found the Hebrew University of Jerusalem. Einstein had many romantic relationships in his life. But at the most personal level, he seems to have been as solitary as Newton. In an essay published in 1931, at the age of 52, Einstein wrote:

> My passionate sense of social justice and social responsibility has always contrasted oddly with my pronounced lack of need for direct contact with other human beings and human communities. I am truly a "lone traveler" and have never belonged to my country, my home, my friends, or even my immediate family with my whole heart.

HULTON-DEUTSCH COLLECTION/CORBIS (*top*); BETTMANN/CORBIS (*bottom*)





Both Newton and Einstein fiercely guarded their independence. Both worshipped their solitude.

Isaac Newton and Albert Einstein left profound legacies. Newton conquered the notion that some areas of knowledge were inaccessible to the human mind, an idea ingrained in Western culture for centuries. In much thinking before Newton, humankind was entitled to comprehend only what God deigned to reveal. Adam and Eve were banished from Eden for eating from the tree of knowledge, God's knowledge. Zeus chained Prometheus to a rock for giving fire, the secret of the gods, to mortal man. When Adam, in John Milton's *Paradise Lost,* questioned the angel Raphael about celestial mechanics, Raphael offered some vague hints and then said that "the rest from Man or Angel the great Architect did wisely to conceal." All these limitations and forbidden regions were swept aside with Newton's monumental work *The Principia* (1687). There, in precise, mathematical terms, Newton surveyed all phenomena of the known physical world, from pendulums to springs to comets to the grand trajectories of planets. After Newton, the division between the spiritual and physical was more clear. And the physical world was knowable by human beings.

Einstein, with his extraordinary and seemingly absurd postulates of special relativity, demonstrated that the great truths of nature cannot be arrived at merely by close observation of the external world. Rather scientists must sometimes begin within their own minds, inventing hypotheses and logical systems that only later can be tested against experiment. For example, all of our experience since birth screams at us that time flows at a uniform rate, and yet this belief is not true. Modern physics has at last advanced to an understanding of nature beyond human sense perception and experience, teaching us that our commonsense grasp of the world can be mistaken. In this legacy, Einstein overturned centuries of thought about the supremacy of empirical study and experience. He also contradicted Newton's famous dictum *hypotheses non fingo* ("I frame no hypotheses"), by which the British scientist meant that he was not an armchair philosopher, like Aristotle, but a scientist who based his theories on observable facts.

In his autobiography, Einstein expressed his departure from Newton in this way: "Newton, forgive me; you found the only way which, in your age, was just about possible for a man of highest thought and creative power. The concepts, which you created, are even today still guiding our thinking in physics, although we now know that they will have to be replaced by others farther removed from the sphere of immediate experience."

In an introduction to a 1931 edition of Newton's *Opticks,* Einstein wrote of Newton, "Nature to him was an open book.... In one person he combined the experimenter, the theorist, the mechanic, and, not least, the artist in exposition. He stands before us strong, certain, and alone." If Newton could reappear in the future, in a forbidden trick of time travel, he would probably say similar words about Einstein. SA

Alan Lightman is a physicist and novelist.

YO-YO

String Theory

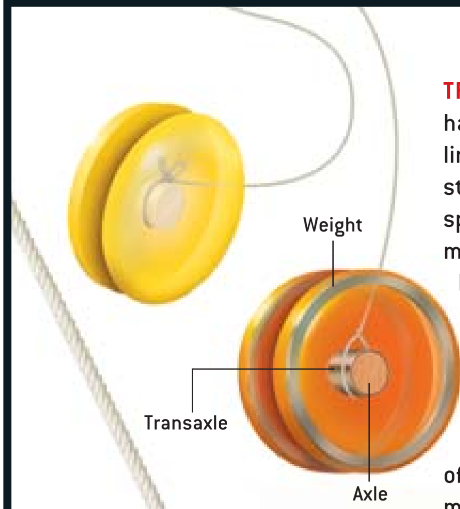
The yo-yo is just a simple toy, right? Not anymore. Rim weights and axle technologies now exploit the physics of angular momentum to make possible all sorts of tricks and traits.

Yo-yos date back more than 2,000 years to China and Greece. They rolled their way into Europe, and by the 18th century the "émigrette" or "quiz" had become a favored toy of aristocrats.

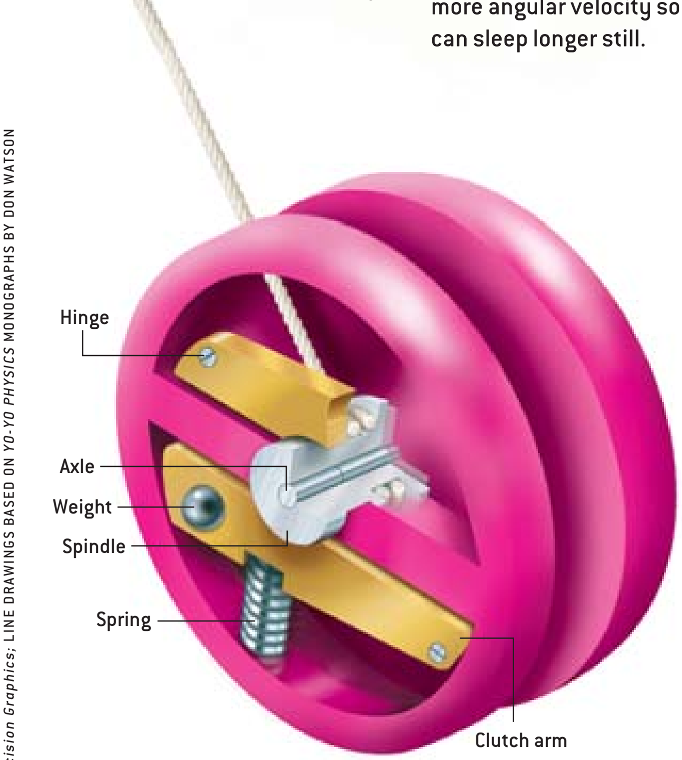
All along, the string was tied to the axle, causing the spinning disks to return up the cord immediately after they hit bottom. But aficionados in the Philippines looped a string around the axle, so the wooden disks could spin freely, or sleep, while hanging down. This innovation made possible numerous tricks with names such as cat's cradle and walk the dog. Filipino Pedro Flores immigrated to the U.S., started manufacturing yo-yos in 1928, and began the first American craze for this toy. Cheap and durable, it was one of the few commercial successes of the Great Depression.

In 1932 businessman Donald Duncan bought out Flores, began widespread contests among players to generate publicity, and trademarked "yo-yo," leaving competitors with poor alternatives, like "twirler." The Duncan name eventually became synonymous with yo-yo; in 1962 the company sold 45 million toys in a country with only 40 million children. In 1965, however, a federal court ruled that "yo-yo" had become a generic term. Duncan lost its trademark protection and went bankrupt but was later bought by Flambeau Plastics, which revived the brand.

Although plastic and metal began to replace wood, the design remained essentially the same. In the late 1980s and 1990s, however, several companies introduced a flurry of improvements such as weighted rims, ball-bearing axles and clutches that suddenly made possible much longer sleep times: the record rose from 51 seconds in 1991 to 13 minutes five seconds a decade later. The "arms race" has created "more design innovation since 1990 than there was in the 100 years prior," says Don Watson, a retired industrial engineer and professional yo-yo player known as Captain Yo. Longer sleep time led to hundreds of new tricks and a resurgence in popularity that continues today. —*Mark Fischetti*



TRADITIONAL yo-yo (*far left*) has a string tied to a fixed axle linking two sides. Today the string is looped so the disks can spin, or sleep—the basis for most tricks. Modern yo-yos may have a transaxle that slips freely, reducing friction on the string so the disks can sleep longer. Rims may be weighted around the edge, which enlarges the moment of inertia and gives the disks more angular velocity so they can sleep longer still.



CLUTCH stays open as a result of centrifugal force when the yo-yo spins quickly. The free-standing spindle allows the axle and disks to sleep. When the rotation slows, the force drops, and the springs can then squeeze the clutch arms against the spindle so it engages the axle and spins with it, "automatically" rewinding the string.

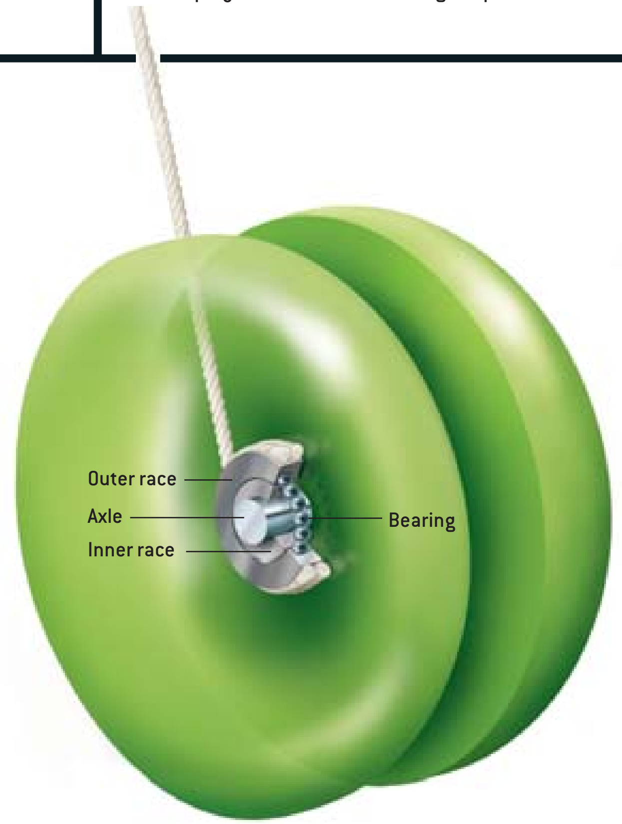
KENT SNODGRASS *Precision Graphics*; LINE DRAWINGS BASED ON *YO-YO PHYSICS* MONOGRAPHS BY DON WATSON

DID YOU KNOW . . .

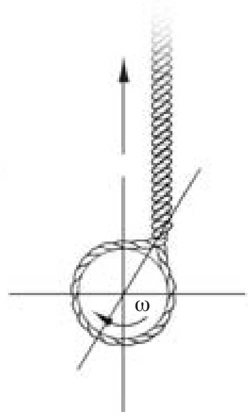
➤ YO, PHYSICISTS: Detailed descriptions of the forces that act on a yo-yo and string are hard to find. Captain Yo to the rescue! The retired industrial engineer and professional yo-yo player has handwritten five tidy monographs on yo-yo physics that cover everything from inertial moments to rpm generation. The photocopied notebooks can be purchased through www.skilltoys.com and www.yoyoguy.com. Not for the faint of heart.

➤ DISCONNECT: Two radical trick styles have recently burst forth at competitions. In "off-string," the cord wraps around the axle as if it were a top. A player flings the disk upward, it leaves the string, and the player uses the cord as a tightrope for tricks, finally looping it around the spinning axle to lasso and retrieve it again. In "freehand," the string links a disk at one end to a counterweight (not the player's finger) at the other end; the player releases and then catches either the string or the counterweight to propel the whirling disk in aerial maneuvers.

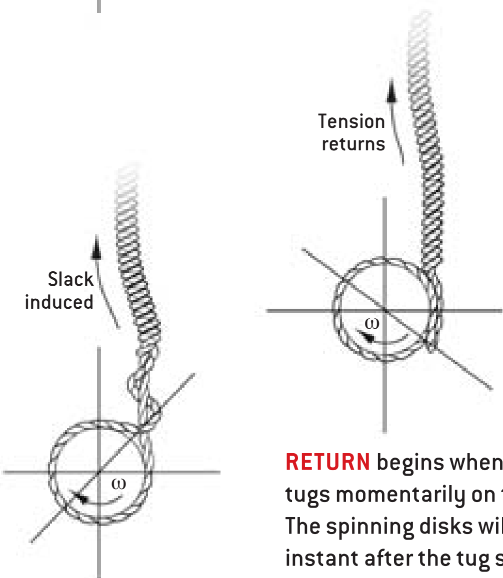
➤ READ IT HERE FIRST: Yo-yo histories can be sketchy, but several say that *Scientific American* itself introduced the toy's name to America. The accounts cite a July 1, 1916, article in *Scientific American Supplement* entitled "Filipino Toys." The article showed how to make a spinning disk, said its proper name was yo-yo and advised that "considerable skill is required to operate it well."



BALL-BEARING transaxle minimizes string friction more than any other design, offering the longest spins.

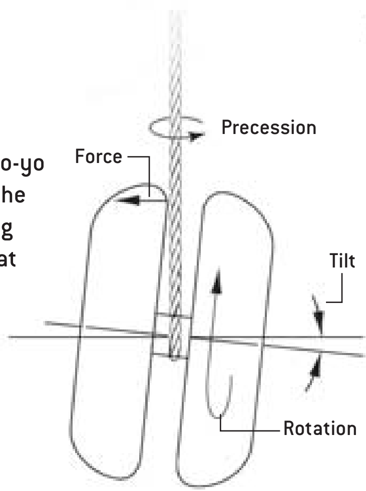


SLEEP begins when the string is fully unwound. A player who can throw down the yo-yo hard yet ease its bounce by slightly dropping his wrist as the yo-yo reaches bottom imparts the greatest angular velocity (ω) to the disks, maximizing sleep duration for tricks.



RETURN begins when a player tugs momentarily on the string. The spinning disks will rise for an instant after the tug stops (*left*), which pushes slack into the braid and then pulls the slack down around the axle. The bunching forces the string against the disks (*above*), raising friction sharply, which causes the disks to grab the string and climb back up.

PRECESSION can cause a spinning yo-yo to flare out. If a player holds or tugs the string at too great an angle, the string will strike the rim, inducing a force that causes the yo-yo to wobble (precess) about the string. At the same time, friction between the string and spinning rim produces torque that tilts the yo-yo. The two effects throw the yo-yo out of control.



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VOYAGES

Hiking Underground

THE LONGEST CAVE IN THE WORLD WENDS BELOW KENTUCKY'S MAMMOTH CAVE NATIONAL PARK. HERE VISITORS CAN VIEW CAVE FORMATION UP CLOSE BY MARGUERITE HOLLOWAY

I emerge from Fat Man's Misery—a narrow, twisted low-roofed passage where the rocks have gone shiny and smooth from the touch of countless hands reaching out for balance or perhaps solace—only to find myself just a short walk from the River Styx. The sliver of water apparent between walls of rock is green and seemingly leisurely; it imparts no sense of foreboding, no mythical beings spring to life. Yet this small river is a powerful force. This flow built one of the most extensive cave systems on earth; it sculpted limestone into the more than 360 miles of tunnels, chambers and beautiful shapes that compose Mammoth Cave.

Our group—45 enterprising people who have been soundly warned about the physical demands of our two-and-a-half-hour "Making of Mammoth" tour—has descended to the fifth and lowest level of the cave system to see the River Styx. Down here the air is humid and thick, the ground muddy in places, and the knowledge of depth, of the weight of layers of rock above us, is more oppressive than in the higher, dry realms of the cave. But it is only down here, in the potentially claustrophobia-inducing depths, that water is still at work, carving new passageways. And only here that some of the cavern's most unusual creatures—colorless Mammoth Cave shrimp, Indiana eyeless crayfish and eyeless cavefish—make their home.

As we descended, our National Park Service guide explained how Mammoth became so mammoth—a story of seawater, rainwater and eons. Some 350 million years ago central Kentucky was undersea.

HISTORIC ENTRANCE serves as a flyway for the 12 species of bat that inhabit the cave, albeit in small numbers (*above*). Flowstone formations, such as the Drapery in the Frozen Niagara area of the cave (*right*), are among the site's most dramatic features.

The calcium carbonate shells of the ocean's organisms settled on the bottom, becoming, over time, layers of limestone—several hundred feet or so of soft rock by the time the Mississippian period was over. A river then deposited sand and mud, forming a cap of hardier sandstone and shale.

As the climate shifted and the sea receded and the river ran a different course, rainwater began its work. Percolating through the ground to the constantly lowering water table, and thence to the sea, some of it combined with carbon dioxide in the soil to become carbonic acid. The weak acid ate through the limestone, trickling down in ever widening cracks, ultimately forming underground rivers that became labyrinthine caves. These water-hollowed passages exist today only because of the sandstone; without that protective covering, the cave would have no roof—it would be a canyon, not even a grand one at that.

After a brief musical interlude, in which our guide leads us in song to demonstrate the remarkable acoustics near Echo River, just beyond the River Styx, we begin the climb out. Panting from the steep ascent, we emerge at the Historic Entrance, where long ago an accumulation of water weighted down the ground, creating a sinkhole that eventually collapsed, opening a part of the cave. A few feet beyond the entrance, the cave's cool air—around 54 degrees Fahrenheit year-round—is replaced by the hot southern summer and the damp of a fresh rain. The light is dizzying.

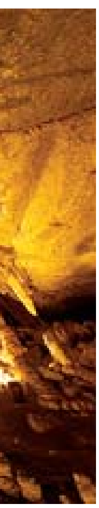
The geology walk is just one of many that Mammoth Cave National Park offers each day. The tours vary by season: some, for instance, are offered only in the fall or winter, when fewer people visit the park and the groups are smaller. But most of the time, visitors can choose the aspects of the cave they most want to see and select accordingly.

To experience the cave without the extensive electric light system that most tours rely on, I take the "Violet City Lantern" tour. The cave has been many things over the centuries, and on this three-hour walk our group, this time consisting of about 60 people, learns about much of its human history. Native people explored the cave and mined for gypsum 4,000 to 2,000 years ago, as the mummified remains of one ancient visitor attested. Discovered by European settlers in the late 1790s, the cave was then mined for saltpeter (a component of gunpowder) during the War of 1812. Shortly after the war, the cave became principally a tourist attraction—something that continues today. In 1842, while the public tours continued, tuberculosis patients were housed in underground stone huts. Their physician thought subterranean life would cure them. It didn't; the doctor, who owned the cave at the time, also died of consumption.

Neither the geology tour nor the lantern tour centers on the cave's incredible sculptural formations, however, so I also take the "Travertine" tour—which one guide calls the "cheater's tour." Only an hour or so and not very taxing—no Fat Man's Misery, no 560 stairs to ascend from the River Styx—this circuit passes 80 percent of the various cave for-

PHOTOGRAPHS BY MARC MUENCH

GREEN RIVER FERRY shuttles visitors to the western section of the park for camping and trails (*below*).



mations that exist at Mammoth. We hike by a curtain of flowstone called the Drapery, and we see stalactites, stalagmites, columns, and the myriad other lovely organic forms and textures that water makes of rock. The shapes conjure tube worms, coral, roots, druids, moss, the soft inner flaps of mushroom caps.

Mammoth Cave National Park is open every day except Christmas. There is no park fee; visitors must pay for each tour. Some, including "Wild Cave," are only for those who are extremely physically fit and meet certain dimensional requirements. Two of the options are relatively easy. The others range from two to four-and-a-half hours and are often quite strenuous. Guides make clear at the outset that people with respiratory or heart problems or other health issues should not participate. Despite the stringent warnings, overweight and otherwise unhealthy people take the tours, and there have been several deaths and emergency evacuations from the cave as a result.

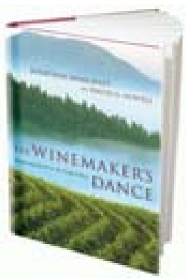
For a description of the tours, see www.mammoth.cave.national-park.com/hike.htm. The cave gets more than 400,000 visitors a year, and the rangers recommend making reservations well in advance (www.reservations.nps.gov or 1-800-967-2283) because many of the tours often sell out.

If you decide not to take the more challenging tours, there is plenty to see aboveground in the park's 53,000 acres. At the bottom of the hill, just past the Historic Entrance, the River Styx empties into the daylight and makes its way to the nearby Green River. And past the Heritage Trail, which runs next to the park's visitor center and the Mammoth Cave Hotel and through the region's lush oak and hickory woods, is the Mammoth Dome Sink. Decades from now this sinkhole will probably collapse as well, opening another portal into the dark, cool hallways of the earth. SA

This is the final Voyages column.

Existential *Terroir* in Northern California

140 MILLION YEARS OF GEOLOGIC HISTORY IN A BOTTLE OF WINE **BY HENRY GEE**



THE WINEMAKER'S DANCE: EXPLORING TERROIR IN THE NAPA VALLEY
by Jonathan Swinchatt and David G. Howell
University of California Press, Berkeley, Calif., 2004 ($34.95)

Time was when Americans in Britain would be sternly corrected were they to use the term "English" when what they really meant was "British." These days the British themselves are no longer sure which is which. Yet one distinction still rises above all ambiguity, and its identity might be surprising—wine. "British" wine is made in Britain from imported grapes. "English" wine, in contrast, is a handcrafted, homegrown product. The distinction should be clear: whereas British wine is made without reference to its place of origin, English wine is sold on its location. A sense of place is central to its image, its taste and its success.

In *The Winemaker's Dance,* geologists Jonathan Swinchatt and David G. Howell argue that this sense of place is central to the standing and the understanding of wine from California's Napa Valley, although their contention would be just as true wherever grapes are grown and wine is made. As such, Swinchatt and Howell take what they themselves see as a controversial stand, contending that winemakers should reassert a sense of place, to buck what they see as the trend toward a homogeneous "international" style of wine, fostered by the personal tastes of a small circle of influential critics.

At the heart of their thesis is an appreciation of *terroir,* which, like many words in French, is both untranslatable and full of meaning. Coming from the classic French tradition of winemaking, *terroir* means the situation in which wine is made. "At its core," Swinchatt and Howell note, "the notion of terroir refers to all the qualities that characterize place: topography, bedrock, sediments and soils, temperature, and rainfall. Some wine writers and professionals include viticultural practices, and others recognize the impact of … the winemaker."

Terroir is not an object, then, but an epiphenomenon, an indefinable summation of the winemaker's dance, which starts with the careful selection of a vineyard and ends with the bottle on your table. The authors venture that the story of any bottle of wine starts much earlier than that, with the history of the land itself. In the words of David Jones, winemaker and geologist, "What you're tasting in a bottle of wine is a hundred million years of geologic history."

Using this as the cue to take the broadest possible view of terroir, Swinchatt and Howell sketch the geologic history of the Napa Valley, starting with its origin as ocean floor squeezed up against the North American mainland 140 million years ago. Volcanoes have come and gone, rivers have woven their courses, and the weather has exacted its remorseless toll, to produce in the Napa Valley a rugged terrain of great variety in bedrock, soil and microclimate, despite its tiny size (just 40 miles long and 21 broad).

For much of the book, Swinchatt and Howell show how winemakers have exploited the varied topography and climate

UNIQUE TOPOGRAPHY and climate of California's Napa Valley, shown here looking south over rolling hills to the flat terrain bordering San Pablo Bay, are embodied in its distinctive wines.

COURTESY OF UNIVERSITY OF CALIFORNIA PRESS of the Napa Valley as an expression of a characteristically American individuality. Yet they note a paradox. The finest Napa wines come from hot, water-stressed grapes clinging to marginal hillside soils, farmed by winemakers often new to the craft and therefore free to experiment. On the other hand, the classic wines of Bordeaux on which Napa wines are modeled come from cooler, more fertile lowland settings and are crafted by winemakers steeped in regulation and tradition. And yet Napa wines have ranked alongside the best that France can offer for more than a quarter of a century. The relation between quality and terroir is, it seems, not a simple one—and this is the central problem of contemporary winemaking. In crafting the best possible wine, is it better to follow the latest global fashion or remain true to the terroir that gives wine its sense of place, come what may?

This is where Swinchatt and Howell might find their message controversial in some quarters. After months of exploration in Napa, interviewing winemakers and learning their secrets, they admit that their favorite wines are those that seek to harmonize all the aspects of terroir, without any one aspect becoming dominant, and that these balanced wines are, more often than not, French.

With disarming frankness they admit that their most memorable drop was a 1988 Chateau Clerc Milon from Pauillac: "By no means an overpowering wine, it nevertheless stopped conversation at the table on the first mouth-filling taste and kept drawing our attention just as vividly throughout a leisurely dinner.... If the winemaker's intent is to 'let the terroir speak,' then the goal will be to balance the elements." In the adherence to a certain style of wine that tends toward aggressive fruitiness at the expense of subtlety, Napa wine risks losing its balance and possibly its way. With increasing use of technology and analysis that characterize those elements of flavor that make certain wines distinctive, it is becoming easier for a winemaker to craft any wine in imitation of any other.

Were this trend to continue indefinitely, wine would lose the sense of place on which rests much of its allure and become any other foodstuff. Like no other agricultural product, wine depends on its location for its appeal. Throw the dice of time a little askew, and the Napa Valley would have been a sleepy farming community like many others, not the greatest tourist draw in California outside Disneyland.

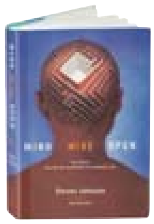
Two sections of *The Winemaker's Dance* are guides for visitors to the Napa Valley, pointing out which vineyards are where and—in the context of geology and topography—why. While I was reading the book, I found these sections incongruous, and I had planned to add a patronizing note that every visitor to the region should have this book in his glove compartment. I'd say so still, but for a different reason. Now that I have drained the authors' beaker of warm South to the dregs, the tourist-guide sections have an elegiac quality. Go see the Napa Valley today, before fashion drains its individuality. *The Winemaker's Dance* is a full-bodied book with somewhat hard-edged, granitic notes and a distinctly disturbing finish. But don't wait for it to age, for it might be too late. It's ready to read right now. SA

Henry Gee, a senior editor of Nature, *is author of* Jacob's Ladder: The History of the Human Genome *(W. W. Norton, 2004) and the upcoming* The Science of Middle Earth: Explaining the Science behind the Greatest Fantasy Epic Ever Told! *(Cold Spring Press, 2004).*

THE EDITORS **RECOMMEND**

MIND WIDE OPEN: YOUR BRAIN AND THE NEUROSCIENCE OF EVERYDAY LIFE

by Steven Johnson. Scribner, New York, 2004 ($25)



"Over the past three decades, science has given us extraordinary glimpses of the brain's inner geography.... We now have the technology in place to picture that inner landscape, in itself as it really is. These are tools, in other words, for exploring our individual minds, with all their quirkiness and inimitability." Johnson, who was co-founder and editor of the Internet science magazine *Feed,* tested several of the tools and reports on what they and various experiments can reveal about such mental activities as mind reading, the fear response, neurofeedback, the roots of laughter and how one gets flashes of insight. "Knowing something about the brain's mechanics—and particularly *your* brain's mechanics—widens your own self-awareness as powerfully as any therapy or meditation or drug."

EINSTEIN SIMPLIFIED: CARTOONS ON SCIENCE

by Sidney Harris. Revised edition. Rutgers University Press, 2004 ($12.95)

They're not all about Einstein, but they're all funny.

The books reviewed are available for purchase through www.sciam.com

Terror Bull

MISTAKES, DAMNED MISTAKES AND STATISTICS **BY STEVE MIRSKY**

In April the U.S. government released its yearly report called "Patterns of Global Terrorism." This edition showed a welcome decrease: the number of people wounded in terrorist incidents in 2003 fell to 1,593 from 2,013 the year before. The decrease in injuries, as well as in deaths and in terrorist incidents, prompted Deputy Secretary of State Richard Armitage to say, "You will find in these pages clear evidence that we are prevailing in the fight."

Then, in June, the State Department updated the original document's incorrect statistics and revealed that terror-related injuries in 2003 in fact totaled 3,646. This number, according to mathematicians, is higher than 2,013. The updated report also revealed more deaths and terrorist incidents in 2003 than had the first document. The new data raise a question: If the interpretation of the original report led the deputy secretary of state to the conclusion that "we are prevailing in the fight," has the corrected report compelled him to announce that we are losing the fight?

Logical consistency would force that conclusion. I looked for any news stories in which he or his colleagues made such an announcement but found none. In the interests of full disclosure, I didn't look too hard, because I figured the odds of finding such a statement were about equivalent to the chances of getting injured in a terrorist attack, which are still exceedingly low, although the idea of it is, well, you know, terrifying.

Now, I'm sure that there are pundits out there who can convincingly make the case that the increase in incidents and injuries in 2003 also represents "clear evidence that we are prevailing in the fight." Because terrorists are getting increasingly desperate, yada yada, insert tortured reasoning here. Anyway, here are some other examples of how one can interpret bad facts to be good news.

Scenario: A major-league baseball team has a team batting average of .260 and hires a new batting coach.
Result: The team batting average plummets to .217.
Conclusion: Well done—you are prevailing in the fight to hit major-league pitching. Your hitters are now so feared that teams use their best pitchers against you, leading to a drop in your collective batting average. (Actually, that makes some sense, but the new coach still gets fired.)

Scenario: The Iraqi city of Basra suffers from severe gasoline shortages.
Result: There are two days of rioting.
Conclusion: Excellent—you are prevailing in the fight to strengthen the local economy. The raging demand for gas shows that more people have the financial wherewithal to want to drive places. (Actually, there were two days of rioting over gas shortages in Basra in August 2003, and officials did say it was a sign of an improving economy.)

Scenario: You pledge a fraternity.
Result: You perform depraved acts of self-humiliation and are enthusiastically accepted into the fold.
Conclusion: Fantastic—you are prevailing in the fight to become a member of an important group. Hey, it must be an important group, because how else can you explain the gusto with which you roll around in cow pies while singing "Tomorrow" from the Broadway musical *Annie* with only a non-Equity contract? (Actually, the belief that a frat must be important because otherwise how could you explain the ridiculous things you're doing to get into one *is* pretty much the logic behind the willingness to be hazed.)

In reality, simple statistics on casualties and incidents are not conclusive. For example, if devastating terrorist attacks were secretly averted, perhaps we really would be prevailing in the fight despite a given year's increased casualty count. It's complicated, but Americans can handle a bit of complexity. Just don't tell us that chocolate ice cream is vanilla, especially when it's not even chocolate ice cream but only something a frat boy rolled in. SA

ILLUSTRATION BY MATT COLLINS; PHOTOGRAPH BY FRANK VERONSKY

ASK **THE EXPERTS**

Q Why is the fuel economy of a car better in the summer?

—C. Staf, New York City

Harold Schock, professor of mechanical engineering and director of the Automotive Research Experiment Station at Michigan State University, explains:

Temperature and precipitation affect the inner workings of a vehicle and the actions of its driver, both of which have an impact on the mileage. In cold, snowy weather, the fuel economy during trips of less than 10 minutes in urban stop-and-go traffic can easily be 50 percent lower than during operation of the same vehicle in light traffic with warm weather and dry roads.

Auto components such as electric motors, engines, transmissions and the axles that drive the tires consume more energy at low temperatures, especially during start-up. Oil and other fluids become more viscous as temperatures drop, which means that more work—and thus fuel—is required to overcome friction in the drivetrain components. In addition, the initial rolling resistance of a tire is about 20 percent greater at zero degrees Fahrenheit than it is at 80 degrees F. This rolling resistance decreases as the vehicle starts to move, and in trips of a few miles the temperature rise—and its effect on mileage—is modest.

The aerodynamic drag acting on a vehicle increases in colder weather as well. Air density is 17 percent lower on a hot, 80-degree day than it is on a cold, zero-degree day. This percentage makes little difference in city driving, but on an open highway the colder temperature reduces mileage by about 7 percent, even taking into account the improvement in fuel efficiency that cars typically experience during highway driving.

Personal driving habits can also have a major effect on the efficiency slide. In winter, we use heater motors, defrosters and windshield wipers to keep our fingers warm and our sight line clear. We often bring the automobile interior to a comfortable temperature before driving and then keep our engines idling to maintain that temperature when we have to wait in the car.

In any season, you can improve your mileage with a few simple steps: Keep tire pressure at the recommended level (lower pressure reduces mileage). Avoid storing excessive weight in the car and driving in heavy stop-and-go traffic. Finally, courteous, careful motorists have lower gas-pump bills than those who employ frequent acceleration and braking.

Q Why does inhaling helium make one's voice sound strange?

—C. Graves, Renville, Minn.

Craig Montgomery, chair of the chemistry department at Trinity Western University in British Columbia, provides an answer:

The culprit is the difference between the density of the helium in one's larynx and that of the nitrogen and oxygen that make up most of the air a person normally breathes. Per given unit of volume, any type of gas contains the same number of particles. But because helium atoms have approximately one seventh the mass of nitrogen molecules, the density of helium is about one seventh that of air.

To explain how the voice change happens, we first have to discuss some basics about sound. Sound waves form when something, such as vocal cords or a drum skin, vibrates in a medium, such as air. As the skin of a drum moves upward, it compresses the gases above it. Each successive down-up motion of the skin creates additional compression, and this series of moving compressions constitutes sound waves. The frequency is the number of compressions created in a given period.

Like that of a drum, the vibration frequency of vocal cords is independent of the type of medium through which the waves pass. Because the pitch of a tone depends on the wave frequency, inhaling helium does not alter the pitch of the voice. Rather the density of the medium affects the velocity of the sound waves, as well as the timbre of the tone. (The timbre is what makes middle C on a piano sound different from middle C played on, say, a cello.) That's why, if you listen closely to a person who has just inhaled helium, you will notice that his or her voice is not squeaky but instead sounds more like Donald Duck's. SA

For a complete text of these and other answers from scientists in diverse fields, visit www.sciam.com/askexpert

SARA CHEN