SPECIAL ISSUE: UNDERSTANDING ORIGINS

SCIENTIFIC AMERICAN

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57 INNOVATIONS and Insights That Shape the World Today

ORIGINS OF

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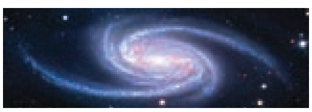

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MECHANICAL LOOM

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THE MIND

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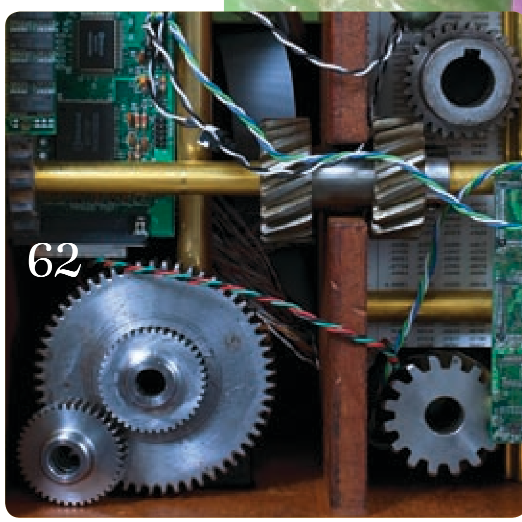
WHERE THERE IS WATER THERE IS LIFE. It is one of the fundamental principles of planet Earth. And to insure that it will always be so, we are constantly improving desalination technology and water purification solutions desperately needed by both developing and developed countries. All the while, the scientist and the chemist in us, ever mindful of the elements that hold the answer. Hydrogen. Oxygen. And Human.

ORIGINS

SPECIAL ISSUE



ON THE COVER

Life, the universe and … well … everything are the subjects of this special single-topic issue on origins. We trace their beginnings and key insights into the physical and life sciences and technology.

FROM TOP ON COVER: JEN CHRISTIANSEN; ROBERT GENDLER *Photo Researchers, Inc.*; CHRIS COLLINS *Corbis*; GETTY IMAGES

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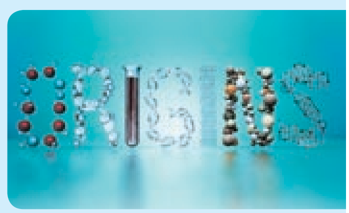
"Origins" Online

Want more information on origins? Go online for added stories, slide shows, details from the Origins Symposium this past spring, and other extras.



More at **www.ScientificAmerican.com/sep2009**

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great grandmother could be
the same as yours.

Starter Menu

The editors at *Scientific American* can always look forward to creating our annual single-topic issues. These special editions give us the opportunity to more fully explore an area that is of deep scientific and public interest and to share that comprehensive package with you.

About a year ago, when the editorial board first began discussing possibilities for the issue you now hold in your hands, we decided to harness our ambitions in a different way. Instead of narrowly focusing on one subject, we would think more expansively. We settled on an all-encompassing topic that would provide the intellectual charge we sought but also would be fun. We decided to probe some of the most profound questions that humans ask about our existence, such as, Where did everything we see in the universe today come from? How did life begin? What led to the remarkable sophistication of the human mind? We knew we would want to provide in-depth feature articles on key topics in technology and in the physical and life sciences. To round out the issue, we also wanted to take on a few dozen other intellectual puzzles—from the origins of the paper clip to the placenta to paper money—in shorter pieces.

We dedicated extra pages to this issue to encompass the span of our questions, but it still was difficult to winnow our wish lists to what could be accommodated in print. Naturally, more short stories and other items of interest are available at www.ScientificAmerican.com. For now, turn to page 35 for the start of "Origins"—we hope you will find it candy for the curious mind.

In an issue focused on beginnings, it also seems appropriate to inaugurate a set of improvements to *Scientific American*'s pages. We've tightened the design of the table of contents, to make it easier to find what you are looking for in each issue. We have organized the popular News Scan department by topic; the adjusted layouts are easier to navigate, and the stories will continue to provide the concise analyses of news that you have come to expect.

A new columnist's pointed commentary will also sharpen the offerings in the front of the magazine. Lawrence M. Krauss, an astrophysicist, social critic and best-selling author of *The Physics of Star Trek* and other books, brings a scientist's perspective and practice of rational analysis to matters of broad scientific and policy concern. Fittingly, his first installment examines the unrealized vision of C. P. Snow, who 50 years ago wrote his famous "Two Cultures" essay. Snow noted the distressing cultural divide between science and the arts and hoped for a future that would bridge the two. We share that hope.

Last, Anti Gravity moves to a featured position as the back page, where Steve Mirsky's wry prose adds an entertaining punctuation mark to each issue; flip the pages to find his look at Kindle's foibles.

As always, we welcome your feedback. ■

MARIETTE DICHRISTINA
acting editor in chief

ETHAN HILL (*DiChristina*); BRYAN CHRISTIE DESIGN (*illustration*)

Among Our Contributors

MARTIN CAMPBELL-KELLY
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MARC HAUSER
is a professor at Harvard University, where he studies the evolutionary and developmental foundations of the human mind. He is author of *Moral Minds* and other books.

ALONSO RICARDO
is a research associate at the Howard Hughes Medical Institute at Harvard University. He has a long-standing interest in the origin of life and studies self-replicating chemical systems.

JACK W. SZOSTAK
is professor of genetics at Harvard Medical School. His interest in the laboratory construction of biological structures dates back to work he described in the November 1987 *Scientific American.*

MICHAEL S. TURNER
pioneered the interdisciplinary union of particle physics, astrophysics and cosmology and led the National Academy study that laid out the vision for the new field earlier this decade.


how
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Global Famine ■ Big Government ■ Big Pharma

MAY 2009

"The only way to save the human race is to reduce our numbers."

—*"Mithremakor"* VIA WWW.SCIENTIFICAMERICAN.COM

■ Crash of Civilizations

The obvious driver of the huge issues raised by Lester Brown in "Could Food Shortages Bring Down Civilization?" is overpopulation. Most rational people will agree that this planet does have a limit to the population of humans it can support. Sooner or later we will reach that limit, and then the natural world will abruptly step in and make a major correction through famine, disease and resulting conflict.

"Top it off and let it idle"
via www.ScientificAmerican.com

As usual, the real problem reverts to money. Our current socioeconomic system is predicated on the idea of unlimited economic growth. That requires unlimited population growth. In the late 1970s and early 1980s we had achieved zero population growth. That was not good for business, and corporate America began using the media to steer our cultural consciousness back to large families, a trend that continues today. The only way to save the human race is to reduce our numbers, and the only way to do that is to restructure our entire socioeconomic system.

"Mithremakor"
via www.ScientificAmerican.com

Brown begins his rant by insisting that mankind faces imminent food shortages. But based on the actual statistics, this is complete balderdash. Over the past 50 years grain production worldwide has grown only faster than population. On a per capita basis, the United Nation reports, annual grain yields are up 40 percent during the past five decades. Moreover, millions of hectares of fallow alluvial (uncultivated and fertile) land exist globally that could be exploited for crop production, especially via the spread of drip irrigation.

U.S. crop yields average approximately 10 tons per hectare as a result largely of mechanization, fertilizers, pesticides, herbicides, genetically modified seeds, and in some instances irrigation. The comparable figure in all of Asia and Latin America is only about three tons per hectare, leaving massive potential for additional increases in global agricultural output.

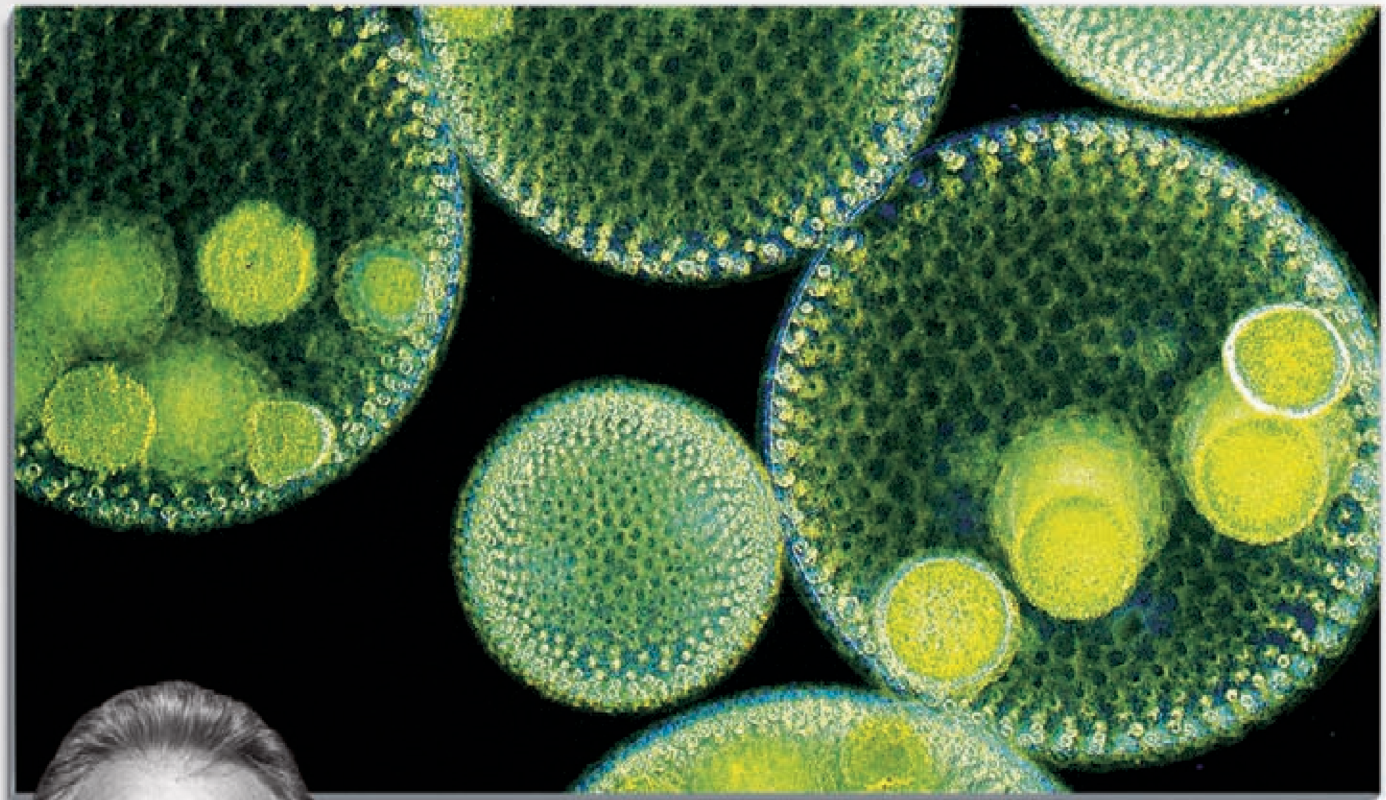
Emil Wagner
Malvern, Pa.

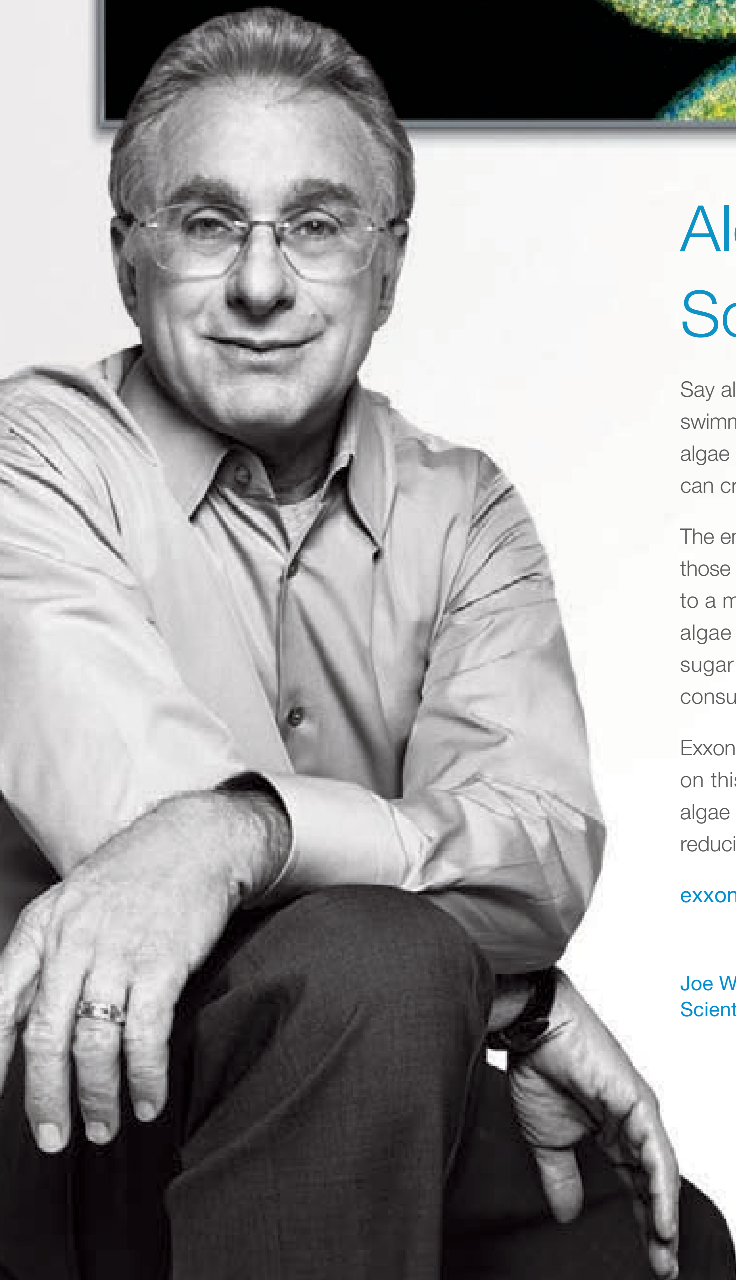
BROWN REPLIES: *It is true that grain production has expanded faster than population, from 249 kilograms per person in 1950 to 342 kilograms per person in 1984. But since then, it has fallen to an estimated 320 kilograms per person for this year.*

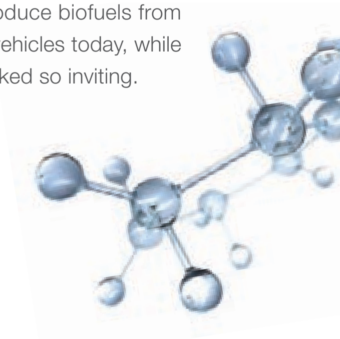
As to Wagner's data on yields, U.S. corn yields an average of 10 tons per hectare, but U.S. wheat yields are under three tons per hectare.

The bottom line is that the number of hungry and malnourished people in the world, which was declining historically, bottomed out around 2000 at just more than 800 million. That figure is now approaching one billion and is projected by the U.S. Department of Agriculture to hit 1.2 billion within the next decade.

As to the vast potential for expanding production, once grain yields have doubled or tripled, as they have already done in much of the developing world,







including China and India, it then becomes much more difficult to expand production. The billion people who are chronically hungry can only wish that the potential for expanding world food production is as vast and as simple as Wagner claims it to be.

CHILDREN clamor for food in the village of Dubie, Democratic Republic of the Congo. The photograph is from December 2005.

Deal or No Deal

In a phrase that has become fashionable in the past few months, as new government officials criticize the policies of their predecessors, Jeffrey D. Sachs's column rests on a "false choice."

The column accurately predicts that to pay for dramatically enhanced spending by the U.S. government under the spending goals laid out by the new administration, it will be necessary to ramp up the percentage of GDP that the government absorbs through taxes. He predicts that these taxes will come from increased taxes on "the rich"—presumably anyone who makes more than the particular speaker—plus regressive taxes such as a national sales tax or VAT.

Sachs observes that in recent decades, total U.S. federal, state and local taxes have consumed about 33 percent of gross domestic product as compared with average European tax burdens of about 45 percent of GDP. He concludes that we must match European tax levels to avoid funding the proposed budget deficits with crushing debt.

The "false choice" lies in assuming that we must (and should) choose between incurring unsustainable debt and massively increasing taxes to European levels. The alternative way, of course, is to moderate the growth of spending. This policy option escapes mention, but it should not. One consequence of the substantially higher tax burden that many European countries have imposed is that their economies have tended to be more sluggish and less dynamic than the U.S. economy and that they have paid the price in generally higher rates of unemployment and slower technological innovation.

Philip Allen Lacovara
Sanibel, Fla.

Pharma Liabilities

In "Legal Side Effects" [Updates], Kate Wilcox claimed that a recent U.S. Supreme Court decision left drug companies "wide open for lawsuits." The decision upheld laws that are much needed, especially in light of the long-standing practice of pharmaceutical companies to sponsor and pay for "research" of the drugs they manufacture in order to market the drugs' positive effects while concealing their dangerous side effects in patients. The court's decision upholds important constitutional rights afforded to all citizens and should be welcomed by a journal that promotes scientific study.

John Mininno
Mininno Law Office
Collingswood, N.J.

THE EDITORS REPLY: *Updates is part of the magazine's news coverage, not an editorial. Thus, Wilcox was not expressing her personal opinion nor that of* Scientific American.

Letters to the Editor

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Letters may be edited for length and clarity. We regret that we cannot answer each one. Post a comment on any article instantly at
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OYSTER PERPETUAL EXPLORER II

ROLEX

Radiation ▪ Punched Cards ▪ Earthworms

Compiled by Daniel C. Schlenoff

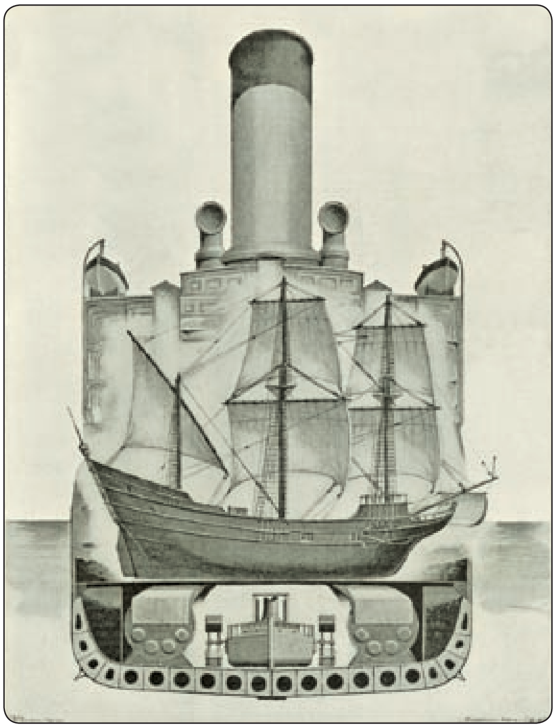
SEPTEMBER 1959

RADIATION— "What should the citizen conclude about ionizing radiation? Ionizing radiation has always been with us and will be for all foreseeable time. Our genetic system is probably well adjusted by natural selection to normal background radiation. Added radiation will increase the frequency of mutations; most of these will be harmful. Exposure to radiation in large amounts will increase malignant disease; small amounts may possibly do the same. In view of these potentially harmful effects every reasonable effort should be made to reduce the levels of ionizing radiation to which man is exposed to the lowest levels that can reasonably be attained. As to fallout from nuclear-weapons tests, the citizen will conclude that it contributes in a small way to worldwide levels of radiation. For this reason alone the tests should be discontinued. —George W. Beadle"

SEPTEMBER 1909

CENSUS— "The counting at the end of each decade of every man, woman, and child in the United States is one of the biggest undertakings the government is called upon to assume. To facilitate counting, machines will be used invented by Mr. James Powers, a mechanical expert of the Census Bureau, for use in the thirteenth census, which were successfully tried in the recent Cuban Census and now in use in the Division of Vital Statistics. The mechanical method for counting the census requires two types of machines. The keynote of the system, however, is a punched card, which contains the data collected by the enumerators, who travel from house to house in every nook and corner of the land. The data include the nature and extent of our industries, and the amount of our wealth."

HENRY HUDSON'S 300TH— "The ship 'Half Moon' set sail from Amsterdam April 4th, 1609, with a crew of eighteen Dutch and English sailors. On September 3rd, the 'Half Moon' let go her anchor inside of Sandy Hook (New Jersey). The week was spent exploring the bay with a small boat, and 'they found a good entrance between two headlands' (The Narrows) and thus entered on the 12th of September 'as fine a river as can be found.' When the replica of Henry Hudson's 'Half Moon' was lifted by the floating crane at the Brooklyn navy yard from the deck of the 'Soestdyk,' on which she was brought over from Holland, and lowered into the water, there was a general expression of surprise at her diminutive appearance; for she was no larger than a small harbor tug."



THREE CENTURIES OF SHIP DESIGN: Henry Hudson's *Half Moon* of 1609 shown in scale with a cross section of the RMS *Mauretania*, holder of the record for the fastest crossing of the Atlantic in 1909.

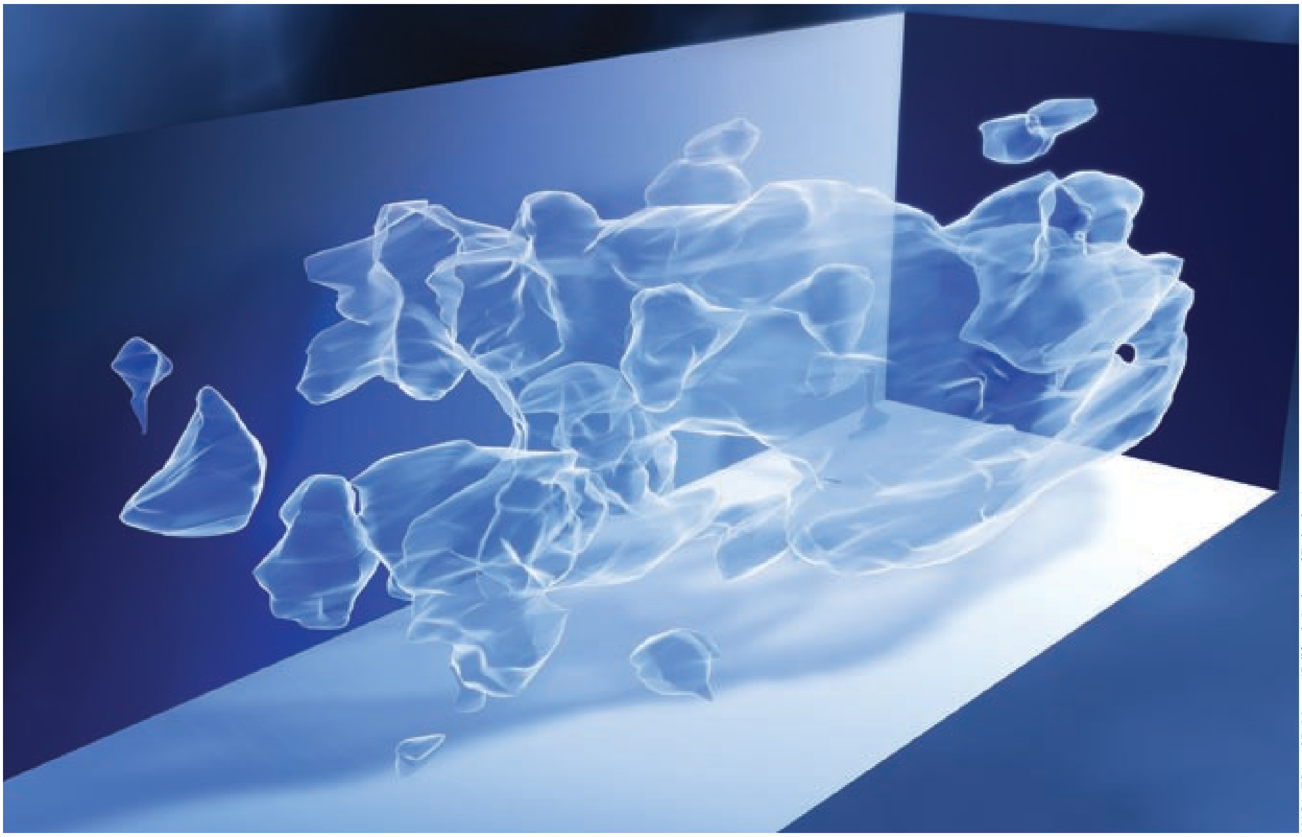
SEPTEMBER 1859

WORMS— "The common earthworm, though apt to be despised and trodden on, is really a useful creature. According to Mr. [Charles] Darwin, they give a kind of under tillage to the land, performing the same below ground that the spade does above for the garden, and the plow for arable soil. Fields which have been overspread with lime, burnt marl, or cinder, become, in time, covered by finely-divided soil. This result, usually attributed by farmers to the 'working down' of these materials, is really due to the action of earthworms. Mr. Darwin says, 'A field manured with marl has been covered, in the course of 80 years, with a bed of earth averaging 13 inches in thickness.'"

COTTON MARKET— "The 'crop year' for cotton has just closed, and it has been somewhat eventful. The previous year of the financial panic had passed with a very small consumption, leaving large stocks of goods in the hands of merchants and considerable supplies of raw materials with the manufacturers. Returning ease in the money market has been accompanied by abundant crops, cheap food, low rates for transportation, and a large consumption of goods, promising to absorb the whole of the crop. Up to January, purchases at home and abroad were very large, at improving prices."

EVIL BROADCLOTH— "Professor Hamilton says: 'Gentlemen have adopted as a national costume a thin, tight-fitting black suit of broadcloth. To foreigners, we seem always in mourning: we travel in black, we write in black, we work in black. Even the day-laborer chooses always the same unvarying, monotonous black broadcloth. It is too thin to be warm in the winter, and too black to be cool in the summer.'"

SCIENTIFIC AMERICAN, VOL. CI, NO. 13; SEPTEMBER 25, 1909



NASA, ESA and R. Massey (California Institute of Technology).

Medicine & Health

Tribulations of a Trial

Lessons learned by the scientist behind the first gene therapy death BY MELINDA WENNER

PHILADELPHIA—TEN YEARS AGO THIS MONTH THE PROMISE OF using normal genes to cure hereditary defects crashed and burned, as Jesse Gelsinger, an 18-year-old from Tucson, Ariz., succumbed to multiorgan failure during a gene therapy trial at the University of Pennsylvania. Today the boardroom of the Translational Research Lab at the university is filled with artifacts reminiscent of the trial. Books such as *Building Public Trust* and *Biosafety in the Laboratory* sit on the shelves, and "IL-6" and "TNF-α" are scribbled on the whiteboard—abbreviations representing some of the very immune factors that fatally spiraled out of control in Gelsinger's body.

These allusions to the past aren't surprising considering how drastically the clinical trial changed gene therapy and, in particular, the career of James M. Wilson, the medical geneticist who headed Penn's Institute for Human Gene Therapy, where the test took place. The U.S. Food and Drug Administration banned it from conducting human trials, and Wilson left his post at the now defunct institute (but he continued doing research at Penn). He disappeared from the public spotlight until 2005, when the agency announced he could begin clinical trials with a designated monitor but could not lead trials for five years and asked him to write an article about the lessons he has learned. He published it in *Molecular Genetics and Metabolism* this past April. Since then, he has begun giving university lectures about the importance of exercising caution as a clinical scientist, especially when it comes to stem cells, which today have the cachet once held by gene therapy.

Wilson talks about what happened in 1999 with a quiet deliberateness suggestive of a painful topic. "With what I know now, I wouldn't have proceeded with the study," he says in the boardroom, his back facing the whiteboard. In the 1990s scientists such as himself, he explains, were too caught up in the promise of gene therapy to realize that they did not know enough about it to warrant human testing. "We were drawn into the simplicity of the concept. You just put the gene in," Wilson says.

The trial he conducted tested the safety of a therapy for ornithine transcarbamylase (OTC) deficiency, a rare disorder in which the liver lacks a functional copy of the OTC gene. The defect prevents the body from eliminating ammonia, a toxic breakdown product of protein metabolism. The Penn scientists had engineered a weakened adenovirus, or cold virus, to deliver a normal copy of the OTC gene into the liver.

Seventeen patients had undergone treatment before Gelsinger, who was in the final cohort—the one receiving the highest dose of the therapy. Many scientists, as well as the FDA, have raised questions as to why Gelsinger was being treated, given that several patients in earlier cohorts suffered severe liver reactions. Wilson says that they moved forward because it was "the kind of toxicity we would have expected," based on their work in animals, and they thought it would be manageable. According to Mark Batshaw, director of the Children's Research Institute at the Children's National Medical Center in Washington, D.C., Wilson and the rest of the scientific community had to learn the hard way "that what you've learned from animals will not necessarily predict what's going to happen in humans." Batshaw was also involved in the 1999 trial.

SEVERE SETBACK: James M. Wilson ran the institute where a fatal gene therapy experiment occurred in 1999. He now offers advice to stem cell researchers so that they can avoid similar mistakes.

The FDA questioned the decision to treat Gelsinger for other reasons, too. Just before starting treatment, Gelsinger—who suffered from a mild form of the disease—had high levels of ammonia in his blood, indicating that his liver was not functioning well. But because his levels were within acceptable parameters when he had enrolled in the trial three months earlier, the scientists moved forward anyway. Wilson, who was responsible for the protocol and its compliance, admits now that "the protocol was not written in a way in which there was enough clarity to know when the ammonia had to be what [level], and that was a significant shortcoming."

Did Gelsinger's high ammonia levels play a role in his death? The question prompts a long pause from Wilson. "Well, I don't think so," he says softly.

NEWSCOM

"But things are rarely proven in biology." No one knows for sure just how the procedure, Gelsinger's liver function and his immune response are all connected, but Wilson now believes that the teen died from a rare phenomenon called antibody-dependent enhancement. He may have been exposed to a similar adenovirus in the past, which caused his body to create antibodies against it, Wilson explains. Normally antibodies control a virus when the body encounters it again. But occasionally they elicit a dangerous immune response. Wilson admits, however, that there is no way to prove it, because none of Gelsinger's pretreatment blood samples remain.

Wilson says that even if Gelsinger did die from a rare and unforeseeable complication, he is not trying to dodge responsibility. "The university here, the field and the families who were relying on us to succeed—I just feel as if I've disappointed all of them," he says. "Quite frankly I don't know how many different ways I can say it. [I feel] regret, remorse, awful. I'm sorry." The university settled a wrongful death lawsuit brought by the Gelsinger family for an undisclosed sum.

In his "lessons learned" article, Wilson advises researchers against putting themselves in situations that might create potential financial conflicts (in 1992 Wilson had founded a biotechnology company focused on gene therapy). He also argues that scientists who develop therapies should not be the ones testing them in humans. "You can't be the person who acts on behalf of the research subject," he says. Ultimately, Wilson argues, clinical scientists should always ask themselves this question: "If the worst-case scenario played itself out—not the potential or likely, but the worst—would that be acceptable?" If he had asked himself that question in 1999, Wilson says, he would not have proceeded.

It has been a difficult decade for gene therapy, but Wilson believes that its fall from favor was inevitable. Gelsinger's death "clearly was a precipitating event," he says, but "stars were lining up, and the field was just going to encounter a difficult time." Although some gene therapy trials have seen limited success, many have produced adverse reactions in volunteers.

Wilson hasn't given up on the field, though—he is trying to make it safer. Since 1999, with a grant from GlaxoSmithKline, his lab has identified 120 new adenovirus-associated viruses that can more easily sneak past the immune system and deliver gene therapies with lower risk, and he has distributed them to 700 investigators around the world for further study. He hopes, as do others, that there will be no more Jesse Gelsingers.

Melinda Wenner is based in New York City.

ANWAR AMRO *Getty Images*

THAT'S NOT ALL, FOLKS: Besides the flu, pigs on farms have been detected harboring a strain of Ebola virus that is harmless to humans—so far.

Swine Ebola

A new reservoir for the infamous Ebola virus BY BRENDAN BORRELL

DON'T WORRY, IT CAN'T HURT YOU—YET. Scientists have identified *Reston ebolavirus*—a member of the deadly Ebola group of hemorrhagic fever viruses—in domestic swine from the Philippines. Ebola is infamous for being highly contagious and causing death rates as high as 90 percent in some human outbreaks. This particular strain, first identified in monkeys in 1989 in a research laboratory in Reston, Va., is the only one of the family that is harmless to humans.

The outbreak in swine was discovered in July 2008 in the Philippines during an investigation of so-called blue ear disease in pigs, a respiratory condition that causes their ears to turn blue from lack of oxygen. Investigators there sent tissue and blood samples to Michael McIntosh of the U.S. Department of Agriculture at the Plum Island Animal Disease Center in Greenport, N.Y. McIntosh was surprised to find that the tissue samples also contained the *Reston* strain, which had not been previously identified in swine.

His team also confirmed pig-to-human Ebola transmission, identifying six pig handlers whose blood tested positive for antibodies to the virus. The individuals showed no symptoms, indicating that this strain is as harmless to humans now as it was in 1989. Authorities in Manila had announced preliminary findings in January, and McIntosh's details appear in the July 10 *Science*.

McIntosh says there are still a lot of unknowns, including how the virus was transmitted to the pigs and whether they show any symptoms independent of blue ear disease. He worries that the virus's passage through pigs could enable it to mutate into something more dangerous. The research also raises the possibility that pigs could become infected with lethal Ebola strains. "What is the level of risk? We really don't know," he says. "The fact that it shows up in domestic pigs raises that risk."

Technology

Radio for Responders

As multiband radio for public safety proceeds, digital spectrum for it still lags

BY LARRY GREENEMEIER

One lesson in the 9/11 attacks eight years ago was the importance of police officers, firefighters and other first responders being able to communicate with one another. Many died because they did not get the call to evacuate from the World Trade Center towers that were about to collapse. To tackle this problem, the U.S. Department of Homeland Security will begin a pilot program this month to test multiband radios designed to let responders communicate across a number of different radio frequencies. Meanwhile a long-touted nationwide public safety broadband network, made possible by the freeing of broadcast spectrum in the country's switch to digital television this past June, continues to stagnate.

The radios of public safety agencies currently operate on separate, discrete frequencies, making it impossible for a firefighter, for example, to communicate with a police officer. "There's no single band with enough room for all of the public responders," says David Boyd, director of command, control and interoperability in the Homeland Security's Science and Technology Directorate. As a result, public safety agencies have been forced to spread their signals throughout the four different frequency bands available to them—namely, at megahertz frequencies of 150, 400, 700 and 800.

Several manufacturers are developing multiband radios, but currently only a version made by Thales Communications in Clarksburg, Md., meets criteria set by Homeland Security—that is, the device is roughly the same size and weight as the radios that police and other responders carry today, and it costs no more than $5,000, similar to the high-end single-band radios now on the market, Boyd says. (They must also work with an auxiliary power pack that can be charged by a battery.)

This summer the security personnel of several organizations—including Amtrak along its Northeast Corridor, the Metro Area Transit Authority in Washington, D.C., the 2010 U.S. Olympic Security Planning Committee and 11 others—began using the Thales radio as part of Homeland Security's program. Each agency will evaluate the radio in the field through pilot tests lasting at least 30 days, with the government publishing the results early next year, Boyd says. This test is actually the last of a three-phase program to determine the radio's viability; it already passed a lab test and a nonemergency demonstration on May 2 at the Kentucky Derby.

CALLING ALL UNITS: **In the 9/11 attacks, emergency responders from different branches had trouble communicating with one another. New radios may soon solve that problem, although a dedicated data band created by the U.S. switch to digital TV remains in limbo.**

RON AGAM *Getty Images*

Although the radio voice-communication part of the public safety efforts is proceeding, first responders will not have an emergency broadband data network anytime soon. The 700-megahertz band (actually covering 698 to 806 megahertz), freed up from the switch to digital TV, has space designated by the Federal Communications Commission for data. Called the D block, it will be used for a national wireless public safety broadband network to enable local, state and federal emergency responders to send text messages and large amounts of data, such as digital images and streaming video. "Public safety doesn't currently have this broadband ability," Boyd remarks.

But the move to make use of the D block has hit some snags. Because establishing a nationwide network on it would be costly, the government wants a public-private partnership to develop the block. The proposed wireless broadband network would be built and used by both public-sector emergency responders and private-sector businesses, which would also be able to license part of the network for commercial purposes.

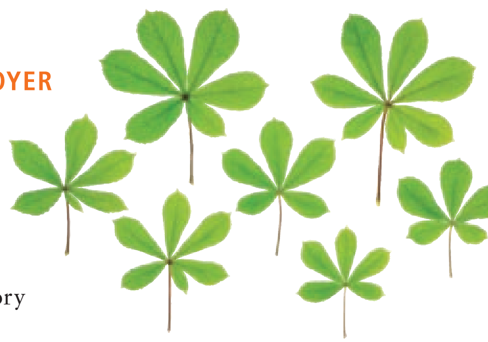
Although the FCC succeeded in selling the right to use the old television spectrum in an auction last year (it raked in $20 billion, twice as much as it expected), it ultimately refused to sell a D block license because it had not been offered enough money by any of D block's suitors, Boyd says. Harlin McEwen, chair of the Public Safety Spectrum Trust (PSST) Corporation—formed in 2007 by the FCC to work with industry to develop the national wireless public safety broadband network—gave a more pointed reason: the companies bidding for the space wanted priority access to the D block space over first responders, even in times of emergency.

Without a proper suitor and with a new FCC chair, Julius Genachowski, confirmed only in late June, McEwen says the FCC has delayed bidding for the D block indefinitely. He plans to meet with Genachowski to discuss the agency officials' options for the D block. "They can schedule another D block auction with the rule that the winner has to work with the PSST," McEwen says. "Or they can auction the block without restriction, which they are unlikely to do."

Although broadband data access is important during emergencies, some experts do not think that the delays in its implementation will seriously undermine public safety. Voice communication will continue to be the most important lifeline among responders, Boyd states, which is why the Homeland Security's upcoming multiband pilot program is so important. "Data are not going to replace voice as the fundamental emergency communication, because voice is interactive in a way that text will never be," he notes as an example. "In environments where you have to use your eyes and hands for other things, you have to be able to talk."

Chlorophyll Power

Quantum details of photosynthesis could yield better solar cells BY MICHAEL MOYER



MARTIN RUEGNER *Getty Images*

As nature's own solar cells, plants convert sunlight into energy via photosynthesis. New details are emerging about how the process is able to exploit the strange behavior of quantum systems, which could lead to entirely novel approaches to capturing usable light from the sun.

All photosynthetic organisms use protein-based "antennas" in their cells to capture incoming light, convert it to energy and direct that energy to reaction centers—critical trigger molecules that release electrons and get the chemical conversion rolling. These antennas must strike a difficult balance: they must be broad enough to absorb as much sunlight as possible yet not grow so large that they impair their own ability to shuttle the energy on to the reaction centers.

This is where quantum mechanics becomes useful. Quantum systems can exist in a superposition, or mixture, of many different states at once. What's more, these states can interfere with one another—adding constructively at some points, subtracting at others. If the energy going into the antennas could be broken into an elaborate superposition and made to interfere constructively with itself, it could be transported to the reaction center with nearly 100 percent efficiency.

A new study by Mohan Sarovar, a chemist at the University of California, Berkeley, shows that some antennas—namely, those found on a certain type of green photosynthetic bacteria—do just that. Moreover, nearby antennas split incoming energy between them, which leads not just to mixed states but to states that are entangled over a broad (in quantum terms) distance. Gregory

Scholes, a chemist at the University of Toronto, shows in a soon to be published study that a species of marine algae utilizes a similar trick. Interestingly, the fuzzy quantum states in these systems are relatively long-lived, even though they exist at room temperature and in complicated biological systems. In quantum experiments in the physics lab, the slightest intrusion will destroy a quantum superposition (or state).

These studies mark the first evidence of biological organisms that exploit strange quantum behaviors. A better understanding of this intersection of microbiology and quantum information, researchers say, could lead to "bioquantum" solar cells that are more efficient than today's photovoltaics.

Energy & Environment

Conflicted Conservation

Saving the earth might mean trampling indigenous rights BY MADHUSREE MUKERJEE

EVEN AS INDUSTRIAL CIVILIZATION REACHES INTO THE FARTHEST corners of the globe to extract resources such as oil, timber and fish, environmentalists are striving to mitigate its deleterious effects on the biosphere. Projects to reduce pollution, prevent climate change and protect biodiversity, however, are drawing criticism that they could drive indigenous people off their lands and destroy their livelihoods.

Conservationists have historically been at odds with the people who inhabit wildernesses. During the last half of the 20th century, millions of indigenous people in Africa, South America and Asia were ousted from their homelands to establish nature sanctuaries free of humans. Most succumbed to malnutrition, disease and exploitation, recounts anthropologist Michael Cernea of George Washington University. Such outcomes—coupled with the realization that indigenous groups usually help to stabilize ecosystems by, for instance, keeping fire or invasive weeds at bay—have convinced major conservation groups to take local human concerns into account. The World Wildlife Fund (WWF) now describes indigenous peoples as "natural allies," and the Nature Conservancy pledges to seek their "free, informed and prior" consent to projects impacting their territories.

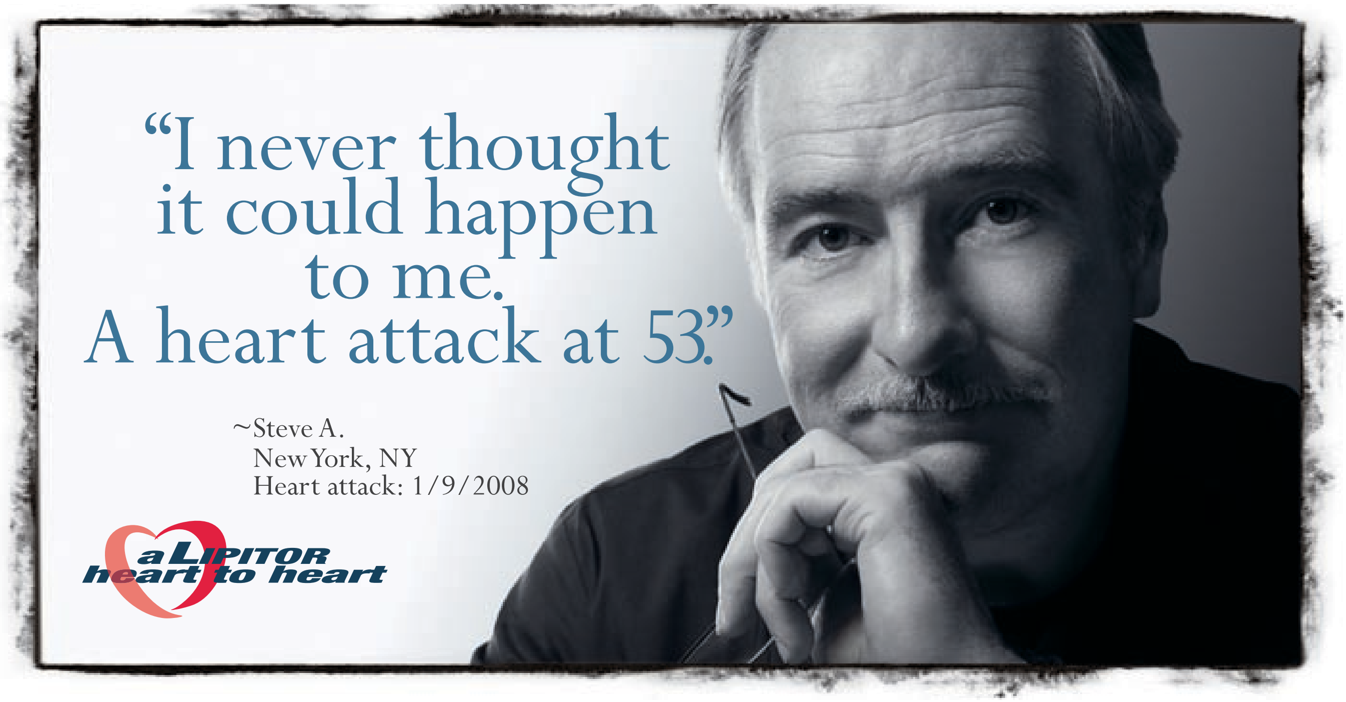
THREATENED TRIBESMAN: **The Melayu of Indonesia may lose fishing and hunting grounds to a forest-saving carbon plan.**

Recent incidents, however, have made some observers wonder. "They're talking the talk, but are they walking the walk?" asks Jim Wickens of the advocacy group Forest Peoples Program, based in Moreton-in-Marsh, England. Wickens cites a "huge cry of concern" by 71 grassroots groups protesting a WWF effort to set up a certification scheme for shrimp aquaculture. Shrimp farms have often been established along tropical coastlines by cutting down mangroves, and their effluents have damaged neighboring fisheries and farmlands. The Mangrove Action Project, an advocacy group based in Port Angeles, Wash., considers intensive shrimp aquaculture impossible to make sustainable.

The WWF counters that less than one third of shrimp manufacturers worldwide are currently achieving the standards that it hopes to set. As such, certification should "certainly make shrimp farming cleaner," says Jason Clay, WWF's vice president of markets. Geographer Peter Vandergeest of York University in Toronto worries, however, that the endeavor will falter unless the communities that are affected by shrimp farms have a say in setting standards and enforcement. Given the remoteness of many shrimp farms, he explains, auditors' checks will be rare, and "you can easily put on a show."

Perhaps more worrisome to advocates for indigenous peoples, however, are so-called carbon-offset schemes that seek to protect standing forests. Several of the large environmental organizations hold that the carbon saved by preventing deforestation could be sold as offsets, thereby generating funds for conservation and communities. A scheme referred to as REDD (reducing emissions from deforestation and degradation) may be introduced this December into the United Nations Climate Change Convention, and it could be partly financed by offsets. The Nature Conservancy hopes that three billion tons of such credits, valued at $45 billion, can be generated by 2020.

But Marcus Colchester of Forest Peoples Program comments: "We see a risk that the prospect of getting a lot of money for biodiversity could lead to indigenous peoples' concerns falling by the wayside." In particular, increasing the financial value of forests could lead to "the biggest land grab of all time," claims Tom B. K. Goldtooth of the Indigenous Environmental Network, based in Bemidji, Minn. Interpol has warned that unscrupulous



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*Patient's risk factors include age, gender, smoking, and high blood pressure.

IMPORTANT INFORMATION: LIPITOR is a prescription drug. It is used in patients with multiple risk factors for heart disease such as family history, high blood pressure, age, low HDL ('good' cholesterol) or smoking to reduce the risk of heart attack, stroke and certain kinds of heart surgeries. When diet and exercise alone are not enough, LIPITOR is used along with a low-fat diet and exercise to lower cholesterol.

LIPITOR is not for everyone. It is not for those with liver problems. And it is not for women who are nursing, pregnant or may become pregnant. If you take LIPITOR, tell your doctor if you feel any new muscle pain or weakness. This could be a sign of rare but serious muscle side effects. Tell your doctor about all medications you take. This may help avoid serious drug interactions. Your doctor should do blood tests to check your liver function before and during treatment and may adjust your dose. The most common side effects are gas, constipation, stomach pain and heartburn. They tend to be mild and often go away.

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IMPORTANT FACTS

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WHO IS LIPITOR FOR?

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- People with liver problems
- People allergic to anything in LIPITOR

BEFORE YOU START LIPITOR

Tell your doctor:

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- If you have diabetes or kidney problems
- If you have a thyroid problem

ABOUT LIPITOR

LIPITOR is a prescription medicine. Along with diet and exercise, it lowers "bad" cholesterol in your blood. It can also raise "good" cholesterol (HDL-C).

LIPITOR can lower the risk of heart attack or stroke in patients who have risk factors for heart disease such as:

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POSSIBLE SIDE EFFECTS OF LIPITOR

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Symptoms of muscle or liver problems include:

- Unexplained muscle weakness or pain, especially if you have a fever or feel very tired
- Nausea, vomiting, or stomach pain
- Brown or dark-colored urine
- Feeling more tired than usual
- Your skin and the whites of your eyes turn yellow

If you have these symptoms, call your doctor right away.

The most common side effects of LIPITOR are:

- Headache
- Diarrhea, gas
- Rash
- Constipation
- Upset stomach and stomach pain
- Muscle and joint pain

Side effects are usually mild and may go away by themselves. Fewer than 3 people out of 100 stopped taking LIPITOR because of side effects.

HOW TO TAKE LIPITOR

Do:

- Take LIPITOR as prescribed by your doctor.
- Try to eat heart-healthy foods while you take LIPITOR.
- Take LIPITOR at any time of day, with or without food.
- If you miss a dose, take it as soon as you remember. But if it has been more than 12 hours since your missed dose, wait. Take the next dose at your regular time.

Don't:

- Do not change or stop your dose before talking to your doctor.
- Do not start new medicines before talking to your doctor.
- Do not give your LIPITOR to other people. It may harm them even if your problems are the same.
- Do not break the tablet.

NEED MORE INFORMATION?

- Ask your doctor or health care provider.
- Talk to your pharmacist.
- Go to **www.lipitor.com** or call **1-888-LIPITOR**.

Manufactured by Pfizer Ireland Pharmaceuticals, Dublin, Ireland

Printed in the USA.

Distributed by Parke-Davis, Division of Pfizer Inc.
New York, NY 10017 USA
LPIF Rev 2, Dec 2005

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entities plan to profit from REDD: their methods could include expelling an indigenous people from their forest to acquire legal title over it. The Nature Conservancy, which supports indigenous peoples' efforts to acquire legal rights to their territories, counters that "increasing the value of forests through REDD can only provide them benefits."

Concerns of displacement are particularly acute in Indonesia, where villagers opposing logging operations and paper, pulp and palm oil plantations on their territories have experienced violent attacks. Some 20 carbon forestry projects are already in the works there. Colchester warns that the government's regulations on REDD do not adequately protect indigenous peoples. In the Kampar Peninsula, for instance, a forestry company proposes to clear-cut a ring of swamp forest and plant it with acacia—so as to protect the forest in the core area and thereby earn REDD credits. The project would limit the access of the Melayu people to their traditional fishing creeks and hunting grounds; they have protested by preventing company staff from entering the area.

Similar fears of dispossession color attempts to protect coral reefs. In May six nations in Southeast Asia, with technical support from the Nature Conservancy, WWF and Conservation International, committed to the Coral Triangle Initiative, which will protect 75,000 square kilometers of coastline, coral reefs and ocean. M. Riza Damanik of KIARA, the Fisheries Justice Coalition of Indonesia, worries that the richest fishing grounds will be zoned off as protected areas.

Environmental psychologist Lea Scherl of James Cook University in Australia, who has studied the region's marine protected areas, believes that such concerns are justified. In the largest conservation organizations, she explains, scientists design projects on the macro level—as if the map contained only natural features—and factor in culture afterward. "The people rarely have a meaningful voice at the very outset," she says. Furthermore, efforts to mitigate a project's impacts on local communities are underfunded and often unsystematic, compared with the scientific aspects.

In the end, it is those who have intimate details of the land and the seas, accumulated over generations, who hold key insights to conservation. As Scherl puts it: "You lose that knowledge when you take the people away."

Madhusree Mukerjee is a science writer based near Frankfurt.

The Not So Green Skies

New calls for the U.S. airline industry to take recycling seriously

BY DAVID FARLEY

Even the infrequent flier might have noticed that when the flight attendant comes around collecting passenger detritus, all the empty cans, cups, bottles, newspapers and napkins usually end up in the same garbage bag. The U.S. airline industry discards enough aluminum cans every year to build nearly 58 Boeing 747s and enough paper to fill a football field–size hole 230 feet deep—that's 4,250 tons of aluminum and 72,250 tons of paper. The 30 largest airports in the country, with the help of the airlines, create enough waste to equal the trash produced by cities the size of Miami or Minneapolis.

Unlike other aspects of the travel business, the airline industry has moved at a snail's pace to get onboard the green revolution. Although hotels, for instance, have plenty of monetary reasons to encourage patrons not to have their towels changed every day, the airline industry has little economic incentive and even less government pressure to go green.

Several factors have discouraged airlines and airports from following the nation's recycling trends, says Allen Hershkowitz, a senior scientist at the Natural Resources

Defense Council (NRDC). In December 2006 he published a report quantifying the waste from the industry and lambasting it for its lack of initiative toward recycling.

One of the problems is that airports have been reluctant to change their infrastructure to accommodate recyclable materials. Some airlines even separate the recyclables from the trash onboard the airplane, but if the airport is not equipped for recycling, it all goes into the same place. “Airports have been designed without recycling in mind,” Hershkowitz explains. “There are, for example, waste chutes that are all too convenient to dump trash. But there’s no chute for recycling.”

Some airports, however, have made great strides—recycling bins have popped up in terminals in recent years. And some facilities have taken recycling more seriously than others—Fort Lauderdale/Hollywood International, Seattle-Tacoma International and Portland International are a few examples. None, however, yet comes close to the national recycling rate of 31 percent of waste.

TOSSED AWAY: The airline industry in the U.S. trashes enough aluminum cans every year to build nearly five dozen jumbo jets.

JOHN WOOD *Getty Images*

The lack of a recycling infrastructure at airports has meant that an airline that wants to recycle must take on the expense itself—a difficult choice given the financial straits in which most airlines find themselves today. But part of the problem, as Hershkowitz claims, is that some do not realize the payback. “It costs more money to dump in a landfill than it does to put recyclables on the commodities market and get some money back,” he says. Hershkowitz’s study found that the four airports he observed that had aggressive recycling programs saved at least $100,000 a year. (Seattle-Tacoma led the way with $180,000.)

An approach called commingled recycling may be the easiest way to reduce costs and get more airlines to recycle. In this method, trash and reusable materials do not have to be separated onboard—a machine separates the trash from the reusable material and then separates the different types of recyclables. More waste management firms are offering the service to airlines. As a result, Delta Airlines, which recycled onboard trash in only five cities in 2007, recycled it in 23 cities in 2008. Southwest Airlines and JetBlue are in the process of expanding their commingled recycling efforts, too. Southwest would not say how much money it makes from recycling, but a representative for the airline says the goal is to pay for its waste management through recycling rebates and reduction.

Despite such recent efforts, Hershkowitz doesn’t think the recent efforts go far enough, and he hopes that the Obama administration will install some regulations forcing airlines and airports to take recycling more seriously. “The voluntary system hasn’t worked,” he insists. In January, Hershkowitz met with the Government Accountability Office over the problem and recommended that a law be created requiring that all airports receiving federal funds must begin separating recyclables from trash. If the GAO follows through, it will issue a report this fall recommending the regulation of airport recycling.

David Farley, based in New York City, writes frequently about travel issues.

Research & Discovery

Animals by the Numbers

Counting may be an innate ability among many species

BY MICHAEL TENNESEN

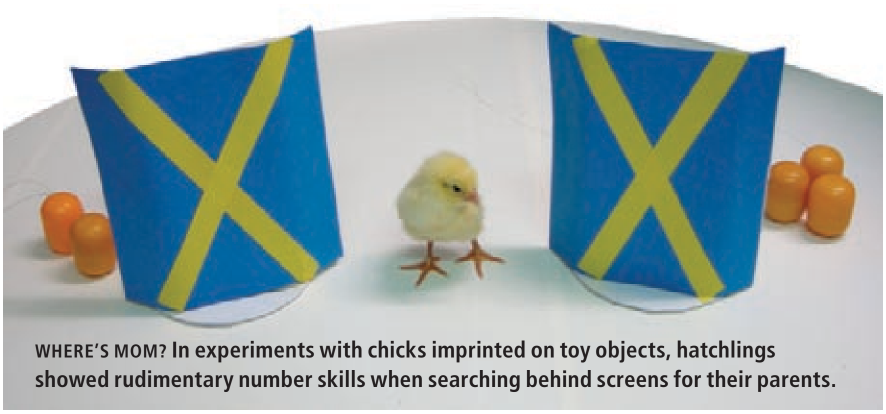
Scientists have been skeptical of claims of mathematical abilities in animals ever since the case of Clever Hans about 100 years ago. The horse, which performed arithmetic and other intellectual tasks to delighted European audiences, was in reality simply taking subconscious cues from his trainer. Modern examples, such as Alex the African grey parrot, which could count up to six and knew sums and differences, are seen by some as special cases or the product of conditioning.

Recent studies, however, have uncovered new instances of a counting skill in different species, suggesting that mathematical abilities could be more fundamental in biology than previously thought. Under certain conditions, monkeys could sometimes outperform college students.

In a study published last summer in the *Proceedings of the Royal Society B,* Kevin C. Burns of Victoria University of Wellington in New Zealand and his colleagues burrowed holes in fallen logs and stored varying numbers of mealworms (beetle larvae) in these holes in full view of wild New Zealand robins at the Karori Wildlife Sanctuary. Not only did the robins flock first to the holes with the most mealworms, but if Burns tricked them, removing some of the insects when they weren't looking, the robins spent twice as long scouring the hole for the missing mealworms. "They probably have some innate ability to discern between small numbers" as three and four, Burns thinks, but they also "use their number sense on a daily basis, and so through trial and error, they can train themselves to identify numbers up to 12."

More recently, in the April issue of the same Royal Society journal, Rosa Rugani of the University of Trento in Italy and her team demonstrated arithmetic in newly hatched chickens. The scientists reared the chicks with five identical objects, and the newborns imprinted on these objects, considering them their parents. But when the scientists subtracted two or three of the original objects and left the remainders behind screens, the chicks went looking for the larger number of objects, sensing that Mom was more like a three and not a two. Rugani also varied the size of the objects to rule out the possibility the chicks were identifying groups based simply on the fact that larger numbers of items take up more space than smaller numbers.

For the past five years Jessica Cantlon of the University of Rochester has been conducting a series of experiments with rhesus monkeys that shows how their numerical skills can rival those of humans. The monkeys, she found, could choose the lesser of two sets of objects when they



WHERE'S MOM? **In experiments with chicks imprinted on toy objects, hatchlings showed rudimentary number skills when searching behind screens for their parents.**

COURTESY OF ROSA RUGANI

were the same in size, shape and color. And when size, shape and color were varied, the monkeys showed no change in accuracy or reaction time. One animal, rewarded with Kool-Aid, was 10 to 20 percent less accurate than college students but beat them in reaction time. "The monkey didn't mind missing every once in a while," Cantlon recounts. "It wants to get past the mistake and on to the next problem where it can get more Kool-Aid, whereas college students can't shake their worry over guessing wrong."

Elizabeth Brannon of Duke University has conducted similar experiments with rhesus monkeys, getting them to match the number of sounds they hear to the number of shapes they see, proving they can do math across different senses. She also tested the monkeys' ability to do subtraction by covering a number of objects and then removing some of them. In all cases, the monkeys picked the correct remainder at a rate greater than chance. And although they might not grasp the deeper concept of zero as a number, the monkeys knew it was less than two or one, conclude Brannon and her colleagues in the May *Journal of Experimental Psychology: General.*

Although Brannon feels that animals do not have a linguistic sense of numbers—they aren't counting "one, two, three" in their heads—they can do a rough sort of math by summing sets of objects without actually using numbers, and she believes that ability is innate. Brannon thinks that it might have evolved from the need for territorial animals "to access the different sizes of competing groups and for foraging animals to determine whether it is good to stay in one area given the amount of food retrieved versus the amount of time invested."

Irene Pepperberg of the Massachusetts Institute of Technology, famous for her 30-year work with Alex the parrot, says that even bees can learn to discriminate among small quantities. "So some degree of 'number sense' seems to be able to be learned even in invertebrates, and such learning is unlikely without some underlying neural architecture on which it is based," she remarks.

Understanding the biological basis of number sense in animals could have relevance to people. According to Brannon, it may suggest to childhood educators that math, usually taught after age four or five, could actually be introduced earlier into the curriculum.

Michael Tennesen is a science writer based near Los Angeles.

Surviving in the Suburbs

A fossil search for why some critters made it past the dinosaur-killing event

BY CHARLES Q. CHOI

OUTSIDE FREEHOLD, N.J.—THE WATER IS icy cold and the stone is slippery as I wade in up to my calves. Along the banks of this slow-flowing stream, guarded by prickly brambles, lies one of the richest caches of fossils dating back to the extinction that claimed the dinosaurs. The remains of marine creatures buried here, kept secret to prevent looting, tell an unusual tale: rather than dying off 65 million years ago, these creatures lived on afterward, albeit briefly. The discovery is causing scientists to rethink why some creatures survived the so-called KT extinction while others did not.

Unlike this one, significant fossil sites tend to be found in exotic locales such as the searing hot Gobi Desert or the windswept pampas of Patagonia, areas remote from the kind of urban development that can ruin them. "You don't expect to find them here in suburban New Jersey some 90 minutes away from New York City," explains Neil Landman, curator of fossil invertebrates at the American Museum of Natural History.

The fossils here are not of dinosaurs, but ammonites. These cousins of squid and octopus were the iconic marine animals of the

OFF THE TURNPIKE: Ammonite trove exists in Agony Creek, in suburban New Jersey.

COURTESY OF CHARLES Q. CHOI

age of dinosaurs, flourishing worldwide for 300 million years or more before the KT extinction wiped them out. They bore shells that often resembled those of nautiluses, which rapidly evolved into hundreds of different shapes, ornamented with undulations and bumps.

Amateur paleontologist Ralph Johnson, a New Jersey park ranger, discovered ammonites in this stream in 2003 when construction workers exposed them while setting up bridge foundations. The site is now kept quiet from all but scientists—poachers have already trawled nearby areas, on the prowl for fossil shark teeth. Although this shallow, inconspicuous creek has no formal name on maps, after enduring many thorns on the way there, Landman and his team dubbed it Agony Creek.

At the time of the KT extinction, the water level at this site was some 30 meters higher than it is now. Landman investigates the iron-rich glauconite rocks here with his colleagues and students from the museum's graduate school, using iron spikes and sledgehammers to knock off slabs that are picked apart with screwdrivers and fingers. They find the fossil bed rich with dozens of species of marine invertebrates, such as crabs, snails, clams, sea urchins, large flat oysters and ammonites, as well as fish teeth and scales.

Past digs unearthed ammonite shells up to some 35 centimeters wide. These lay amid pinna, triangular bivalves that all died here relatively undisturbed: they jut upward as they would have been posed in life. Their position suggests they were all snuffed out rapidly, "perhaps by a Pompeii-like disaster, like a pulse of mud," Landman says. To see if these deaths were linked with the KT extinction, the researchers tested for iridium, the rare metal found throughout the world near the KT boundary, thought by most to be evidence of a cosmic impact.

Unexpectedly, the researchers discovered that the iridium was laid down before the pinna layer, which means that the ammonites and other creatures there died after the event "by 10 to maybe 100 years," Landman concludes. Their survival runs "counter to everything we've been taught," he adds. He plans to go to a site in Denmark to retrieve more potential evidence of ammonite survival past KT.

Their existence in the post-KT world raises a host of questions. "If they made it through this event like they did through other mass extinctions, why didn't they take off again?" asks invertebrate paleontologist Peter Harries of the University of South Florida. "Why did the ancestors of the modern nautiluses make it through and not the ammonites? That's extremely intriguing to me, and the broader message to me is that mass-extinction events are much more complex than we think."

The trove's proximity to cities is a bit of a double-edged sword. "In Mongolia, you don't really have the danger that a good site today might be paved over by asphalt tomorrow, and you can't walk into people's backyards," Landman remarks. "But who knows if we could have found this site otherwise without urban development."

Charles Q. Choi is a frequent contributor based in New York City.

Fossils for All

Paleontologists are overly possessive of human fossils. Science—and the public—suffers as a result

BY THE EDITORS

In June the famed Lucy fossil arrived in New York City. The 3.2-million-year-old partial skeleton of *Australopithecus afarensis* could attract hundreds of thousands of visitors over the course of her four-month engagement—part of a six-year tour that began in 2007.

Before this tour, Lucy had never been on public display outside of Ethiopia. One might expect scholars of human evolution to be delighted by the opportunity to share the discipline's crown jewel with so many members of the science-interested public. But news reports announcing her New York debut included the same objections that aired when she first landed in the U.S.: namely, that the bones could sustain damage and that the tour takes a key specimen out of scientific circulation for too long. Indeed, some major museums turned the exhibit away in part for those reasons.

The objections reflect a larger problem of possessiveness in the field of human origins, which seems appropriate to mention in this single-topic issue. Indeed, fossil hunters often block other scientists from studying their treasures, fearing assessments that could scoop or disagree with their own. In so doing, they are taking the science out of paleoanthropology.

Critics of such secrecy commonly point to the case of *Ardipithecus ramidus,* a 4.4-million-year-old human ancestor discovered by Tim White of the University of California, Berkeley. Fifteen years after White announced the first fossils of *A. ramidus* and touted the importance of this species for understanding human origins, access to the specimens remains highly restricted, prompting outsiders to term the endeavor paleoanthropology's Manhattan Project.

White, for his part, has said that he published only an initial report and that normal practice is to limit access until publication of a full assessment. And he has noted that the condition of a key specimen—a badly crushed skeleton—has slowed the release of the team's detailed report.

The scientists who expend the blood, sweat and tears to unearth the remnants of humanity's past deserve first crack at describing and analyzing them. But there should be clear limits on this period of exclusivity. Otherwise, the self-correcting aspect of science is impeded: outside researchers can neither reproduce the discovery team's findings nor test new hypotheses.

In 2005 the National Science Foundation took steps toward setting limits, requiring grant applicants to include a plan for making specimens and data collected using NSF money available to other researchers within a specified time frame. But paleoanthropologists assert that nothing has really changed. And according to Leslie Aiello of the Wenner-Gren Foundation, a major source of private funding for anthropological research, both public and private funding agencies typically lack the resources to enforce access policies, if they have them at all.

Ultimately, the adoption of open-access practices will depend in large part on paleoanthropologists themselves and the institutions that store human fossils—most of which originate outside the U.S.—doing the right thing. But the NSF, which currently considers failure to make data accessible just one factor in deciding whether to fund a researcher again, should take a firmer stance on the issue and reject without exception those repeat applicants who do not follow the access rules. The agency could also create a centralized database to which researchers could contribute measurements, observations, high-resolution photographs and CT scans—a GenBank for paleoanthropology. And journals could require that authors submit their data prior to publication, as they do with authors of papers containing new genetic sequences.

As for the public display of these fragments of our shared heritage, surely taxpayers, who finance much of this research, deserve an occasional glimpse of them. Irreplaceable objects are routinely transported and displayed. And in countries such as the U.S., where a staggering proportion of the population does not believe in evolution, scientists should embrace the opportunity to share with laypeople the hard evidence for humankind's ancient roots. The future of science education may depend on it. ■

ILLUSTRATION BY MATT COLLINS

Prioritize the Carbon Strategy

The Obama administration needs an energy strategy alongside the ambitious climate bill

BY JEFFREY D. SACHS

The U.S. House of Representatives passed the American Clean Energy and Security Act in June and sent it to the Senate. The House bill, running to 1,428 pages, aspires in one breathtaking stroke to take on renewable energy, carbon capture and sequestration (CCS), nuclear power, electric vehicles, carbon cap and trade, power transmission, energy efficiency and climate adaptation. It ranges from grand vision to minutiae.

Yet missing from this sprawling draft is prioritization. To accomplish a worldwide, fundamental energy overhaul, we will need to keep our eye on the big picture—the technology systems that will make a large, lasting difference—and not get mired in excruciating details.

Of the dozens of actions discussed in the bill, only half a dozen or so are likely to make a consequential difference. Putting a price on carbon is the single most important policy, because that will indeed send a signal through the economy to shift to low-carbon technologies. Alas, a straightforward tax on carbon would be far superior to the cumbersome cap-and-trade system proposed in the House bill. Politicians hate the word "tax" and like to distribute free emissions permits to powerful interest groups. The result is an overly complicated and somewhat arbitrary system but is still much better than nothing. At least carbon emissions would finally bear a market price under the legislation, and the Senate still has time for major improvements.

Ramping up nuclear power is probably the second most important measure, because it is currently the most scalable, cost-competitive source of noncarbon electricity. The legislation is decidedly ambivalent about nuclear power, reflecting the continuing divisions within the environmental community between advocates and staunch foes. Whether or not we choose to expand nuclear power, China and many other countries certainly will. The U.S. should as well; it is necessary for a cost-effective reduction of greenhouse gas emissions.

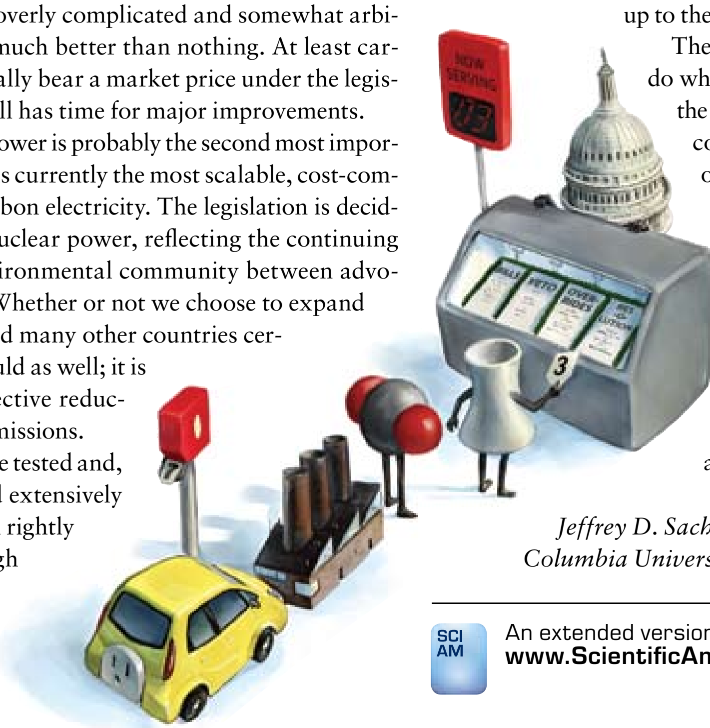
Third, CCS needs to be tested and, if successful, rapidly and extensively deployed. The legislation rightly champions CCS, although many environmentalists continue to oppose coal unconditionally. Yet as with nuclear, even if environmentalists turn up their noses at coal, China, India and other countries will keep on using it heavily. So, too, will the U.S. The key is to ensure that future coal plants are using CCS.

Fourth, we need to develop our tremendous solar potential. Investments in large-scale solar power are very likely to pay off monumentally within years or decades, but an integrated strategy of R&D, feed-in tariffs and other forms of support to bring that great potential to fruition will be essential.

Fifth, the U.S. must speed and complete the changeover of its vehicle fleet to a new generation of electric ones, including plug-in hybrids, battery-operated vehicles and fuel-cell automobiles. Either America will learn to produce such cars competitively, or it will end up importing them from China, Europe and Japan.

Sixth, we need to exploit the vast, unfulfilled opportunities for fuel efficiency in electric motors, lightbulbs, appliances, and home heating and cooling. Energy-efficiency programs in California and Japan during the past 20 years have shown the remarkable gains that can be achieved, often at large savings to consumers.

The bill covers all these topics, along with countless sideshows and boondoggles. There is continuing support for a corn-based biofuel policy, which wastes food supplies and taxpayer dollars without doing much to reduce carbon emissions (chalk this policy up to the political weight of the Iowa caucus).



The White House has so far let Congress do what it does best: to put everything into the stew, with every interest group stroked, compensated or subsidized, but without prioritizing the key steps that will determine success or failure in overhauling the energy system. The administration has shown again its deft political touch in nudging the draft legislation through the House and on to the Senate. Now the challenge cries out for a similarly deft touch in policy design and management. ■

Jeffrey D. Sachs is director of the Earth Institute at Columbia University (www.earth.columbia.edu).

SCI AM An extended version of this essay is available at **www.ScientificAmerican.com/sep2009**

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Every year, maternal and neonatal tetanus (MNT) claims the lives of almost 128,000 infants and 30,000 mothers.[1] MNT has been eliminated in most of the developed world – but it remains a deadly public health threat in 46 developing countries.

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[1] WHO/UNICEF, 2004 data
[2] *FORTUNE*, March 2009
[3] *Ethisphere® Magazine*, April 2009

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Paranoia Strikes Deep

Why people believe in conspiracies

BY MICHAEL SHERMER

After a public lecture in 2005, I was buttonholed by a documentary filmmaker with Michael Moore-ish ambitions of exposing the conspiracy behind 9/11. "You mean the conspiracy by Osama bin Laden and al Qaeda to attack the United States?" I asked rhetorically, knowing what was to come.

"That's what they want you to believe," he said. "Who is *they?*" I queried. "The government," he whispered, as if "they" might be listening at that very moment. "But didn't Osama and some members of al Qaeda not only say they did it," I reminded him, "they gloated about what a glorious triumph it was?"

"Oh, you're talking about that video of Osama," he rejoined knowingly. "That was faked by the CIA and leaked to the American press to mislead us. There has been a disinformation campaign going on ever since 9/11."

Conspiracies do happen, of course. Abraham Lincoln was the victim of an assassination conspiracy, as was Austrian archduke Franz Ferdinand, gunned down by the Serbian secret society called Black Hand. The attack on Pearl Harbor was a Japanese conspiracy (although some conspiracists think Franklin Roosevelt was in on it). Watergate was a conspiracy (that Richard Nixon *was* in on). How can we tell the difference between information and disinformation? As Kurt Cobain, the rocker star of Nirvana, once growled in his grunge lyrics shortly before his death from a self-inflicted (or was it?) gunshot to the head, "Just because you're paranoid don't mean they're not after you."

But as former Nixon aide G. Gordon Liddy once told me (and he should know!), the problem with government conspiracies is that bureaucrats are incompetent and people can't keep their mouths shut. Complex conspiracies are difficult to pull off, and so many people want their quarter hour of fame that even the Men in Black couldn't squelch the squealers from spilling the beans. So there's a good chance that the more elaborate a conspiracy theory is, and the more people that would need to be involved, the less likely it is true.

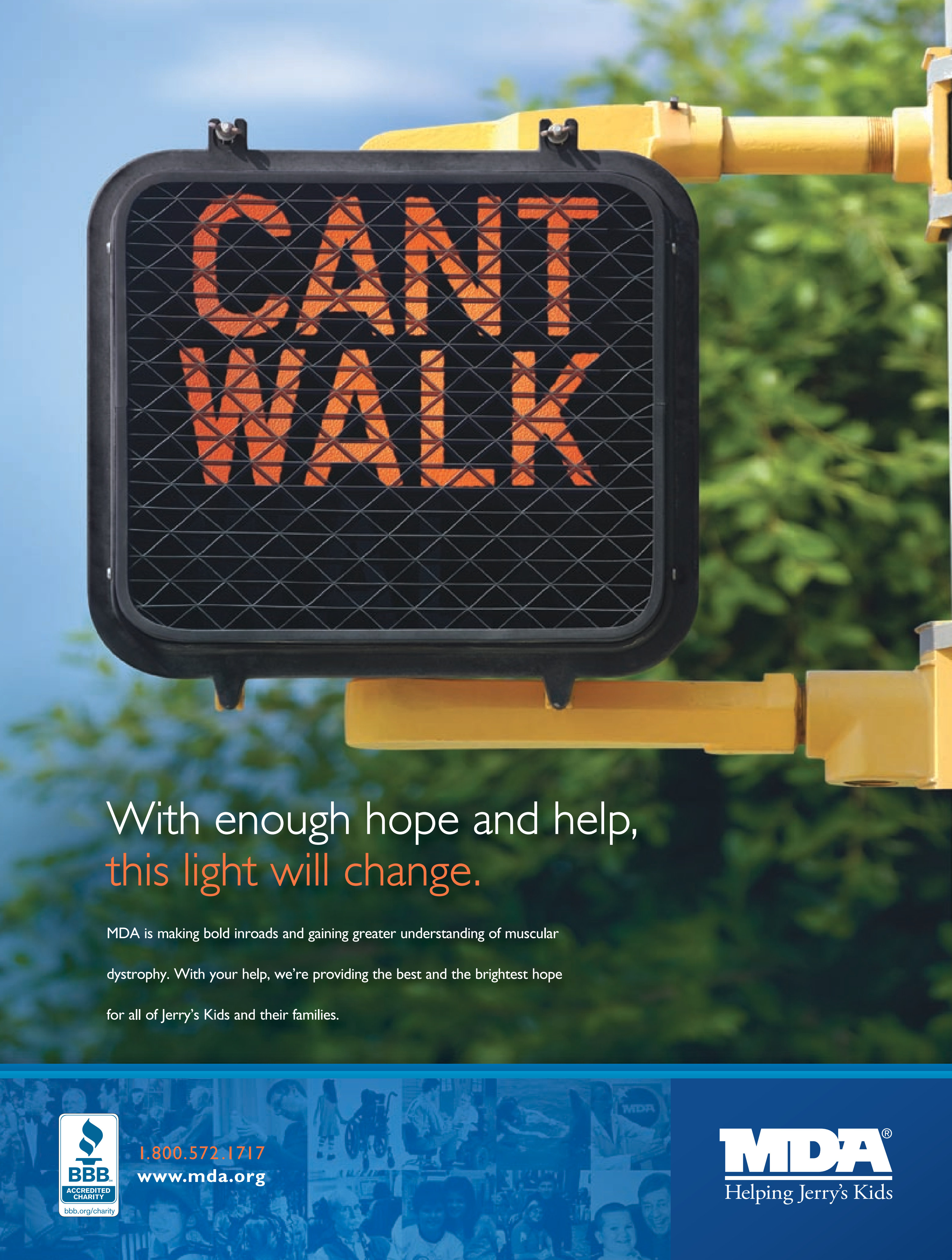
Why do people believe in highly improbable conspiracies? In previous columns I have provided partial answers, citing patternicity (the tendency to find meaningful patterns in random noise) and agenticity (the bent to believe the world is controlled by invisible intentional agents). Conspiracy theories connect the dots of random events into meaningful patterns and then infuse those patterns with intentional agency. Add to those propensities the confirmation bias (which seeks and finds confirmatory evidence for what we already believe) and the hindsight bias (which tailors after-the-fact explanations to what we already know happened), and we have the foundation for conspiratorial cognition.

Examples of these processes can be found in journalist Arthur Goldwag's marvelous new book, *Cults, Conspiracies, and Secret Societies* (Vintage, 2009), which covers everything from the Freemasons, the Illuminati and the Bilderberg Group to black helicopters and the New World Order. "When something momentous happens, everything leading up to and away from the event seems momentous, too. Even the most trivial detail seems to glow with significance," Goldwag explains, noting the JFK assassination as a prime example. "Knowing what we know now ... film footage of Dealey Plaza from November 22, 1963, seems pregnant with enigmas and ironies—from the oddly expectant expressions on the faces of the onlookers on the grassy knoll in the instants before the shots were fired (*What were they thinking?*) to the play of shadows in the background (*Could that flash up there on the overpass have been a gun barrel gleaming in the sun?*). Each odd excrescence, every random lump in the visual texture seems suspicious." Add to these factors how compellingly a good narrative story can tie it all together—think of Oliver Stone's *JFK* or Dan Brown's *Angels and Demons*, both equally fictional.

What should we believe? Transcendentalists tend to believe that everything is interconnected and that all events happen for a reason. Empiricists tend to think that randomness and coincidence interact with the causal net of our world and that belief should depend on evidence for each individual claim. The problem for skepticism is that transcendentalism is intuitive; empiricism is not. Or as folk rock group Buffalo Springfield once intoned: *Paranoia strikes deep. Into your life it will creep ...* ■

Michael Shermer is publisher of Skeptic *(www.skeptic.com) and author of* Why People Believe Weird Things.

PHOTOGRAPH BY BRAD SWONETZ; ILLUSTRATION BY MATT COLLINS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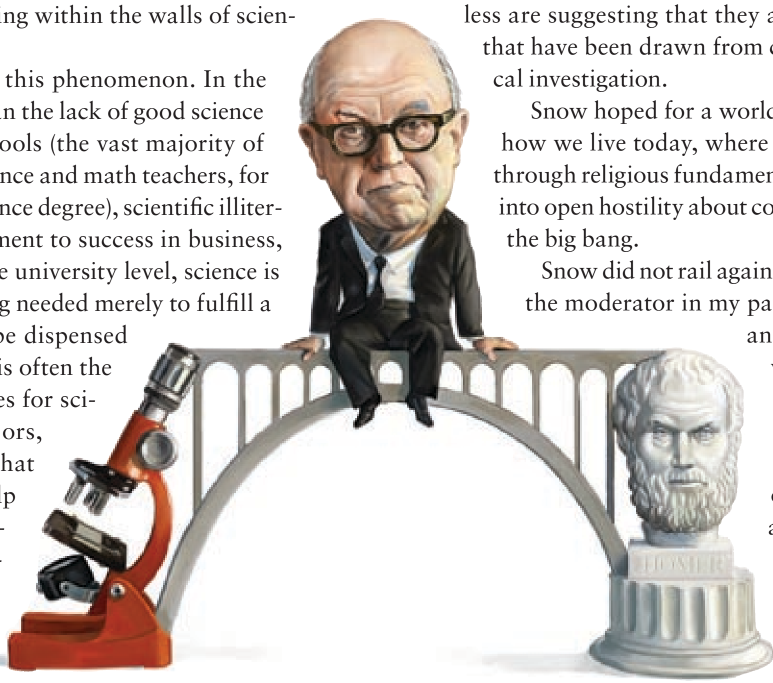
C. P. Snow in New York

A new column that examines the intersection between science and society provides an update on the "two cultures"

BY LAWRENCE M. KRAUSS

Earlier this summer marked the 50th anniversary of C. P. Snow's famous "Two Cultures" essay, in which he lamented the great cultural divide that separates two great areas of human intellectual activity, "science" and "the arts." Snow argued that practitioners in both areas should build bridges, to further the progress of human knowledge and to benefit society.

Alas, Snow's vision has gone unrealized. Instead literary agent John Brockman has posited a "third culture," of scientists who communicate directly with the public about their work in media such as books without the intervening assistance of literary types. At the same time, many of those in the humanities, arts and politics remain content living within the walls of scientific illiteracy.



Good reasons exist for this phenomenon. In the first place, while we bemoan the lack of good science teaching in our public schools (the vast majority of middle school physical science and math teachers, for example, do not have a science degree), scientific illiteracy is not a major impediment to success in business, politics and the arts. At the university level, science is too often seen as something needed merely to fulfill a requirement and then to be dispensed with. To be fair, the same is often the case for humanities courses for science and engineering majors, but the big difference is that these students cannot help but be bombarded by literature, music and art elsewhere as a part of the pop culture that permeates daily life. And what's more, individuals often proudly proclaim that science isn't their thing, almost as a badge of honor to indicate their cultural bent.

There is another factor, one that was on display at the World Science Festival in New York City this summer, which helps to undermine the role of science in society. Amid events on the cosmos, modern biology, quantum mechanics and other areas at the forefront of science, I participated in a panel discussion on science, faith and religion.

Why would such an event be a part of a science festival? We accord a special place to religion, in part thanks to groups such as the Templeton Foundation, which has spent millions annually raising the profile of "big questions," which tend to suggest that science and religious belief are somehow related and should be treated as equals.

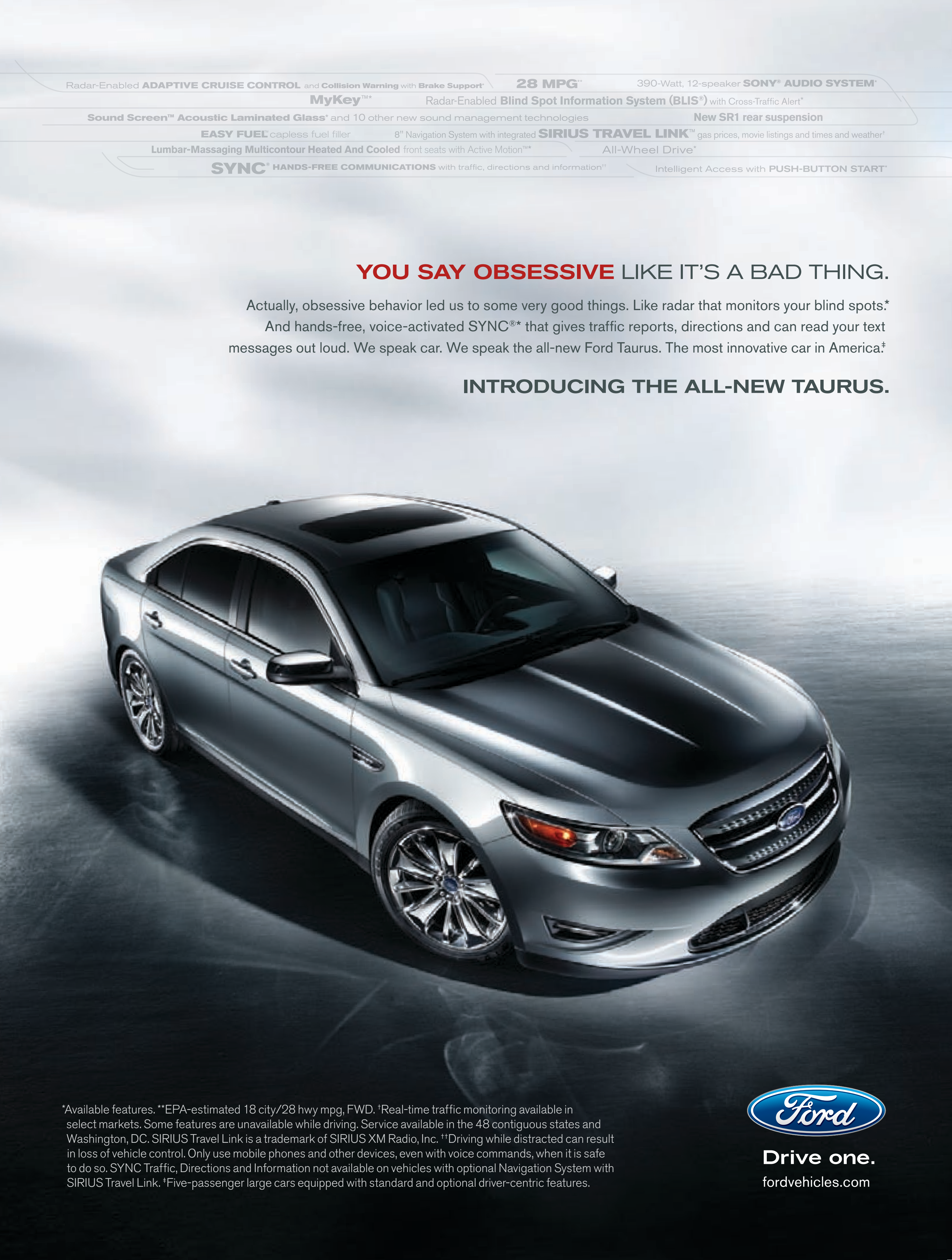
The problem is, they are not. Ultimately, science is at best only consistent with a God that does not directly intervene in the daily operations of the cosmos, certainly not the personal and ancient gods associated with the world's great religions. Even though, as physicist Steven Weinberg has emphasized, most people who call themselves religious tend to adhere to only those bits and pieces from scripture that appeal to them, by according undue respect for ancient religious beliefs in general, we nonetheless are suggesting that they are on par with conclusions that have been drawn from centuries of rational empirical investigation.

Snow hoped for a world that is quite different from how we live today, where indifference to science has, through religious fundamentalism, sometimes morphed into open hostility about concepts such as evolution and the big bang.

Snow did not rail against religion, but ignorance. As the moderator in my panel finally understood after an hour of discussion, the only vague notions of God that may be compatible with science ensure that God is essentially irrelevant to both our understanding of nature and our actions based on it. Until we are willing to accept the world the way it is, without miracles that all empirical evidence argues against, without myths that distort our comprehension of nature, we are unlikely to bridge the divide between science and culture and, more important, we are unlikely to be fully ready to address the urgent technical challenges facing humanity. ■

Lawrence M. Krauss, a theoretical physicist, commentator and book author, is Foundation Professor and director of the Origins Initiative at Arizona State University (http://krauss.faculty.asu.edu).

PHOTOGRAPH BY JOHN BOSWELL; ILLUSTRATION BY MATT COLLINS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IN THE BEGINNING

A powerful urge to understand the emergence of the cosmos or even life itself fuels the scientific enterprise

A Greek statesman who lived in the sixth century B.C. put forward the first explanation, shorn of theological trappings, that captured the essence of all things living and inanimate. Thales of Miletus noticed that water could exist as a liquid, gas or solid and posited that it was the fundamental constituent of matter from which the earth's denizens—men, goats, flowers, rocks, and whatnot—somehow sprang forth.

As with all natural philosophy (a pursuit now known as science), Thales' observation immediately provoked an argument. Anaximander, a disciple of Thales (today what would be called a graduate student), asked how water could be the single basic element if rock, sand and other substances appeared to be devoid of moisture.

The bickering about beginnings and the nature of our existence has not ceased in ensuing millennia, although Thales' aqueous cosmology persists only as a passing citation in histories of philosophy and science. A definitive answer to the identity of the most basic ingredient of matter—and how it could ultimately lead to a world populated by iPhones and reruns of *American Idol*—still eludes today's natural philosophers.

In early April a colloquy of 70 leading scientists assembled at Arizona State University to launch an Origins Initiative to ponder such questions as whether infinitesimal, stringlike particles may be candidates as the latest substitute for Thales' vision of a wet world. An urge to deduce beginnings energizes the entire scientific endeavor—and of course that extends into the realm of biology. Appropriately, this year's 150th anniversary of the publication of Charles Darwin's *On the Origin of Species* coincides with a significant advance toward the milestone of demonstrating how life sprang from inanimate matter. A British team of chemists showed that one of the basic building blocks of life could form spontaneously from a warm soup of organic chemicals.

The immediacy of these themes is why this single-topic issue of *Scientific American* is devoted to origins in physics, chemistry, biology and technology. In the following pages, a physicist grapples with the overarching question of how the universe began. A chemist addresses possible ways in which life first started, and a biologist takes on what has made the human mind different from that of any other animal's. Then a historian of technology contemplates the first computer, perhaps the most extraordinary invention of the human mind. A final section provides brief chronicles of the inception of dozens of physical and biological phenomena, in addition to a series of remarkable human inventions.

Whether related to rainbows, antibiotics or paper money, beginnings—and the stories they generate—serve as an endless source of fascination about the world around us. —*The Editors*

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BRYAN CHRISTIE DESIGN

THE UNIVERSE

ORIGIN OF

BY MICHAEL S. TURNER

Cosmologists are closing in on the ultimate processes that created and shaped the universe

The universe is big in both space and time and, for much of humankind's history, was beyond the reach of our instruments and our minds. That changed dramatically in the 20th century. The advances were driven equally by powerful ideas—from Einstein's general relativity to modern theories of the elementary particles—and powerful instruments—from the 100- and 200-inch reflectors that George Ellery Hale built, which took us beyond our Milky Way galaxy, to the Hubble Space Telescope, which has taken us back to the birth of galaxies. Over the past 20 years the pace of progress has accelerated with the realization that dark matter is not made of ordinary atoms, the discovery of dark energy, and the dawning of bold ideas such as cosmic inflation and the multiverse.

The universe of 100 years ago was simple: eternal, unchanging, consisting of a single galaxy, containing a few million visible stars. The picture today is more complete and much richer. The cosmos began 13.7 billion years ago with the big bang. A fraction of a second after the beginning, the universe was a hot, formless soup of the most elementary particles, quarks and leptons. As it expanded and cooled, layer on layer of structure developed: neutrons and protons, atomic nuclei, atoms, stars, galaxies, clusters of galaxies, and finally superclusters. The observable part of the universe is now inhabited by 100 billion galaxies, each containing 100 billion stars and probably a similar number of planets. Galaxies themselves are held together by the gravity of the mysterious dark matter. The universe continues to expand and indeed does so at an accelerating pace, driven by dark energy, an even more mysterious form of energy whose gravitational force repels rather than attracts.

The overarching theme in our universe's story is the evolution from the simplicity of the quark soup to the complexity we see today in galaxies, stars, planets and life. These features emerged one by one over billions of years, guided by the basic laws of physics. In our journey back to the beginning of creation, cosmologists first travel through the well-established history of the universe back to the first

KEY CONCEPTS

- Our universe began with a hot big bang 13.7 billion years ago and has expanded and cooled ever since. It has evolved from a formless soup of elementary particles into the richly structured cosmos of today.
- The first microsecond was the formative period when matter came to dominate over antimatter, the seeds for galaxies and other structures were planted, and dark matter (the unidentified material that holds those structures together) was created.
- The future of the universe lies in the hands of dark energy, an unknown form of energy that caused cosmic expansion to begin accelerating a few billion years ago. *—The Editors*

HOLLY LINDEM (*photoillustration*); GENE BURKHARDT (*styling*)


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[THE AUTHOR]

Michael S. Turner pioneered the interdisciplinary union of particle physics, astrophysics and cosmology and led the National Academy study that laid out the vision for the new field earlier this decade. He is a professor at the Kavli Institute for Cosmological Physics at the University of Chicago. From 2003 to 2006 he headed the National Science Foundation mathematical and physical sciences directorate. His honors include the Warner Prize of the American Astronomical Society, the Lilienfeld Prize of the American Physical Society and the Klopsted Award from the American Association of Physics Teachers.

microsecond; then to within 10^{-34} second of the beginning, for which ideas are well formed but the evidence is not yet firm; and finally to the earliest moments of creation, for which our ideas are still just speculation. Although the ultimate origin of the universe still lies beyond our grasp, we have tantalizing conjectures, including the notion of the multiverse, whereby the universe comprises an infinite number of disconnected subuniverses.

Expanding Universe

Using the 100-inch Hooker telescope on Mount Wilson in 1924, Edwin Hubble showed that fuzzy nebulae, studied and speculated about for several hundred years, were galaxies just like our own—thereby enlarging the known universe by 100 billion. A few years later he showed that galaxies are moving apart from one another in a regular pattern described by a mathematical relation now known as Hubble's law, according to which galaxies that are farther away are moving faster. It is Hubble's law, played back in time, that points to a big bang 13.7 billion years ago.

Hubble's law found ready interpretation within general relativity: space itself is expanding, and galaxies are being carried along for the ride [*see box below*]. Light, too, is being stretched, or redshifted—a process that saps its energy, so that the universe cools as it expands. Cosmic expansion provides the narrative for understanding how today's universe came to be. As cosmologists imagine rewinding the clock, the universe becomes denser, hotter, more extreme and simpler. In exploring the beginning, we also probe the inner workings of nature by taking advantage of an accelerator more powerful than any built on Earth—the big bang itself.

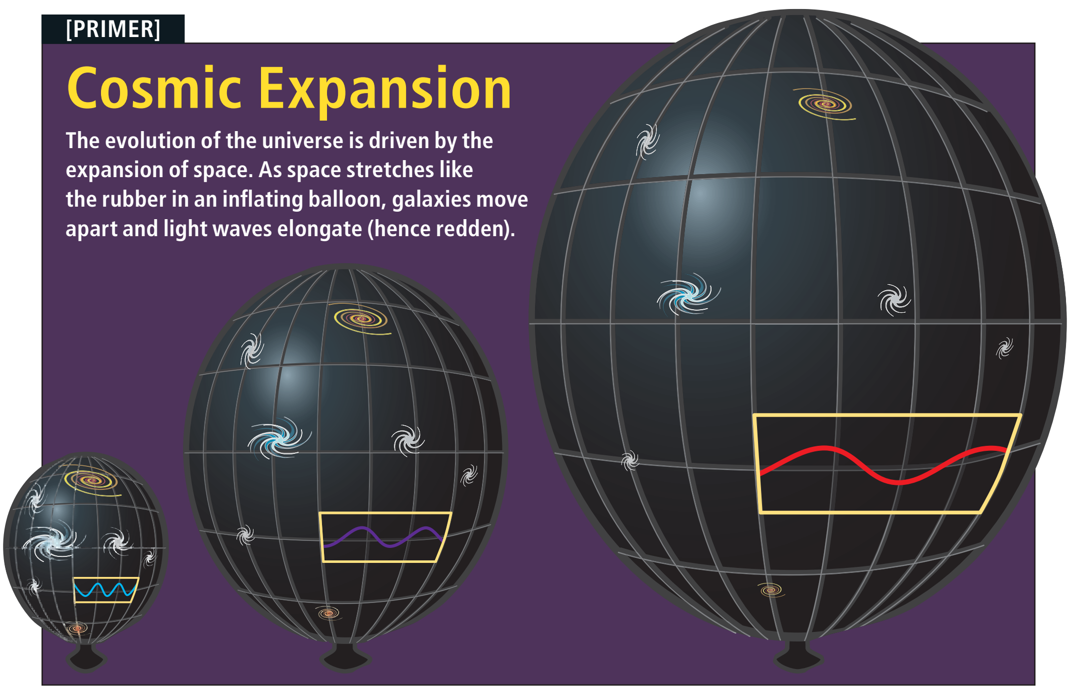
By looking out into space with telescopes, astronomers peer back in time—and the larger the telescope, the farther back they peer. The light from distant galaxies reveals an earlier epoch, and the amount this light has redshifted indicates how much the universe has grown in the intervening years. The current record holder has a redshift of about eight, representing a time when the universe was one-ninth its present size and only a few hundred million years old. Telescopes such as the Hubble Space Telescope and the 10-meter Keck telescopes on Mauna Kea routinely take us back to the epoch when galaxies like ours were forming, a few billion years after the big bang. Light from even earlier times is so strongly redshifted that astronomers must look for it in the infrared and radio bands. Upcoming telescopes such as the James Webb Space Telescope, a 6.5-meter infrared telescope, and the Atacama Large Millimeter Array (ALMA), a network of 64 radio dishes in northern Chile, will take us back to the birth of the very first stars and galaxies.

Computer simulations say those stars and galaxies emerged when the universe was about 100 million years old. Before then, the universe went through a time called the "dark ages," when it was almost pitch-black. Space was filled with a

[PRIMER]

Cosmic Expansion

The evolution of the universe is driven by the expansion of space. As space stretches like the rubber in an inflating balloon, galaxies move apart and light waves elongate (hence redden).



COURTESY OF ARGONNE NATIONAL LABORATORY (*Turner*); MELISSA THOMAS (*illustration*) featureless gruel, five parts dark matter and one part hydrogen and helium, that thinned out as the universe expanded. Matter was slightly uneven in density, and gravity acted to amplify these density variations: denser regions expanded more slowly than less dense ones did. By 100 million years the densest regions did not merely expand more slowly but actually started to collapse. Such regions contained about one million solar masses of material each. They were the first gravitationally bound objects in the cosmos.

Dark matter accounted for the bulk of their mass but was, as its name suggests, unable to emit or absorb light. So it remained in an extended cloud. Hydrogen and helium gas, on the other hand, emitted light, lost energy and became concentrated in the center of the cloud. Eventually it collapsed all the way down to stars. These first stars were much more massive than today's—hundreds of solar masses. They lived very short lives before exploding and leaving behind the first heavy elements. Over the next billion years or so the force of gravity assembled these million-solar-mass clouds into the first galaxies.

Radiation from primordial hydrogen clouds, greatly redshifted by the expansion, should be detectable by giant arrays of radio antennas with a total collecting area of up to one square kilometer. When built, these arrays will watch as the first generation of stars and galaxies ionize the hydrogen and bring the dark ages to an end [see "The Dark Ages of the Universe," by Abraham Loeb; Scientific American, November 2006].

Faint Glow of a Hot Beginning

Beyond the dark ages is the glow of the hot big bang at redshift of 1,100. This radiation has been redshifted from visible light (a red-orange glow) beyond even the infrared to microwaves. What we see from that time is a wall of microwave radiation filling the sky—the cosmic microwave background radiation (CMB) discovered in 1964 by Arno Penzias and Robert Wilson. It provides a glimpse of the universe at the tender age of 380,000 years, the period when atoms formed. Before then, the universe was a nearly uniform soup of atomic nuclei, electrons and photons. As it cooled to a temperature of about 3,000 kelvins, the nuclei and electrons came together to form atoms. Photons ceased to scatter off electrons and streamed across space unhindered, revealing the universe at a simpler time before the existence of stars and galaxies.

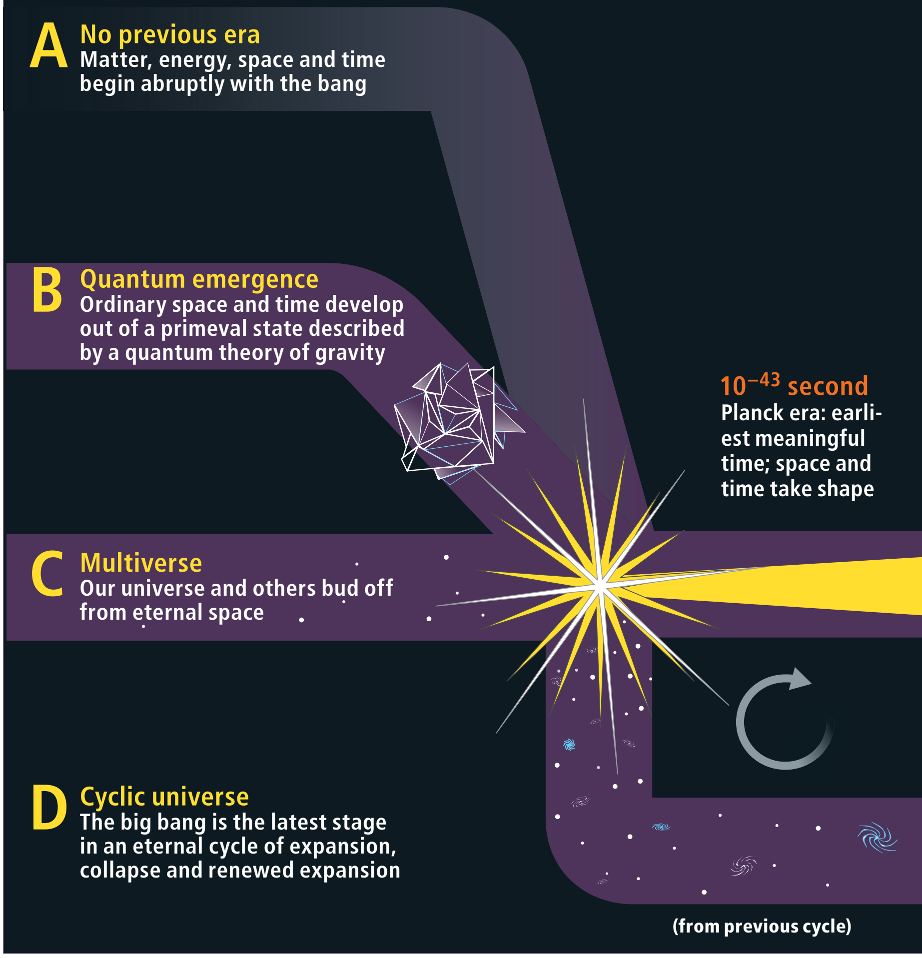
In 1992 NASA's Cosmic Background Explorer satellite discovered that the intensity of the CMB has slight variations—about 0.001 percent—reflecting a slight lumpiness in the distribution of matter. The degree of primordial lumpiness was enough to act as seeds for the galaxies and larger structures that would later emerge from the action of gravity. The pattern of these variations in the CMB across the sky also encodes basic properties of the universe, such as its overall density and composition, as well as hints about its earliest moments; the careful study of these variations has revealed much about the universe [*see illustration on page 41*].

As we roll a movie of the universe's evolution back from that point, we see the primordial plasma becoming ever hotter and denser. Prior to about 100,000 years, the energy density of radi-

[COSMIC TIMELINE]

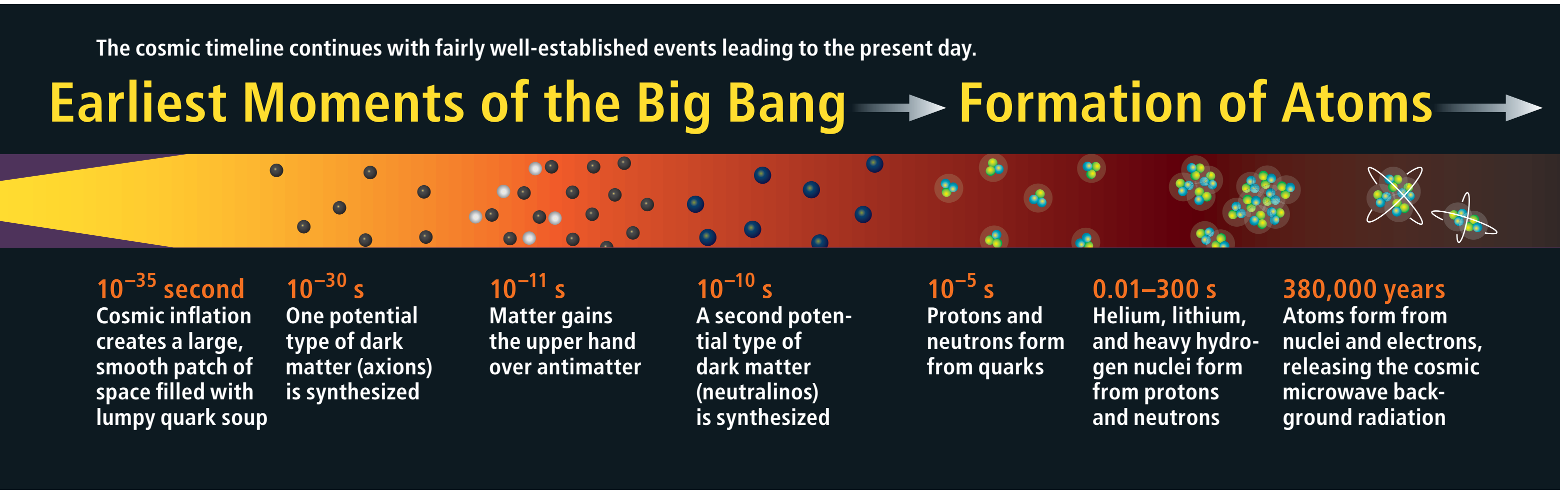
Before the Big Bang

Cosmologists do not yet know how the universe began, but this question has now come within the realm of science, with a number of speculative scenarios being discussed.



HUBBLE ULTRA DEEP FIELD, the most sensitive optical image of the cosmos ever made, reveals more than 1,000 galaxies in their early stages of formation.

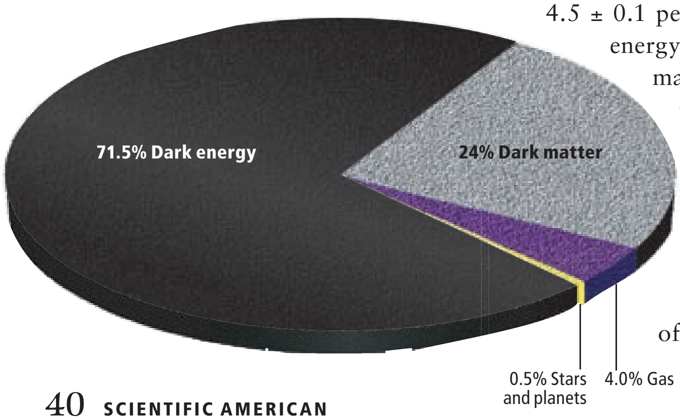
R. THOMPSON *University of Arizona*, NASA AND ESA (*Hubble Ultra Deep Field*); MELISSA THOMAS (*illustration*)



ation exceeded that of matter, which kept matter from clumping. Thus, this time marks the beginning of gravitational assembly of all the structure seen in the universe today. Still further back, when the universe was less than a second old, atomic nuclei had yet to form; only their constituent particles—namely, protons and neutrons—existed. Nuclei emerged when the universe was seconds old and the temperatures and densities were just right for nuclear reactions. This process of big bang nucleosynthesis produced only the lightest elements in the periodic table: a lot of helium (about 25 percent of the atoms in the universe by mass) and smaller amounts of lithium and the isotopes deuterium and helium 3. The rest of the plasma (about 75 percent) stayed in the form of protons that would eventually become hydrogen atoms. All the rest of the elements in the periodic table formed billions of years later in stars and stellar explosions.

Nucleosynthesis theory accurately predicts the abundances of elements and isotopes measured in the most primeval samples of the universe—namely, the oldest stars and high-redshift gas clouds. The abundance of deuterium, which is very sensitive to the density of atoms in the universe, plays a special role: its measured value implies that ordinary matter amounts to 4.5 ± 0.1 percent of the total energy density. (The remainder is dark matter and dark energy.) This estimate agrees precisely with the composition that has been gleaned from the analysis of the CMB. This correspondence is a great triumph. That these two very different measures, one based on nuclear physics when the universe was a second old and the other based on atomic physics when the universe was 380,000 years old, agree is a strong check not just on our model of how the cosmos evolved but on all of modern physics.

BULK OF UNIVERSE consists of dark energy and dark matter, neither of which has been identified. Ordinary matter of the kind that makes up stars, planets and interstellar gas accounts for only a small fraction.



Answers in the Quark Soup

Earlier than a microsecond, even protons and neutrons could not exist and the universe was a soup of nature's basic building blocks: quarks, leptons, and the force carriers (photons, the *W* and *Z* bosons and gluons). We can be confident that the quark soup existed because experiments at particle accelerators have re-created similar conditions here on Earth today [see "The First Few Microseconds," by Michael Riordan and William A. Zajc; SCIENTIFIC AMERICAN, May 2006].

To explore this epoch, cosmologists rely not on bigger and better telescopes but on powerful ideas from particle physics. The development of the Standard Model of particle physics 30 years ago has led to bold speculations, including string theory, about how the seemingly disparate fundamental particles and forces are unified. As it turns out, these new ideas have implications for cosmology that are as important as the original idea of the hot big bang. They hint at deep and unexpected connections between the world of the very big and of the very small. Answers to three key questions—the nature of dark matter, the asymmetry between matter and antimatter, and the origin of the lumpy quark soup itself—are beginning to emerge.

It now appears that the early quark soup phase was the birthplace of dark matter. The identity of dark matter remains unclear, but its existence

MELISSA THOMAS (*illustrations*)

Dark Ages → Modern Era

380,000–300 million yr Gravity continues to amplify density differences in the gas that fills space

300 million yr First stars and galaxies form

1 billion yr Limit of current observations (highest-redshift objects)

3 billion yr Clusters of galaxies form; star formation peaks

9 billion yr Solar system forms

10 billion yr Dark energy takes hold and expansion begins to accelerate

13.7 billion yr Today

is very well established. Our galaxy and every other galaxy as well as clusters of galaxies are held together by the gravity of unseen dark matter. Whatever the dark matter is, it must interact weakly with ordinary matter; otherwise it would have shown itself in other ways. Attempts to find a unifying framework for the forces and particles of nature have led to the prediction of stable or long-lived particles that might constitute dark matter. These particles would be present today as remnants of the quark soup phase and are predicted to interact very weakly with atoms.

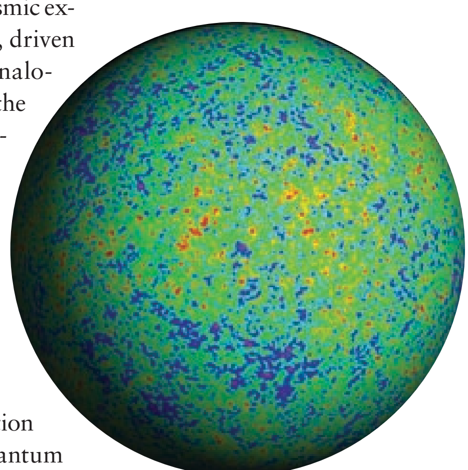
One candidate is the called the neutralino, the lightest of a putative new class of particles that are heavier counterparts of the known particles. The neutralino is thought to have a mass between 100 and 1,000 times that of the proton, just within the reach of experiments to be conducted by the Large Hadron Collider at CERN near Geneva. Physicists have also built ultrasensitive underground detectors, as well as satellite and balloon-borne varieties, to look for this particle or the by-products of its interactions.

A second candidate is the axion, a superlightweight particle about a trillionth the mass of the electron. Its existence is hinted at by subtleties that the Standard Model predicts in the behavior of quarks. Efforts to detect it exploit the fact that in a very strong magnetic field, an axion can transform into a photon. Both neutralinos and axions have the important property that they are, in a specific technical sense, "cold." Although they formed under broiling hot conditions, they were slow-moving and thus easily clumped into galaxies.

The early quark soup phase probably also holds the secret to why the universe today contains mostly matter rather than both matter and antimatter. Physicists think the universe originally had equal amounts of each, but at some point it developed a slight excess of matter—about one extra quark for every billion antiquarks. This imbalance ensured that enough quarks would survive annihilation with antiquarks as the universe expanded and cooled. More than 40 years ago accelerator experiments revealed that the laws of physics are ever so slightly biased in favor of matter, and in a still to be understood series of particle interactions very early on, this slight bias led to the creation of the quark excess.

The quark soup itself is thought to have arisen at an extremely early time—perhaps 10^{-34} second after the big bang in a burst of cosmic expansion known as inflation. This burst, driven by the energy of a new field (roughly analogous to the electromagnetic field) called the inflaton, would explain such basic properties of the cosmos as its general uniformity and the lumpiness that seeded galaxies and other structures in the universe. As the inflaton field decayed away, it released its remaining energy into quarks and other particles, thus creating the heat of the big bang and the quark soup itself.

Inflation leads to a profound connection between the quarks and the cosmos: quantum fluctuations in the inflaton field on the subatomic scale get blown up to astrophysical size by the rapid expansion and become the seeds for all the structure we see today. In other words, the pattern seen on the CMB sky is a giant image of the subatomic world. Observations of the CMB agree with this prediction, providing the strongest evidence that inflation or something like it occurred very early in the history of the universe.



COSMIC MICROWAVE background radiation is a snapshot of the universe at the tender age of 380,000 years. Tiny variations in the intensity of the radiation (*color-coded here*) are a cosmic Rosetta Stone that reveals key features of the universe, including its age, density, geometry and overall composition.

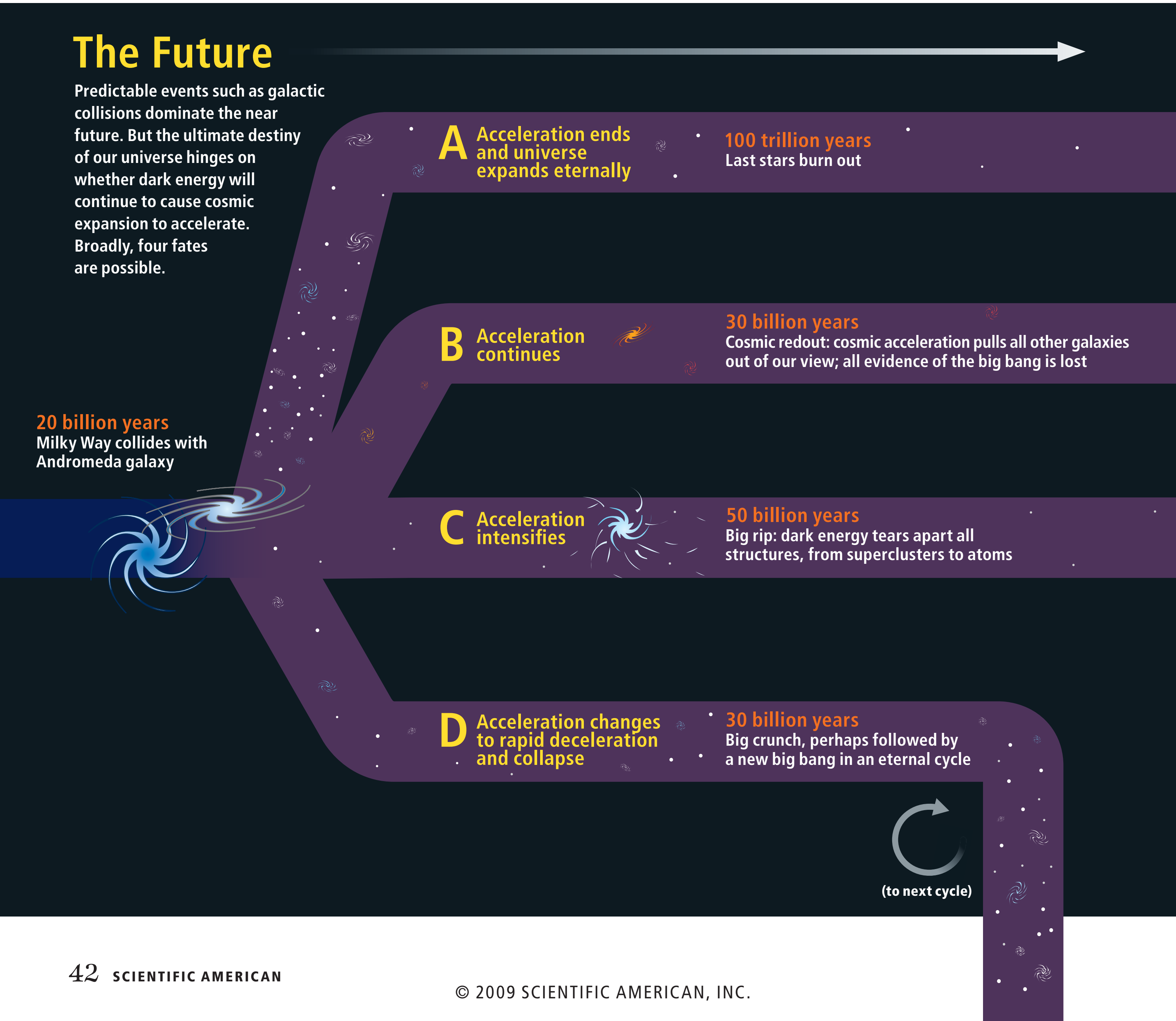
MAX TEGMARK AND ANGELICA DE OLIVERA-COSTA (*cosmic microwave radiation*)

Birth of the Universe

As cosmologists try to go even further to understand the beginning of the universe itself, our ideas become less firm. Einstein's general theory of relativity has provided the theoretical foundation for a century of progress in our understanding of the evolution of the universe. Yet it is inconsistent with the other pillar of contemporary physics, quantum theory, and the discipline's greatest challenge is to reconcile the two. Only with such a unified theory will we be able to address the very earliest moments of the universe, the so-called Planck era prior to about 10^{-43} second, when spacetime itself was taking shape.

Tentative attempts at a unified theory have led to some remarkable speculations about our very beginnings. String theory, for example, predicts the existence of additional dimensions of space and possibly other universes floating in that larger space. What we call the big bang may have been the collision of our universe with another [see "The Myth of the Beginning of Time," by Gabriele Veneziano; Scientific American, May 2004]. The marriage of string theory with the concept of inflation has led perhaps to the boldest idea yet, that of a multiverse—namely, that the universe comprises an infinite number of disconnected pieces, each with its own local laws of physics [see "The String Theory Landscape," by Raphael Bousso and Joseph Polchinski; Scientific American, September 2004].

MELISSA THOMAS



[COSMIC ACCELERATION AND DARK ENERGY]

In the Dark

A central feature of our current view of the universe, as well as its biggest mystery, is dark energy, the recently discovered and very weird form of energy that is causing cosmic expansion to speed up. Dark energy took control from matter a few billion years ago. Prior to that, the expansion had been slowing because of the gravitational attraction exerted by matter, and gravity was able to forge structures from galaxies to superclusters. Now, because of the influence of dark energy, structures larger than superclusters cannot form. In fact, had dark energy taken over earlier than it did—say, when the universe was only 100 million years old—structure formation would have ceased before even galaxies could have developed, and we would not be here.

Cosmologists have only rudimentary clues as to what dark energy might be. To speed up expansion requires a repulsive force, and Einstein's general theory of relativity predicts that the gravity of an extremely elastic form of energy can be actually be repulsive. The quantum energy that fills empty space acts in this way. The trouble is that theoretical estimates of the amount of quantum vacuum energy do not match the amount required by observations; in fact, they exceed it by many orders of magnitude. Alternatively, cosmic acceleration might be driven not by a new type of energy but by a process that mimics such energy, perhaps the breakdown of general relativity or the influence of unseen spatial dimensions [see "A Cosmic Conundrum," by Lawrence M. Krauss and Michael S. Turner; SCIENTIFIC AMERICAN, September 2004].

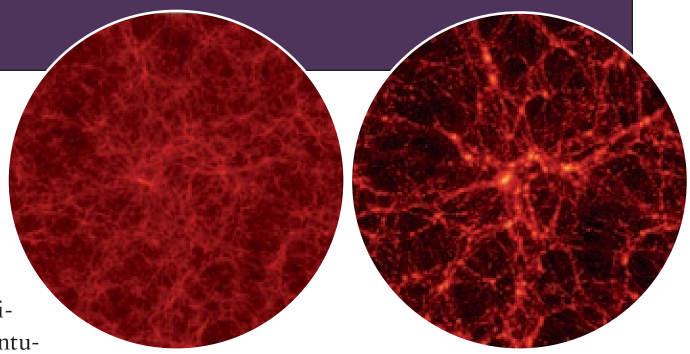
If the universe continues to accelerate at the current rate, then in 30 billion years all traces of the big bang will disappear [see "The End of Cosmology?" by Lawrence M. Krauss and Robert J. Scherrer; SCIENTIFIC AMERICAN, March 2008]. The light from all but a handful of nearby galaxies will be too redshifted to detect; the temperature of the cosmic background radiation will be too low to measure; and the universe will appear similar to one that astronomers knew 100 years ago before their instruments were powerful enough to reveal the universe we know today. *—M.S.T.*

The multiverse concept, which is still in its infancy, turns on two key theoretical findings. First, the equations describing inflation strongly suggest that if inflation happened once, it should happen again and again, with an infinite number of inflationary regions created over time. Nothing can travel between these regions, so they have no effect on one another. Second, string theory suggests that these regions have different physical parameters, such as the number of spatial dimensions and the kinds of stable particles.

The idea of the multiverse provides novel answers to two of the biggest questions in all of science: what happened before the big bang and why the laws of physics are as they are (Einstein's famous musing about "whether God had any choice" about the laws). The multiverse makes moot the question of before the big bang, because there were an infinite number of big bang beginnings, each triggered by its own burst of inflation. Likewise, Einstein's question is pushed aside: within the infinity of universes, all possibilities for the laws of physics have been tried, so there is no particular reason for the laws that govern our universe.

Cosmologists have mixed feelings about the multiverse. If the disconnected subuniverses are truly incommunicado, we cannot hope to test their existence; they seem to lie beyond the realm of science. Part of me wants to scream, One universe at a time, please! On the other hand, the multiverse solves various conceptual problems. If correct, it will make Hubble's enlargement of the universe by a mere factor of 100 billion and Copernicus's banishment of Earth from the center of the universe in the 16th century seem like small advances in the understanding of our place in the cosmos.

Modern cosmology has humbled us. We are made of protons, neutrons and electrons, which together account for only 4.5 percent of the universe, and we exist only because of subtle connections between the very small and the very large. Events guided by the microscopic laws of physics allowed matter to dominate over antimatter, generated the lumpiness that seeded galaxies, filled space with dark matter particles that provide the gravitational infrastructure, and ensured that dark matter could build galaxies before dark energy became significant and the expansion began to accelerate [*see box above*]. At the same time, cosmology by its very nature is arrogant. The idea that we can understand something as vast in both space and time as our universe is, on the face of it, preposterous. This strange mix of humility and arrogance has gotten us pretty far in the past century in advancing our understanding of the present universe and its origin. I am bullish on further progress in the coming years, and I firmly believe we are living in a golden age of cosmology. ■



IF THE UNIVERSE had even more dark energy than it does, it would have remained almost formless (*left*), without the large structures that we see (*right*).

LIANG GAO, CARLOS FRENK AND ADRIAN JENKINS *Institute for Computational Cosmology, Durham University*

➡ MORE TO EXPLORE

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ORIGIN OF THE MIND

BY MARC HAUSER

The first step in figuring out how the human mind arose is determining what distinguishes our mental processes from those of other creatures

Not too long ago three aliens descended to Earth to evaluate the status of intelligent life. One specialized in engineering, one in chemistry and one in computation. Turning to his colleagues, the engineer reported (translation follows): "All of the creatures here are solid, some segmented, with capacities to move on the ground, through the water or air. All extremely slow. Unimpressive." The chemist then commented: "All quite similar, derived from different sequences of four chemical ingredients." Next the computational expert opined: "Limited computing abilities. But one, the hairless biped, is unlike the others. It exchanges information in a manner that is primitive and inefficient but remarkably different from the others. It creates many odd objects, including ones that are consumable, others that produce symbols, and yet others that destroy members of its tribe."

"But how can this be?" the engineer mused. "Given the similarity in form and chemistry, how can their computing capacity differ?" "I am not certain," confessed the computational alien. "But they appear to have a system for creating new expressions that is infinitely more powerful than those of all the other living kinds. I propose that we place the hairless biped in a different group from the other animals, with a separate origin, and from a different galaxy." The other two aliens nodded, and then all three zipped home to present their report.

Perhaps our alien reporters should not be faulted for classifying humans separately from bees, birds, beavers, baboons and bonobos. After all, our species alone creates soufflés, computers, guns, makeup, plays, operas, sculptures, equations, laws and religions. Not only have bees and baboons never made a soufflé, they have never even contemplated the possibility. They simply lack the kind of brain that has both technological savoir faire and gastronomical creativity.

Charles Darwin argued in his 1871 book *The Descent of Man*

KEY CONCEPTS

- Charles Darwin argued that a continuity of mind exists between humans and other animals, a view that subsequent scholars have supported.
- But mounting evidence indicates that, in fact, a large mental gap separates us from our fellow creatures. Recently the author identified four unique aspects of human cognition.
- The origin and evolution of these distinctive mental traits remain largely mysterious, but clues are emerging slowly.

—The Editors

HOLLY LINDEM (*photoillustration*); GENE BURKHARDT (*styling*)

that the difference between human and nonhuman minds is "one of degree and not of kind." Scholars have long upheld that view, pointing in recent years to genetic evidence showing that we share some 98 percent of our genes with chimpanzees. But if our shared genetic heritage can explain the evolutionary origin of the human mind, then why isn't a chimpanzee writing this essay, or singing backup for the Rolling Stones or making a soufflé? Indeed, mounting evidence indicates that, in contrast to Darwin's theory of a continuity of mind between humans and other species, a profound gap separates our intellect from the animal kind. This is not to say that our mental faculties sprang fully formed out of nowhere. Researchers have found some of the building blocks of human cognition in other species. But these building blocks make up only the cement footprint of the skyscraper that is the human mind. The evolutionary origins of our cognitive abilities thus remain rather hazy. Clarity is emerging from novel insights and experimental technologies, however.

Singularly Smart

If we scientists are ever to unravel how the human mind came to be, we must first pinpoint exactly what sets it apart from the minds of other creatures. Although humans share the vast majority of their genes with chimps, studies suggest that small genetic shifts that occurred in the human lineage since it split from the chimp line produced massive differences in computational power. This rearranging, deleting and copying of universal genetic elements created a brain with four special properties. Together these distinctive characteristics, which I have recently identified based on studies conducted in my lab and elsewhere, constitute what I term our humaniqueness.

The first such trait is generative computation, the ability to create a virtually limitless variety of "expressions," be they arrangements of words, sequences of notes, combinations of actions, or strings of mathematical symbols. Generative computation encompasses two types of operation, recursive and combinatorial. Recursion is the repeated use of a rule to create new expressions. Think of the fact that a short phrase can be embedded within another phrase, repeatedly, to create longer, richer descriptions of our thoughts–for example, the simple but poetic expression from Gertrude Stein: "A rose is a rose is a rose." The combinatorial operation, meanwhile, is the mixing of discrete elements to engender new ideas, which can be expressed as novel words ("Walkman") or musical forms, among other possibilities.

The second distinguishing characteristic of the human mind is its capacity for the promiscuous combination of ideas. We routinely connect thoughts from different domains of knowledge, allowing our understanding of art, sex, space, causality and friendship to combine. From this mingling, new laws, social relationships and technologies can result, as when we decide that it is forbidden [moral domain] to push someone [motor action domain] intentionally [folk psychology domain] in front of a train [object domain] to save the lives [moral domain] of five [number domain] others.

Third on my list of defining properties is the use of mental symbols. We can spontaneously convert any sensory experience—real or imagined—into a symbol that we can keep to ourselves or express to others through language, art, music or computer code.

Fourth, only humans engage in abstract thought. Unlike animal thoughts, which are largely anchored in sensory and perceptual experiences, many of ours have no clear connection to such events. We alone ponder the likes of unicorns and aliens, nouns and verbs, infinity and God.

Although anthropologists disagree about exactly when the modern human mind took shape, it is clear from the archaeological record that a major transformation occurred during a relatively brief period of evolutionary history, starting approximately 800,000 years ago in the Paleolithic era and crescendoing around 45,000 to 50,000 years ago. It is during this period of the Paleolithic, an evolutionary eyeblink, that we see for the first time multipart tools; animal bones punctured with holes to fashion musical instruments; burials with accoutrements suggesting beliefs about aesthetics and the afterlife; richly symbolic cave paintings that capture in exquisite detail events of the past and the perceived future; and control over fire, a technology that combines our folk physics and psychology and allowed our ancestors to prevail over novel environments by creating warmth and cooking foods to make them edible.

These remnants of our past are magnificent reminders of how our forebears struggled to solve novel environmental problems and express themselves in creative new ways, marking their unique cultural identities. Nevertheless, the archaeological evidence will forever remain silent on the origins and selective pressures that led to

KEY INGREDIENTS OF THE HUMAN MIND

The four traits below distinguish the human mind from those of animals. Uncovering the origin of the human mind will require explaining how these unique properties came about.

Generative computation enables humans to create a virtually limitless variety of words, concepts and things. The characteristic encompasses two types of operation: recursive and combinatorial. Recursion is the repeated use of a rule to create new expressions. The combinatorial operation is the mixing of discrete elements to engender new ideas.

Promiscuous combination of ideas allows the mingling of different domains of knowledge—such as art, sex, space, causality and friendship—thereby generating new laws, social relationships and technologies.

Mental symbols encode sensory experiences both real and imagined, forming the basis of a rich and complex system of communication. Such symbols can be kept to oneself or expressed to others as words or pictures.

Abstract thought permits contemplation of things beyond what we can see, hear, touch, taste or smell.

GENERATIVE COMPUTATION by humans but not other animals is reflected in tool usage. Unlike other tool-using creatures, which make implements from a single material and for a single purpose, humans routinely combine materials to form tools and often use a given instrument in a number of ways. Here an orangutan employs a single leaf as an umbrella, whereas humans utilize a pencil made of several materials for a variety of purposes.

COURTESY OF LILAN HAUSER (*Hauser*); JH PETE CARMICHAEL *Getty Images (orangutan)*; PATRICK LANE *Somos Images/Corbis (writing in notebook)*; WILLIAM WHITEHURST *Corbis (pencil in book)*; ALIN DRAGULIN *Getty Images/Vico Collective (erasing with pencil)*; BRAD WILSON *Getty Images (pencil in hair)*

the four ingredients making up our humaniqueness. The gorgeous cave paintings at Lascaux, for instance, indicate that our ancestors understood the dual nature of pictures—that they are both objects and refer to objects and events. They do not, however, reveal whether these painters and their admirers expressed their aesthetic preferences about these artworks by means of symbols that were organized into grammatical classes (nouns, verbs, adjectives) or whether they imagined conveying these ideas equally well through sound or sign, depending on the health of their sensory systems. Similarly, none of the ancient instruments that have been found—such as the 35,000-year-old flutes made of bone and ivory—tell a story about use, about whether a few notes were played over and over again, Philip Glass–style, or about whether the composer imagined, as did Wagner, embedding themes within themes in a recursive manner.

What we can say with utmost confidence is that all people, from the hunter-gatherers on the African savanna to the traders on Wall Street, are born with the four ingredients of humaniqueness. How these ingredients are added to the recipe for creating culture varies considerably from group to group, however. Human cultures may differ in their languages, musical compositions, moral norms and artifacts. From the viewpoint of one culture, another's practices are often bizarre, sometimes distasteful, frequently incomprehensible and occasionally immoral. No other animal exhibits such variation in lifestyle. Looked at in this way, a chimpanzee is a cultural nonstarter.

Chimps and other animals are still interesting and relevant for understanding the origins of the human mind, though. In fact, only by working out which capacities we share with other animals and which are ours alone can scientists hope to piece together the story of how our humaniqueness came to be.

Beautiful Minds

When my youngest daughter, Sofia, was three years old, I asked her what makes us think. She pointed to her head and said: "My brain." I then asked her whether other animals have brains, starting with dogs and monkeys and then birds and fish. She said yes. When I asked her about the

[THE AUTHOR]

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ant that was crawling in front of us, she said: "No. Too small." We adults know that size does not provide a litmus test of whether an animal has a brain, although size does affect some aspects of brain structure and, consequently, some aspects of thought. And research has shown that most of the different cell types in the brain, along with their chemical messengers, are the same across vertebrate species, including humans. Furthermore, the general organization of the different structures in the brain's outermost layer, the cerebral cortex, is largely the same in monkeys, apes and humans. In other words, humans have a number of brain features in common with other species. Where we differ from them is in the relative size of particular regions of the cortex and how these regions connect, differences that give rise to thoughts having no analogue elsewhere in the animal kingdom.

Animals do exhibit sophisticated behaviors that appear to presage some of our capabilities. Take, for example, the ability to create or modify objects for a particular goal. Male bowerbirds construct magnificent architectural structures from twigs and decorate them with feathers, leaves, buttons and paint made from crushed berries to attract females. New Caledonian crows carve blades into fishing sticks for catching insects. Chimpanzees have been observed to use wooden spears to shish-kebab bush babies tucked away in tree crevasses.

In addition, experimental studies in a number of animals have revealed a native folk physics that enables them to generalize beyond their direct experiences to create novel solutions when exposed to foreign challenges in the laboratory. In one such experiment, when orangutans and chimps were presented with a mounted plastic cylinder containing a peanut at the bottom, they accessed the out-of-reach treat by sipping water from their drinking fountains and then spitting the liquid into the cylinder, thus making the peanut float to the top.

Animals also exhibit social behaviors in common with humans. Knowledgeable ants teach their naive pupils by guiding them to essential food resources. Meerkats provide their pups with tutorials on the art of dismembering a lethal but delectable scorpion. And a rash of studies have shown that animals as varied as domestic dogs, capuchin monkeys and chimpanzees object to unfair distributions of food, exhibiting what economists call inequity aversion. What is more, ample evidence demonstrates that animals are not locked into their daily routines for maintaining dominance status, caring for infants, and finding new mates and coalition partners. Rather they can readily respond to novel social situations, as when a subordinate animal with a unique skill gains favors from more dominant individuals.

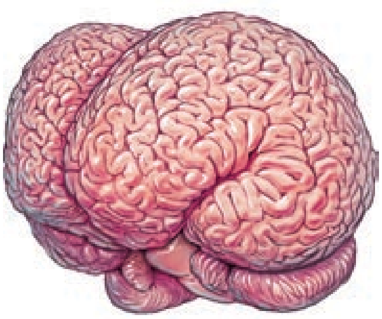
These observations inspire a sense of wonder at the beauty of nature's R&D solutions. But once we get over this frisson, we must confront the gap between humans and other species, a space that is cavernous, as our aliens reported. To fully convey the extent of this gap and the difficulty of deciphering how it arose, let me describe our humaniqueness in more detail.

ANDREW SWIFT

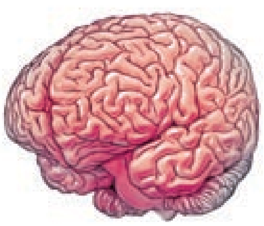
Minding the Gap

One of our most basic tools, the No. 2 pencil, used by every test taker, illustrates the exceptional freedom of the human mind as compared with the limited scope of animal cognition. You hold the painted wood, write with the lead, and erase with the pink rubber held in place by a metal ring. Four different materials, each with a particular function, all wrapped up into a single tool. And although that tool was made for writing, it can also pin hair up into a bun, bookmark a page or stab an annoying insect. Animal tools, in contrast—such as the sticks chimps use to fish termites out from their mounds—are composed of a single material, designed for a single function and never used for other functions. None have the combinatorial properties of the pencil.

Another simple tool, the telescopic, collapsible cup found in many a camper's gear, provides



Killer whale brain
5,620 grams



Human brain
1,350 grams

Etruscan shrew brain
0.1 gram

SIZING UP THE BRAIN

Humans are smarter than creatures whose brains are larger than ours in absolute terms, such as killer whales, as well as those animals whose brains are larger than ours in relative terms (that is, relative to body size), such as shrews. Thus, size alone does not explain the uniqueness of the human mind.

an example of recursion in action. To make this device, the manufacturer need only program a simple rule—add a segment of increasing size to the last segment—and repeat it until the desired size is reached. Humans use recursive operations such as this in virtually all aspects of mental life, from language, music and math to the generation of a limitless range of movements with our legs, hands and mouths. The only glimmerings of recursion in animals, however, have come from watching their motor systems in action.

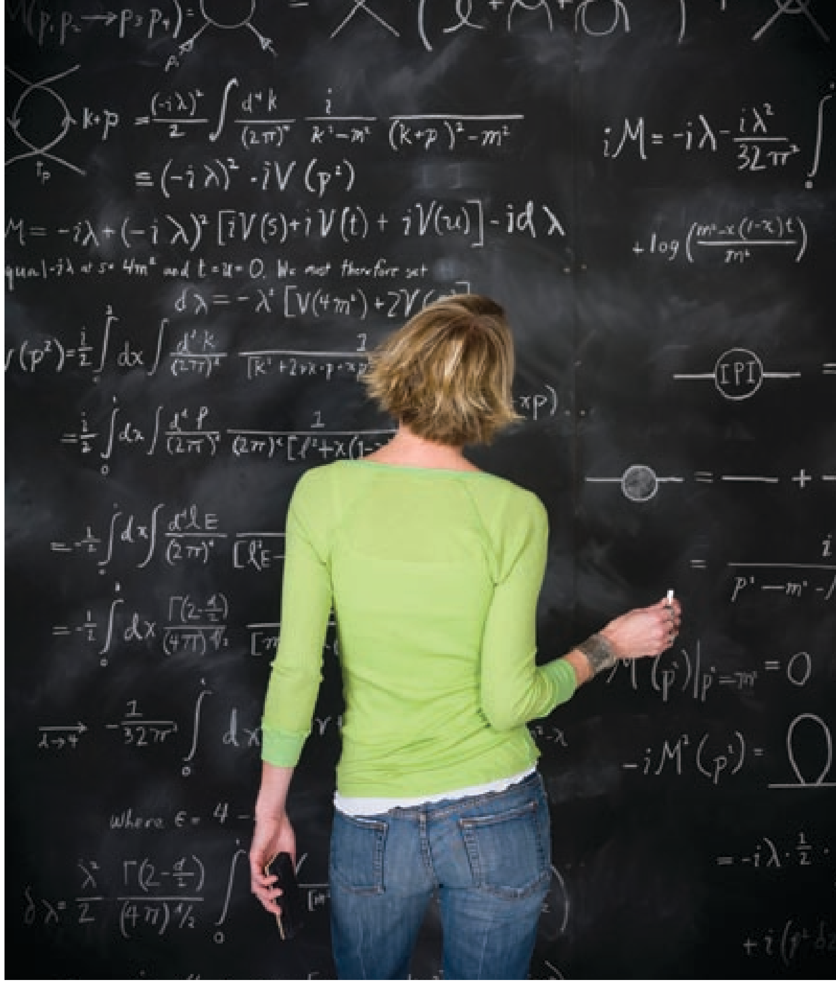
All creatures are endowed with recursive motor machinery as part of their standard operating equipment. To walk, they put one foot in front of the other, over and over again. To eat, they may grasp an object and bring it to the mouth repeatedly until the stomach sends the signal to stop. In animal minds, this recursive system is locked away in the motor regions of the brain, closed off to other brain areas. Its existence suggests that a critical step in acquiring our own distinctive brand of thinking was not the evolution of recursion as a novel form of computation but the release of recursion from its motor prison to other domains of thought. How it was unlocked from this restrictive function links to one of our other ingredients—promiscuous interfaces—which I will turn to shortly.

The mental gap broadens when we compare human language with communication in other species. Like other animals, humans have a nonverbal communication system that conveys our emotions and motivations—the chortles and cries of little babies are part of this system. Humans are alone, however, in having a system of linguistic communication that is based on the manipulation of mental symbols, with each example of a symbol falling into a specific and abstract category such as noun, verb and adjective. Although some animals have sounds that appear to represent more than their emotions, conveying information about objects and events such as food, sex and predation, the range of such sounds pales in relation to our own, and none of them falls into the abstract categories that structure our linguistic expressions.

This claim requires clarification, because it often elicits extreme skepticism. You might think, for example, that animal vocabularies appear small because researchers studying their communications do not really understand what they are talking about. Although scientists have much to learn about animal vocalizations, and communication more generally, I think insufficient study is unlikely to explain the large gap. Most vocal exchanges between animals consist of one grunt or coo or scream, with a single volley back. It is possible that animals pack a vast amount of information into a 500-millisecond grunt—perhaps equivalent to "Please groom my lower back now, and I will groom yours later." But then why would we humans have developed such an arcane and highly verbose system if we could have solved it all with a grunt or two?

ANIMALS MAY USE a handful of simple utterances to represent objects and events in the present, but their range of expression is very limited compared with that of humans, whose ability to engage in abstract thought additionally enables them to discuss not only the future and past but also abstract concepts, such as the spiritual teachings of the Dalai Lama.

ART WOLFE *Getty Images (lion)*; REUTERS/CORBIS *(Dalai Lama)*



MORE THAN MATH: Many animal species can count. But only humans can calculate the circumference of the earth, the speed of light or the likelihood of winning the lottery. In addition, we may combine our number system with various other domains of thought, such as morality, deciding whether to save five people over one, for instance.

Furthermore, even if we grant that the honeybee's waggle dance symbolically represents the delicious pollen located a mile north and that the putty-nosed monkey's alarm calls symbolically represent different predators, these uses of symbols are unlike ours in five essential ways: they are triggered only by real objects or events, never imagined ones; they are restricted to the present; they are not part of a more abstract classification scheme, such as those that organize our words into nouns, verbs and adjectives; they are rarely combined with other symbols, and when they are, the combinations are limited to a string of two, with no rules; and they are fixed to particular contexts.

Human language is additionally remarkable—and entirely different from the communication systems of other animals—in that it operates equally well in the visual and auditory modes. If a songbird lost its voice and a honeybee its waggle, their communication would end. But when a human is deaf, sign language provides an equally expressive mode of communication that parallels its acoustic cousin in structural complexity.

Our linguistic knowledge, along with the computations it requires, also interacts with other domains of knowledge in fascinating ways that strikingly reflect our uniquely human ability to make promiscuous connections between systems of understanding. Consider the ability to quantify objects and events, a capacity that we share with other animals. A wide variety of species have at least two nonlinguistic abilities for counting. One is precise and limited to numbers less than four. The other is unlimited in scope, but it is approximate and limited to certain ratios for discrimination—an animal that can discriminate one from two, for instance, can also discriminate two from four, 16 from 32, and so on. The first system is anchored in a brain region involved in keeping track of individuals, whereas the second is anchored in brain regions that compute magnitudes.

Last year my colleagues and I described a third counting system in rhesus monkeys, one that may help us understand the origins of the human ability to mark the difference between singular and plural. This system operates when individuals see sets of objects presented at the same time—as opposed to individuals presented serially—and causes rhesus monkeys to discriminate one from many but not many from many food items. In our experiment, we showed a rhesus monkey one apple and placed it in a box. We then showed the same monkey five apples and placed all five at once into a second box. Given a choice the monkey consistently picked the second

TIM FLACH *Getty Images (macaque)*; RICHARD SCHULTZ *Corbis (woman at blackboard)* box with five apples. Then we put two apples in one box and five into the other. This time the monkey did not show a consistent preference. We humans do essentially the same thing when we say “one apple” and “two, five or 100 apples.”

But something peculiar happens when the human linguistic system connects up with this more ancient conceptual system. To see how, try this exercise: for the numbers 0, 0.2 and –5, add the most appropriate word: “apple” or “apples.” If you are like most native English speakers, including young children, you selected “apples.” In fact, you would select “apples” for “1.0.” If you are surprised, good, you should be. This is not a rule we learned in grammar school—in fact, strictly speaking, it is not grammatically correct. But it is part of the universal grammar that we alone are born with. The rule is simple but abstract: anything that is not “1” is pluralized.

The apple example demonstrates how different systems—syntax and concepts of sets—interact to produce new ways of thinking about or conceptualizing the world. But the creative process in humans does not stop here. We apply our language and number systems to cases of morality (saving five people is better than saving one), economics (if I am giving $10 and offer you $1, that seems unfair, and you will reject the dollar), and taboo trade-offs (in the U.S., selling our children, even for lots of money, is not kosher).

Alien Thoughts

From didactic meerkats to inequity-averse monkeys, the same observation applies: each of these animals has evolved an exquisite mind that is adapted to singular problems and is thus limited when it comes to applying skills to novel problems. Not so for us hairless bipeds. Once in place, the modern mind enabled our forebears to explore previously uninhabited parts of the earth, to create language to describe novel events, and to envision an afterlife.

The roots of our cognitive abilities remain largely unknown, but having pinpointed the unique ingredients of the human mind, scientists now know what to look for. To that end, I am hopeful that neurobiology will prove illuminating. Although scholars do not yet understand how genes build brains and how electrical activity in the brain builds thoughts and emotions, we are witnessing a revolution in the sciences of the mind that will fill in these blanks—and enrich our understanding of why the human brain differs so profoundly from those of other creatures.

For instance, studies of chimeric animals—in which brain circuits from an individual of one species are transplanted into an individual of another species—are helping to unravel how the brain is wired. And experiments with genetically modified animals are revealing genes that play roles in language and other social processes. Such achievements do not reveal anything about what our nerve cells do to give us our unique mental powers, but they do provide a roadmap for further exploration of these traits.

Still, for now, we have little choice but to admit that our mind is very different from that of even our closest primate relatives and that we do not know much about how that difference came to be. Could a chimpanzee think up an experiment to test humans? Could a chimpanzee imagine what it would be like for us to solve one of their problems? No and no. Although chimpanzees can see what we do, they cannot imagine what we think or feel because they lack the requisite mental machinery. Although chimpanzees and other animals appear to develop plans and consider both past experiences and future options, there is no evidence that they think in terms of counterfactuals—imagining worlds that have been against those that could be. We humans do this all the time and have done so ever since our distinctive genome gave birth to our distinctive minds. Our moral systems are premised on this mental capacity.

Have our unique minds become as powerful as a mind can be? For every form of human expression—including the world’s languages, musical compositions, moral norms and technological forms—I suspect we are unable to exhaust the space of all possibilities. There are significant limitations to our ability to imagine alternatives.

If our minds face inherent constraints on what they can conceive, then the notion of “thinking outside of the box” is all wrong. We are always inside the box, limited in our capacity to envision alternatives. Thus, in the same way that chimpanzees cannot imagine what it is like to be human, humans cannot imagine what it is like to be an intelligent alien. Whenever we try, we are stuck in the box that we call the human mind. The only way out is through evolution, the revolutionary remodeling of our genome and its potential to sculpt fresh neural connections and fashion new neural structures. Such change would give birth to a novel mind, one that would look on its ancestors as we often look on ours: with respect, curiosity, and a sense that we are alone, paragons in a world of simple minds. ■

IVORY BIRD SCULPTURE ▲

LIMITED CLUES

The archaeological record reveals that humans were routinely making art and musical instruments by 35,000 years ago, indicating that they were thinking symbolically by then. But modern scholars have no way of knowing what these long-ago people thought about the symbols they left behind nor how they composed their music. Such artifacts are thus of limited use in piecing together the origins of our unique mental abilities.

BIRD BONE FLUTE ▼

HILDE JENSEN *AP Photo/University of Tübingen/Nature magazine (bird sculpture)*; DANIEL MAURER *AP Photo (bone flute)*

➥ MORE TO EXPLORE

The Faculty of Language: What Is It, Who Has It, and How Did It Evolve? Marc D. Hauser, Noam Chomsky and W. Tecumseh Fitch in *Science,* Vol. 298, pages 1569–1579; November 22, 2002.

Moral Minds: How Nature Designed Our Universal Sense of Right and Wrong. Marc D. Hauser. Harper Collins, 2006.

Baboon Metaphysics: The Evolution of a Social Mind. Dorothy L. Cheney and Robert M. Seyfarth. University of Chicago Press, 2007.

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With a cosmic flight simulator, we'll take a scenic journey through space and time. After exploring our local Galactic neighborhood, we'll travel back 13.7 billion years to explore the Big Bang itself and how state-of-the-art measurements are transforming our understanding of our cosmic origin and ultimate fate.

Mission Design: Exploring the Solar System

Scientific mysteries and huge surprises await all of us space explorers, whether we're viewing Earth from the perspective of space or seeking out our neighbors, that is, the planets, dwarf planets, moons, asteroids, and comets that populate the solar system. But how do we get there? How do we get a spacecraft where we want it to go? What about power? How do we address the demands of the space environment? Dr. Howell will lay out the principles and process of designing a space mission. Get the scoop on the successful engineering techniques and some of the challenges in getting humans and robots to space destinations.

Solar Sailing

Nearly 400 years ago, Johannes Kepler observed that the tails of comets are sometimes blown about what he considered to be a solar "breeze." Kepler suggested that perhaps ships could move through space using large sails to capture the breeze from the Sun. The concept of practical solar sailing was introduced in the 1920's and serious studies of the idea by engineers began in the 1950's. Solar sails are very thin sheets of reflective material that reflect sunlight — they transfer the momentum of light energy to their spacecraft. This sunlight pressure yields a force that pushes a spacecraft through space, without using any fuel. Solar sails are real! Test sails are being constructed; solar sail capabilities are being analyzed; solar sail mission have been planned. Learn the facts with Dr. Howell.

Genetic Medicine: Can knowledge of the genome transform medicine?

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Cloning and Stem Cells: What are the potential uses of plant, animal and human cloning and what is the reality of stem cell uses?

The biology behind cloning has been known for over a century. The first plant was cloned in the mid-1950s and the first animal several decades later. In this lecture, you will learn how and why these feats were accomplished. Human cloning is now a possibility. The promise of using stem cells to treat diseases and even improve athletic performance in healthy people is a related topic. Delve into the realm of cloning and stem cells with Dr. Sadava. You'll learn of the ethical issues surrounding the use of human embryos to get the cells used, and the ways biologists may circumvent these concerns.

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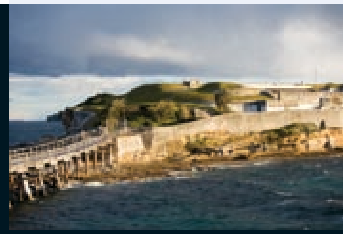


ORIGIN OF LIFE ON EARTH

BY ALONSO RICARDO AND JACK W. SZOSTAK

Fresh clues hint at how the first living organisms arose from inanimate matter

Every living cell, even the simplest bacterium, teems with molecular contraptions that would be the envy of any nanotechnologist. As they incessantly shake or spin or crawl around the cell, these machines cut, paste and copy genetic molecules, shuttle nutrients around or turn them into energy, build and repair cellular membranes, relay mechanical, chemical or electrical messages—the list goes on and on, and new discoveries add to it all the time.

It is virtually impossible to imagine how a cell's machines, which are mostly protein-based catalysts called enzymes, could have formed spontaneously as life first arose from nonliving matter around 3.7 billion years ago. To be sure, under the right conditions some building blocks of proteins, the amino acids, form easily from simpler chemicals, as Stanley L. Miller and Harold C. Urey of the University of Chicago discovered in pioneering experiments in the 1950s. But going from there to proteins and enzymes is a different matter.

A cell's protein-making process involves complex enzymes pulling apart the strands of DNA's double helix to extract the information contained in genes (the blueprints for the proteins) and translate it into the finished product. Thus, explaining how life began entails a serious paradox: it seems that it takes proteins—as well as the information now stored in DNA—to make proteins.

On the other hand, the paradox would disappear if the first organisms did not require proteins at all. Recent experiments suggest it would have been possible for genetic molecules similar to DNA or to its close relative RNA to form spontaneously. And because these molecules can curl up in different shapes and act as rudimentary catalysts, they may have become able to copy themselves—to reproduce—without the need for proteins. The earliest forms of life could have been simple membranes made of fatty acids—also structures known to form spontaneously—that enveloped water and these self-replicating genetic molecules. The genetic material would encode the traits that each generation handed down to the next, just as DNA does in all things that are alive today. Fortuitous mutations, appearing at random in the copying process, would then propel evolution, enabling these early cells to adapt to their environment, to compete with one

KEY CONCEPTS

- Researchers have found a way that the genetic molecule RNA could have formed from chemicals present on the early earth.
- Other studies have supported the hypothesis that primitive cells containing molecules similar to RNA could assemble spontaneously, reproduce and evolve, giving rise to all life.
- Scientists are now aiming at creating fully self-replicating artificial organisms in the laboratory—essentially giving life a second start to understand how it could have started the first time. —*The Editors*

HOLLY LINDEM (*photoillustration*); GENE BURKHARDT (*styling*)


A
U
C
G

another, and eventually to turn into the life-forms we know.

The actual nature of the first organisms and the exact circumstances of the origin of life may be forever lost to science. But research can at least help us understand what is possible. The ultimate challenge is to construct an artificial organism that can reproduce and evolve. Creating life anew will certainly help us understand how life can start, how likely it is that it exists on other worlds and, ultimately, what life is.

Got to Start Somewhere

One of the most difficult and interesting mysteries surrounding the origin of life is exactly how the genetic material could have formed starting from simpler molecules present on the early earth. Judging from the roles that RNA has in modern cells, it seems likely that RNA appeared before DNA. When modern cells make proteins, they first copy genes from DNA into RNA and then use the RNA as a blueprint to make proteins. This last stage could have existed independently at first. Later on, DNA could have appeared as a more permanent form of storage, thanks to its superior chemical stability.

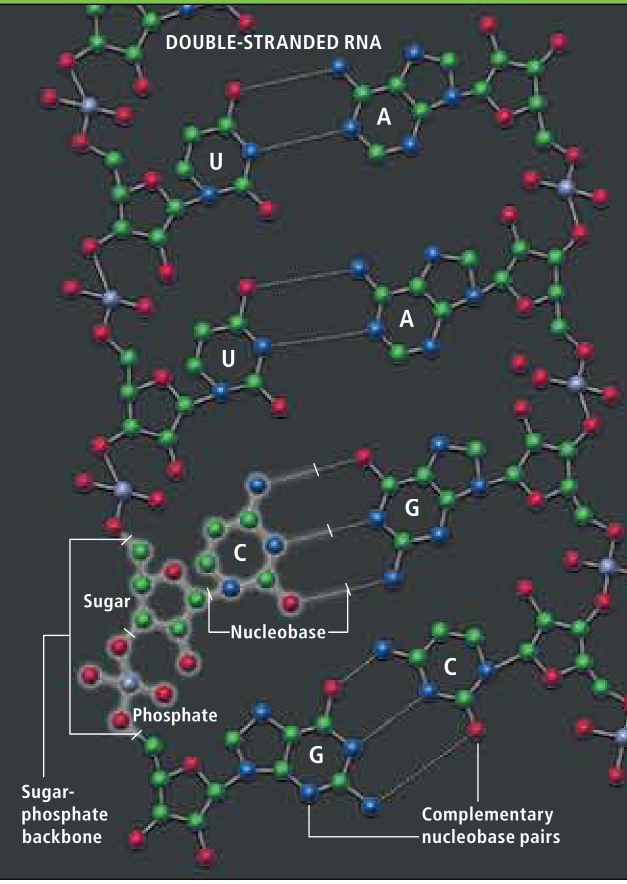
Investigators have one more reason for thinking that RNA came before DNA. The RNA versions of enzymes, called ribozymes, also serve a pivotal role in modern cells. The structures that translate RNA into proteins are hybrid RNA-protein machines, and it is the RNA in them that does the catalytic work. Thus, each of our cells appears to carry in its ribosomes "fossil" evidence of a primordial RNA world.

Much research, therefore, has focused on understanding the possible origin of RNA. Genetic molecules such as DNA and RNA are polymers (strings of smaller molecules) made of building blocks called nucleotides. In turn, nucleotides have three distinct components: a sugar, a phosphate and a nucleobase. Nucleobases come in four types and constitute the alphabet in which the polymer encodes information. In a DNA nucleotide the nucleobase can be A, G, C or T, standing for the molecules adenine, guanine, cytosine or thymine; in the RNA alphabet the letter U, for uracil, replaces the T [*see box above*]. The nucleobases are nitrogen-rich compounds that bind to one another according to a simple rule; thus, A pairs with U (or T), and G pairs with C. Such base pairs form the rungs of DNA's twisted ladder—the familiar double helix—and their exclusive pairings are crucial for faithfully copying the information so a cell can reproduce.

[BUILDING BLOCKS]

FIRST GENETIC MOLECULES

The first entities on earth capable of reproducing and evolving probably carried their genetic information in some molecule similar to RNA, a close relative of DNA. Both DNA and RNA are chains of units called nucleotides (*highlighted, left*), so a major question is how nucleotides first arose from simpler chemicals. The three components of a nucleotide—a nucleobase, a phosphate and a sugar—can each form spontaneously, but they do not readily join together in the right way (*center*). Recent experiments, however, have shown that at least two types of RNA nucleotides, those containing the nucleobases called C and U, could arise through a different route (*far right*). (In modern organisms, RNA nucleobases come in the four types A, C, G and U, the letters of the genetic alphabet.)



WHAT IS LIFE?

Scientists have long struggled to define "life" in a way that is broad enough to encompass forms not yet discovered. Here are some of the many proposed definitions.

1. **Physicist Erwin Schrödinger suggested that a defining property of living systems is that they self-assemble against nature's tendency toward disorder, or entropy.**

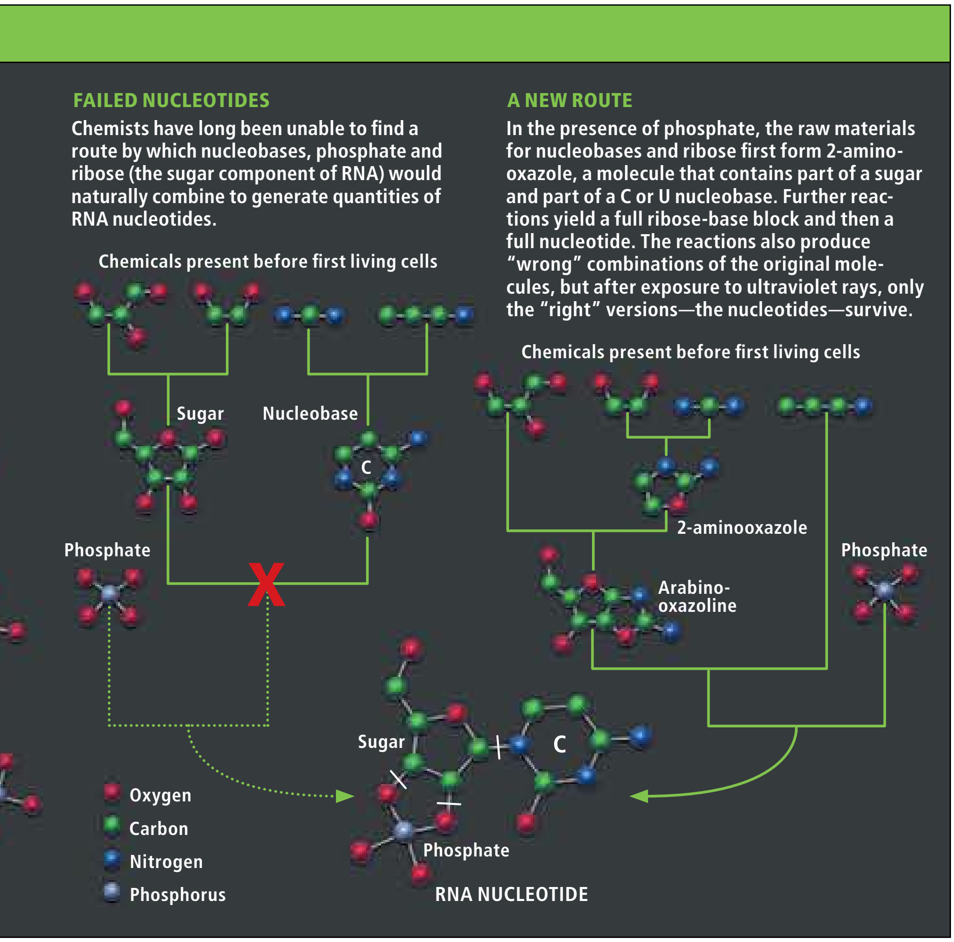
2. **Chemist Gerald Joyce's "working definition," adopted by NASA, is that life is "a self-sustaining chemical system capable of Darwinian evolution."**

3. **In the "cybernetic definition" by Bernard Korzeniewski, life is a network of feedback mechanisms.**

Meanwhile the phosphate and sugar molecules form the backbone of each strand of DNA or RNA.

Nucleobases can assemble spontaneously, in a series of steps, from cyanide, acetylene and water—simple molecules that were certainly present in the primordial mix of chemicals. Sugars are also easy to assemble from simple starting materials. It has been known for well over 100 years that mixtures of many types of sugar molecules can be obtained by warming an alkaline solution of formaldehyde, which also would have been available on the young planet. The problem, however, is how to obtain the "right" kind of sugar—ribose, in the case of RNA—to make nucleotides. Ribose, along with three closely related sugars, can form from the reaction of two simpler sugars that contain two and three carbon atoms, respectively. Ribose's ability to form in that way does not solve the problem of how it became abundant on the early earth, however, because it turns out that ribose is unstable and rapidly breaks down in an even mildly alkaline solution. In the past, this observation has led many researchers to conclude that the first genetic mole-

ANDREW SWIFT; SOURCE: "SYNTHESIS OF ACTIVATED PYRIMIDINE RIBONUCLEOTIDES IN PREBIOTICALLY PLAUSIBLE CONDITIONS," BY MATTHEW W. POWNER, BÉATRICE GERLAND AND JOHN D. SUTHERLAND, IN *NATURE*, VOL. 459; MAY 14, 2009



cules could not have contained ribose. But one of us (Ricardo) and others have discovered ways in which ribose could have been stabilized.

The phosphate part of nucleotides presents another intriguing puzzle. Phosphorus—the central element of the phosphate group—is abundant in the earth's crust but mostly in minerals that do not dissolve readily in water, where life presumably originated. So it is not obvious how phosphates would have gotten into the prebiotic mix. The high temperatures of volcanic vents can convert phosphate-containing minerals to soluble forms of phosphate, but the amounts released, at least near modern volcanoes, are small. A completely different potential source of phosphorus compounds is schreibersite, a mineral commonly found in certain meteors.

In 2005 Matthew Pasek and Dante Lauretta of the University of Arizona discovered that the corrosion of schreibersite in water releases its phosphorus component. This pathway seems promising because it releases phosphorus in a form that is both much more soluble in water than phosphate and much more reactive with organic (carbon-based) compounds.

LAURENT VILLERET

▼ **JOHN SUTHERLAND of the University of Manchester in England and his collaborators solved a long-standing question in prebiotic chemistry this past May by demonstrating that nucleotides can form from spontaneous chemical reactions. He appears below (*second from left*) with members of his lab.**

Some Assembly Required

Given that we have at least an outline of potential pathways leading to the nucleobases, sugars and phosphate, the next logical step would be to properly connect these components. This step, however, is the one that has caused the most intense frustration in prebiotic chemistry research for the past several decades. Simply mixing the three components in water does not lead to the spontaneous formation of a nucleotide—largely because each joining reaction also involves the release of a water molecule, which does not often occur spontaneously in a watery solution. For the needed chemical bonds to form, energy must be supplied, for example, by adding energy-rich compounds that aid in the reaction. Many such compounds may have existed on the early earth. In the laboratory, however, reactions powered by such molecules have proved to be inefficient at best and in most cases completely unsuccessful.

This spring—to the field's great excitement—John Sutherland and his co-workers at the University of Manchester in England announced that they found a much more plausible way that nucleotides could have formed, which also sidesteps the issue of ribose's instability. These creative chemists abandoned the tradition of attempting to make nucleotides by joining a nucleobase, sugar and phosphate. Their approach relies on the same simple starting materials employed previously, such as derivatives of cyanide, acetylene and formaldehyde. But instead of forming nucleobase and ribose separately and then trying to join them, the team mixed the starting ingredients together, along with phosphate. A complex web of reactions—with phosphate acting as a crucial catalyst at several steps along the way—produced a small molecule called 2-aminooxazole, which can be viewed as a fragment of a sugar joined to a piece of a nucleobase [*see box above*].

A crucial feature of this small, stable molecule is that it is very volatile. Perhaps small amounts of 2-aminooxazole formed together with a mix-

ALTERNATIVES TO "RNA FIRST"

PNA FIRST: Peptide nucleic acid is a molecule with nucleobases attached to a proteinlike backbone. Because PNA is simpler and chemically more stable than RNA, some researchers believe it could have been the genetic polymer of the first life-forms on earth.

METABOLISM FIRST: Difficulties in explaining how RNA formed from inanimate matter have led some researchers to theorize that life first appeared as networks of catalysts processing energy.

PANSPERMIA: Because "only" a few hundred million years divide the formation of the earth and the appearance of the first forms of life, some scientists have suggested that the very first organisms on earth may have been visitors from other worlds.

ture of other chemicals in a pond on the early earth; once the water evaporated, the 2-aminooxazole vaporized, only to condense elsewhere, in a purified form. There it would accumulate as a reservoir of material, ready for further chemical reactions that would form a full sugar and nucleobase attached to each other.

Another important and satisfying aspect of this chain of reactions is that some of the early-stage by-products facilitate transformations at later stages in of the process. Elegant as it is, the pathway does not generate exclusively the "correct" nucleotides: in some cases, the sugar and nucleobase are not joined in the proper spatial arrangement. But amazingly, exposure to ultraviolet light—intense solar UV rays hit shallow waters on the early earth—destroys the "incorrect" nucleotides and leaves behind the "correct" ones. The end result is a remarkably clean route to the C and U nucleotides. Of course, we still need a route to G and A, so challenges remain. But the work by Sutherland's team is a major step toward explaining how a molecule as complex as RNA could have formed on the early earth.

Some Warm, Little Vial

Once we have nucleotides, the final step in the formation of an RNA molecule is polymerization: the sugar of one nucleotide forms a chemical bond with the phosphate of the next, so that nucleotides string themselves together into a chain. Once again, in water the bonds do not form spontaneously and instead require some external energy. By adding various chemicals to a solution of chemically reactive versions of the nucleotides, researchers have been able to produce short chains of RNA, two to 40 nucleotides long. In the late 1990s Jim Ferris and his coworkers at the Rensselaer Polytechnic Institute showed that clay minerals enhance the process, producing chains of up to 50 or so nucleotides. (A typical gene today is thousands to millions of nucleotides long.) The minerals' intrinsic ability to bind nucleotides brings reactive molecules close together, thereby facilitating the formation of bonds between them [*see box above*].

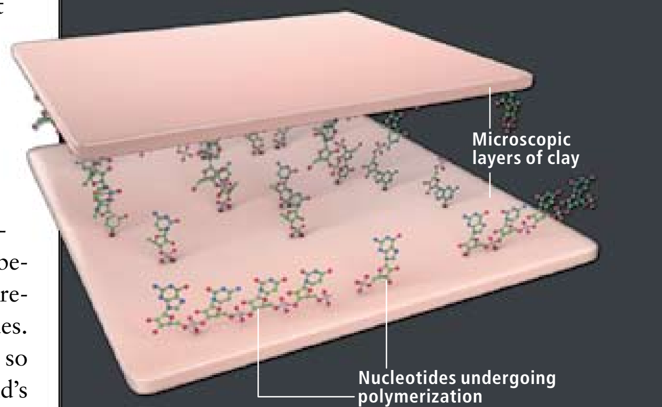
The discovery reinforced the suggestion by some researchers that life may have started on mineral surfaces, perhaps in clay-rich muds at the bottom of pools of water formed by hot springs [see "Life's Rocky Start," by Robert M. Hazen; Scientific American, April 2001].

Certainly finding out how genetic polymers first arose would not by itself solve the problem

[FROM MOLECULES TO ORGANISMS]

ON THE WAY TO LIFE

After chemical reactions created the first genetic building blocks and other organic molecules, geophysical processes brought them to new environments and concentrated them. The chemicals assembled into more complex molecules and then into primitive cells. And some 3.7 billion years ago geophysics may have also nudged these "protocells" to reproduce.



RNA BREEDING GROUNDS

In the water solutions in which they formed, nucleotides would have had little chance of combining into long strands able to store genetic information. But under the right conditions—for example, if molecular adhesion forces brought them close together between microscopic layers of clay (*above*)—nucleotides might link up into single strands similar to modern RNA.

of the origin of life. To be "alive," organisms must be able to go forth and multiply—a process that includes copying genetic information. In modern cells enzymes, which are protein-based, carry out this copying function.

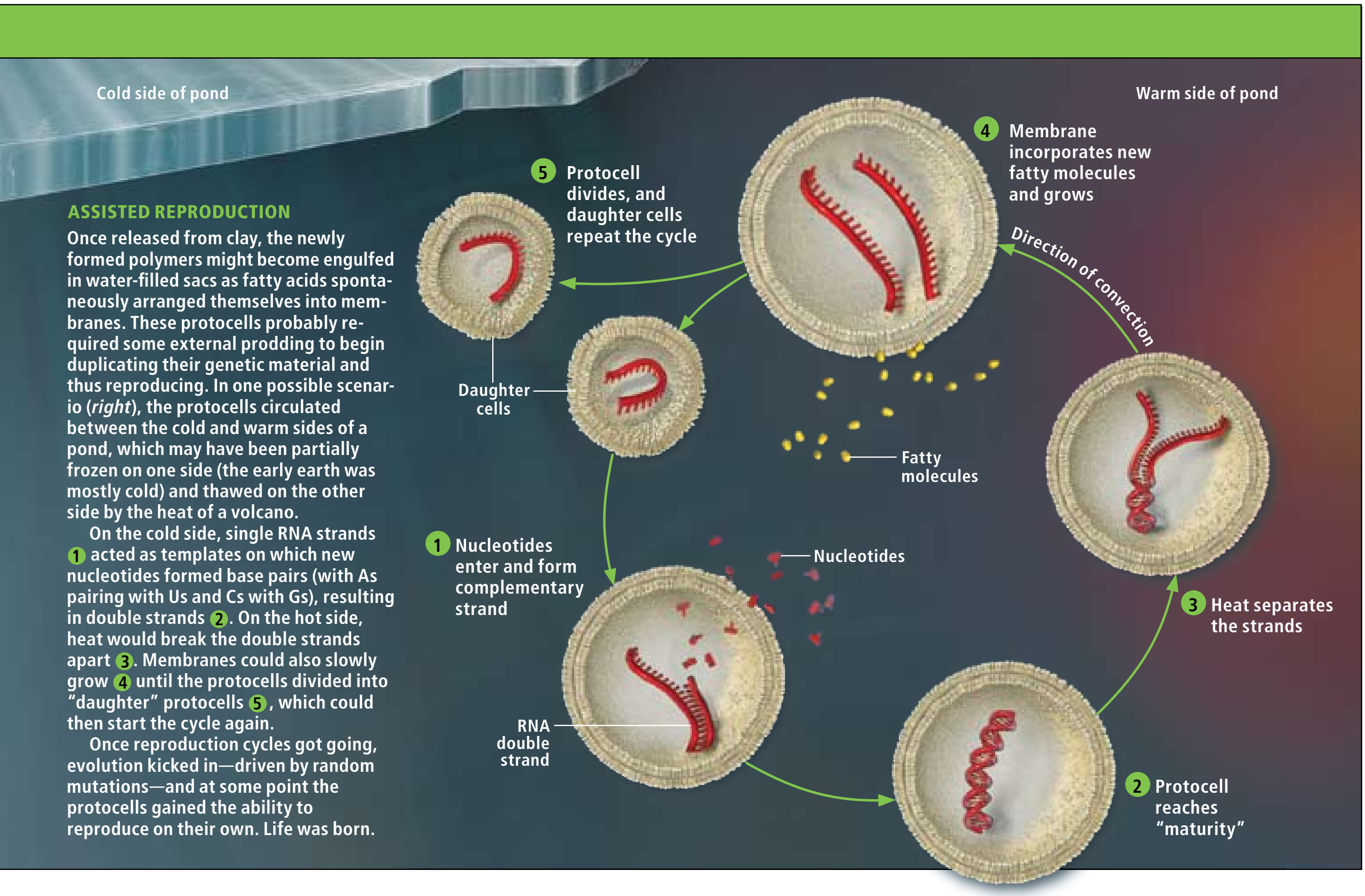
But genetic polymers, if they are made of the right sequences of nucleotides, can fold into complex shapes and can catalyze chemical reactions, just as today's enzymes do. Hence, it seems plausible that RNA in the very first organisms could have directed its own replication. This notion has inspired several experiments, both at our lab and at David Bartel's lab at the Massachusetts Institute of Technology, in which we "evolved" new ribozymes.

We started with trillions of random RNA sequences. Then we selected the ones that had catalytic properties, and we made copies of those. At each round of copying some of the new RNA strands underwent mutations that turned them into more efficient catalysts, and once again we singled those out for the next round of copying. By this directed evolution we were able to produce ribozymes that can catalyze the copying of relatively short strands of other RNAs, although

[THE AUTHORS]

Alonso Ricardo, who was born in Cali, Colombia, is a research associate at the Howard Hughes Medical Institute at Harvard University. He has a long-standing interest in the origin of life and is now studying self-replicating chemical systems. **Jack W. Szostak** is professor of genetics at Harvard Medical School and Massachusetts General Hospital. His interest in the laboratory construction of biological structures as a means of testing our understanding of how biology works dates back to the artificial chromosomes he described in the November 1987 *Scientific American.*

COURTESY OF ALONSO RICARDO (*Ricardo*); COURTESY OF JUSSI PUIKKONEN (*Szostak*); ANDREW SWIFT (*illustration*)



ASSISTED REPRODUCTION
Once released from clay, the newly formed polymers might become engulfed in water-filled sacs as fatty acids spontaneously arranged themselves into membranes. These protocells probably required some external prodding to begin duplicating their genetic material and thus reproducing. In one possible scenario (*right*), the protocells circulated between the cold and warm sides of a pond, which may have been partially frozen on one side (the early earth was mostly cold) and thawed on the other side by the heat of a volcano.

On the cold side, single RNA strands (1) acted as templates on which new nucleotides formed base pairs (with As pairing with Us and Cs with Gs), resulting in double strands (2). On the hot side, heat would break the double strands apart (3). Membranes could also slowly grow (4) until the protocells divided into "daughter" protocells (5), which could then start the cycle again.

Once reproduction cycles got going, evolution kicked in—driven by random mutations—and at some point the protocells gained the ability to reproduce on their own. Life was born.

they fall far short of being able to copy polymers with their own sequences into progeny RNAs.

Recently the principle of RNA self-replication received a boost from Tracey Lincoln and Gerald Joyce of the Scripps Research Institute, who evolved two RNA ribozymes, each of which could make copies of the other by joining together two shorter RNA strands. Unfortunately, success in the experiments required the presence of preexisting RNA pieces that were far too long and complex to have accumulated spontaneously. Still, the results suggest that RNA has the raw catalytic power to catalyze its own replication.

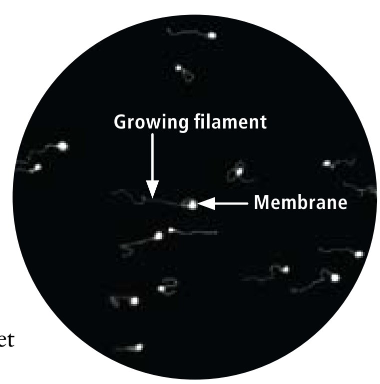
Is there a simpler alternative? We and others are now exploring chemical ways of copying genetic molecules without the aid of catalysts. In recent experiments, we started with single, "template" strands of DNA. (We used DNA because it is cheaper and easier to work with, but we could just as well have used RNA.) We mixed the templates in a solution containing isolated nucleotides to see if nucleotides would bind to the template through complementary base pairing (A joining to T and C to G) and then polymerize, thus forming a full double strand. This would be the first step to full replication: once a double strand had formed, separation of the strands would allow the complement to serve as a template for copying the original strand. With standard DNA or RNA, the process is exceedingly slow. But small changes to the chemical structure of the sugar component—changing one oxygen-hydrogen pair to an amino group (made of nitrogen and hydrogen)—made the polymerization hundreds of times faster, so that complementary strands formed in hours instead of weeks. The new polymer behaved much like classic RNA despite having nitrogen-phosphorus bonds instead of the normal oxygen-phosphorus bonds.

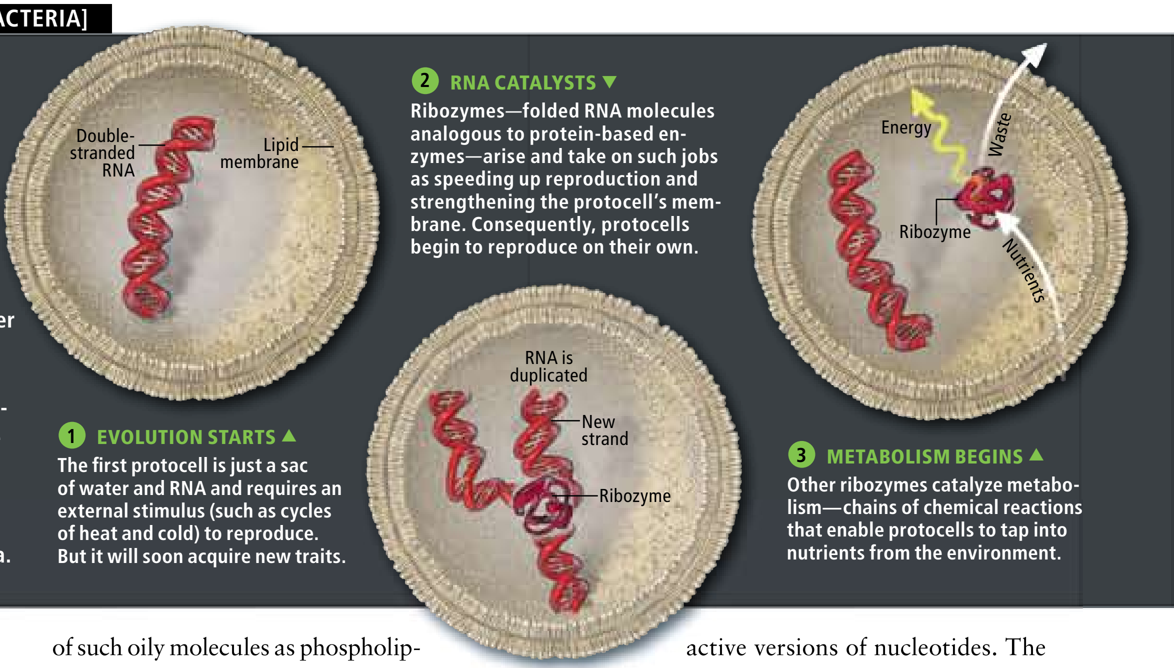
Boundary Issues

If we assume for the moment that the gaps in our understanding of the chemistry of life's origin will someday be filled, we can begin to consider how molecules might have interacted to assemble into the first cell-like structures, or "protocells."

The membranes that envelop all modern cells consist primarily of a lipid bilayer: a double sheet

LIPID MEMBRANES self-assemble from fatty acid molecules dissolved in water. The membranes start out spherical and then grow filaments by absorbing new fatty acids (*micrograph below*). They become long, thin tubes and break up into many smaller spheres. The first protocells may have divided this way.





[FROM RNA WORLD TO BACTERIA]

Journey to the Modern Cell

After life got started, competition among life-forms fueled the drive toward ever more complex organisms. We may never know the exact details of early evolution, but here is a plausible sequence of some of the major events that led from the first protocell to DNA-based cells such as bacteria.

1 EVOLUTION STARTS ▲
The first protocell is just a sac of water and RNA and requires an external stimulus (such as cycles of heat and cold) to reproduce. But it will soon acquire new traits.

2 RNA CATALYSTS ▼
Ribozymes—folded RNA molecules analogous to protein-based enzymes—arise and take on such jobs as speeding up reproduction and strengthening the protocell's membrane. Consequently, protocells begin to reproduce on their own.

3 METABOLISM BEGINS ▲
Other ribozymes catalyze metabolism—chains of chemical reactions that enable protocells to tap into nutrients from the environment.

of such oily molecules as phospholipids and cholesterol. Membranes keep a cell's components physically together and form a barrier to the uncontrolled passage of large molecules. Sophisticated proteins embedded in the membrane act as gatekeepers and pump molecules in and out of the cell, while other proteins assist in the construction and repair of the membrane. How on earth could a rudimentary protocell, lacking protein machinery, carry out these tasks?

Primitive membranes were probably made of simpler molecules, such as fatty acids (which are one component of the more complex phospholipids). Studies in the late 1970s showed that membranes could indeed assemble spontaneously from plain fatty acids, but the general feeling was that these membranes would still pose a formidable barrier to the entry of nucleotides and other complex nutrients into the cell. This notion suggested that cellular metabolism had to develop first, so that cells could synthesize nucleotides for themselves. Work in our lab has shown, however, that molecules as large as nucleotides can in fact easily slip across membranes as long as both nucleotides and membranes are simpler, more "primitive" versions of their modern counterparts.

This finding allowed us to carry out a simple experiment modeling the ability of a protocell to copy its genetic information using environmentally supplied nutrients. We prepared fatty acid–based membrane vesicles containing a short piece of single-stranded DNA. As before, the DNA was meant to serve as a template for a new strand. Next, we exposed these vesicles to chemically reactive versions of nucleotides. The nucleotides crossed the membrane spontaneously and, once inside the model protocell, lined up on the DNA strand and reacted with one another to generate a complementary strand. The experiment supports the idea that the first protocells contained RNA (or something similar to it) and little else and replicated their genetic material without enzymes.

Let There Be Division

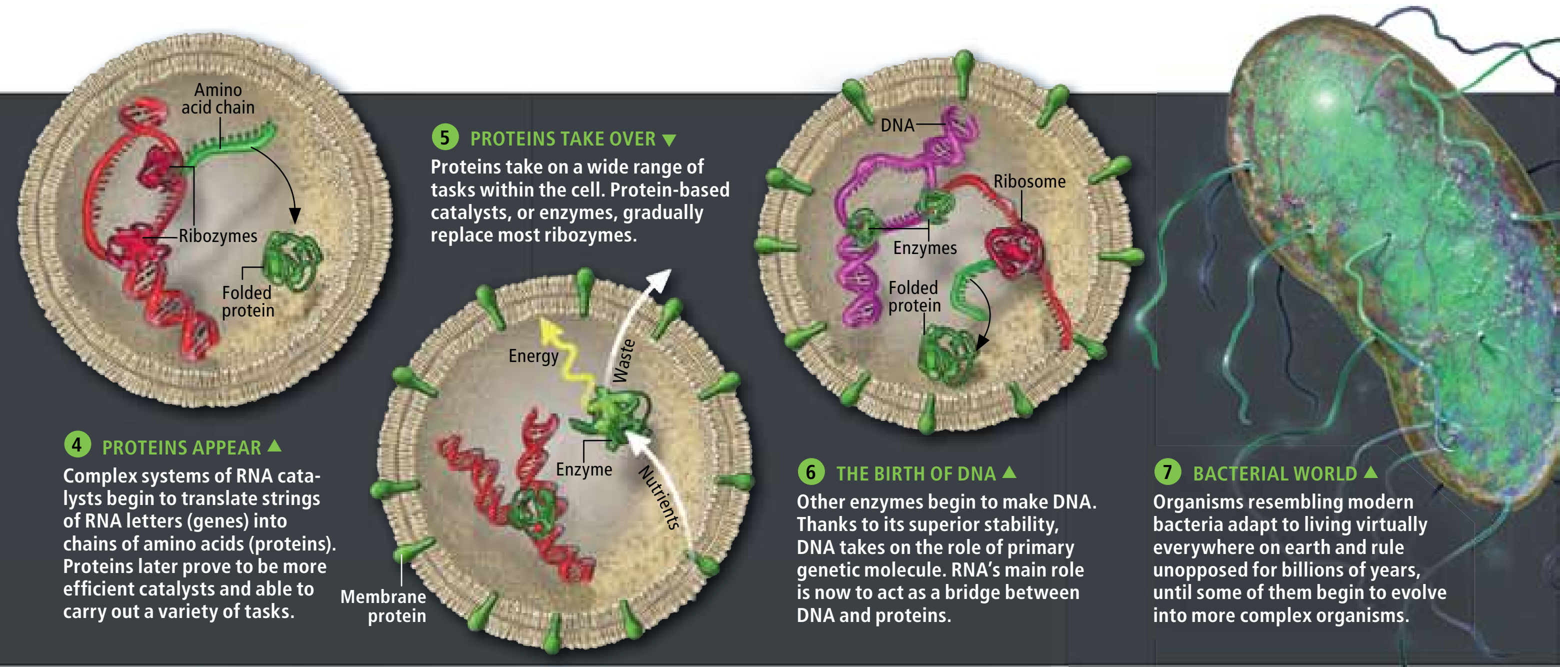
For protocells to start reproducing, they would have had to be able to grow, duplicate their genetic contents and divide into equivalent "daughter" cells. Experiments have shown that primitive vesicles can grow in at least two distinct ways. In pioneering work in the 1990s, Pier Luigi Luisi and his colleagues at the Swiss Federal Institute of Technology in Zurich added fresh fatty acids to the water surrounding such vesicles. In response, the membranes incorporated the fatty acids and grew in surface area. As water and dissolved substances slowly entered the interior, the cell's volume also increased.

A second approach, which was explored in our lab by then graduate student Irene Chen, involved competition between protocells. Model protocells filled with RNA or similar materials became swollen, an osmotic effect resulting from the attempt of water to enter the cell and equalize its concentration inside and outside. The membrane of such swollen vesicles thus came under tension, and this tension drove growth, because adding new molecules relaxes the tension on the membrane, lowering the energy of the system. In fact, swollen vesicles grew

ANDREW SWIFT

LIFE, REDUX

Scientists who study the origin of life hope to build a self-replicating organism from entirely artificial ingredients. The biggest challenge is to find a genetic molecule capable of copying itself autonomously. The authors and their collaborators are designing and synthesizing chemically modified versions of RNA and DNA in the search for this elusive property. RNA itself is probably not the solution: its double strands, unless they are very short, do not easily separate to become ready for replication.



4 PROTEINS APPEAR ▲
Complex systems of RNA catalysts begin to translate strings of RNA letters (genes) into chains of amino acids (proteins). Proteins later prove to be more efficient catalysts and able to carry out a variety of tasks.

5 PROTEINS TAKE OVER ▼
Proteins take on a wide range of tasks within the cell. Protein-based catalysts, or enzymes, gradually replace most ribozymes.

6 THE BIRTH OF DNA ▲
Other enzymes begin to make DNA. Thanks to its superior stability, DNA takes on the role of primary genetic molecule. RNA's main role is now to act as a bridge between DNA and proteins.

7 BACTERIAL WORLD ▲
Organisms resembling modern bacteria adapt to living virtually everywhere on earth and rule unopposed for billions of years, until some of them begin to evolve into more complex organisms.

by stealing fatty acids from relaxed neighboring vesicles, which shrank.

In the past year Ting Zhu, a graduate student in our lab, has observed the growth of model protocells after feeding them fresh fatty acids. To our amazement, the initially spherical vesicles did not grow simply by getting larger. Instead they first extended a thin filament. Over about half an hour, this protruding filament grew longer and thicker, gradually transforming the entire initial vesicle into a long, thin tube. This structure was quite delicate, and gentle shaking (such as might occur as wind generates waves on a pond) caused it to break into a number of smaller, spherical daughter protocells, which then grew larger and repeated the cycle [*see micrograph on page 59*].

Given the right building blocks, then, the formation of protocells does not seem that difficult: membranes self-assemble, genetic polymers self-assemble, and the two components can be brought together in a variety of ways, for example, if the membranes form around preexisting polymers. These sacs of water and RNA will also grow, absorb new molecules, compete for nutrients, and divide. But to become alive, they would also need to reproduce and evolve. In particular, they need to separate their RNA double strands so each single strand can act as a template for a new double strand that can be handed down to a daughter cell.

This process would not have started on its own, but it could have with a little help. Imagine, for example, a volcanic region on the otherwise cold surface of the early earth (at the time, the sun shone at only 70 percent of its current power). There could be pools of cold water, perhaps partly covered by ice but kept liquid by hot rocks. The temperature differences would cause convection currents, so that every now and then protocells in the water would be exposed to a burst of heat as they passed near the hot rocks, but they would almost instantly cool down again as the heated water mixed with the bulk of the cold water. The sudden heating would cause a double helix to separate into single strands. Once back in the cool region, new double strands—copies of the original one—could form as the single strands acted as templates [*see box on page 59*].

As soon as the environment nudged protocells to start reproducing, evolution kicked in. In particular, at some point some of the RNA sequences mutated, becoming ribozymes that sped up the copying of RNA—thus adding a competitive advantage. Eventually ribozymes began to copy RNA without external help.

It is relatively easy to imagine how RNA-based protocells may have then evolved [*see box above*]. Metabolism could have arisen gradually, as new ribozymes enabled cells to synthesize nutrients internally from simpler and more abundant starting materials. Next, the organisms might have added protein making to their bag of chemical tricks.

With their astonishing versatility, proteins would have then taken over RNA's role in assisting genetic copying and metabolism. Later, the organisms would have "learned" to make DNA, gaining the advantage of possessing a more robust carrier of genetic information. At that point, the RNA world became the DNA world, and life as we know it began. ■

➥ MORE TO EXPLORE

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Exploring Life's Origins. Multimedia project at the Museum of Science. http://**exploringorigins.org**

ORIGIN OF COMPUTING

BY MARTIN CAMPBELL-KELLY

The information age began with the realization that machines could emulate the power of minds

In the standard story, the computer's evolution has been brisk and short. It starts with the giant machines warehoused in World War II–era laboratories. Microchips shrink them onto desktops, Moore's Law predicts how powerful they will become, and Microsoft capitalizes on the software. Eventually small, inexpensive devices appear that can trade stocks and beam video around the world. That is one way to approach the history of computing—the history of solid-state electronics in the past 60 years.

But computing existed long before the transistor. Ancient astronomers developed ways to predict the motion of the heavenly bodies. The Greeks deduced the shape and size of Earth. Taxes were summed; distances mapped. Always, though, computing was a human pursuit. It was arithmetic, a skill like reading or writing that helped a person make sense of the world.

The age of computing sprang from the abandonment of this limitation. Adding machines and cash registers came first, but equally critical was the quest to organize mathematical computations using what we now call "programs." The idea of a program first arose in the 1830s, a century before what we traditionally think of as the birth of the computer. Later, the modern electronic computers that came out of World War II gave rise to the notion of the universal computer—a machine capable of any kind of information processing, even including the manipulation of its own programs. These are the computers that power our world today. Yet even as computer technology has matured to the point where it is omnipresent and seemingly limitless, researchers are attempting to use fresh insights from the mind, biological systems and quantum physics to build wholly new types of machines.

The Difference Engine

In 1790, shortly after the start of the French Revolution, Napoleon Bonaparte decided that the republic required a new set of maps to establish a fair system of property taxation. He also ordered a switch

KEY CONCEPTS

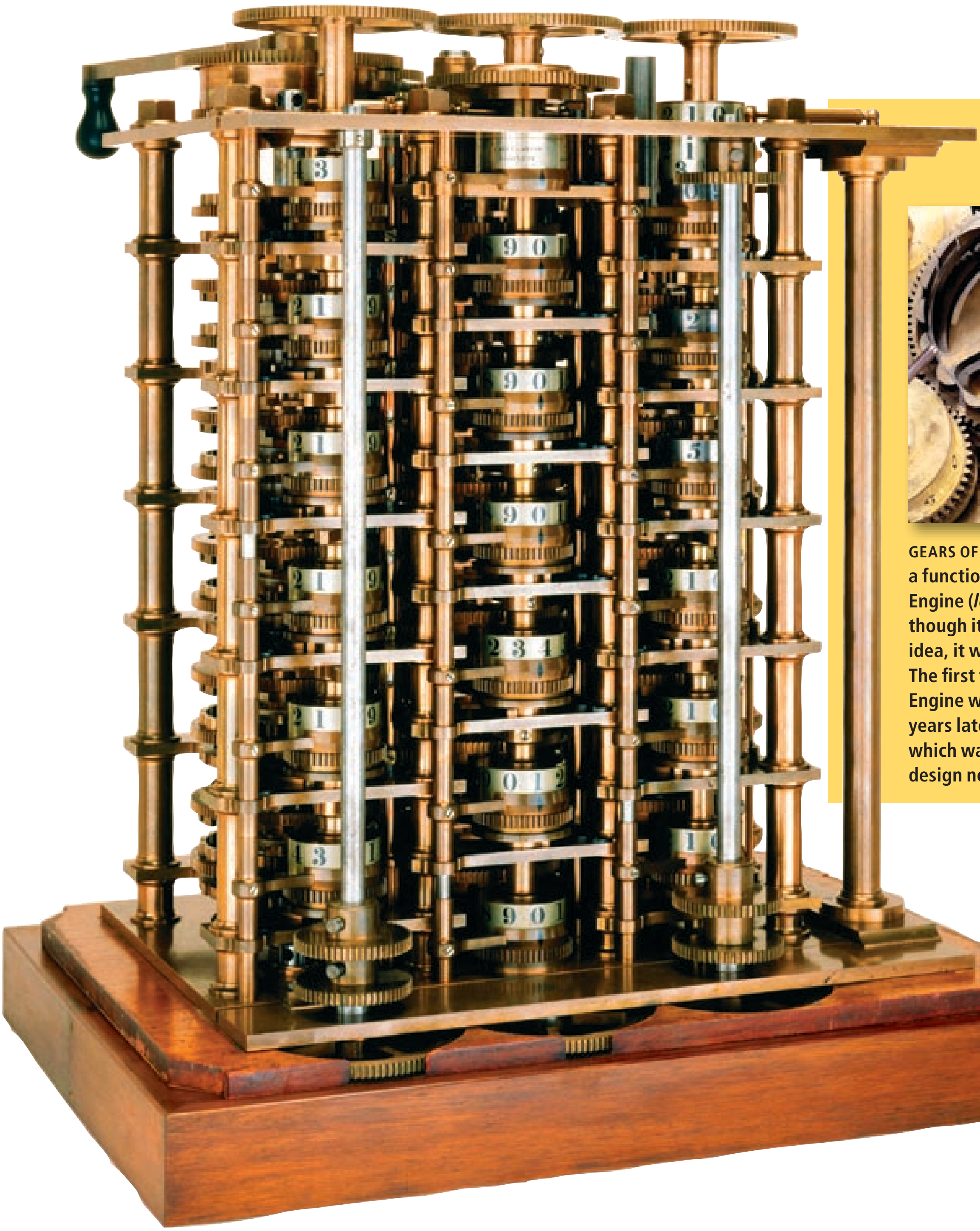
- The first "computers" were people—individuals and teams who would tediously compute sums by hand to fill in artillery tables.
- Inspired by the work of a computing team in revolutionary France, Charles Babbage, a British mathematician, created the first mechanical device that could organize calculations.
- The first modern computers arrived in the 1950s, as researchers created machines that could use the result of their calculations to alter their operating instructions.

HOLLY LINDEM (*photoillustration*); GENE BURKHARDT (*styling*)

from the old imperial system of measurements to the new metric system. To aid the engineers and mathematicians making the change, the French ordinance survey office commissioned a fresh set of mathematical tables.

In the 18th century, however, computations were done by hand. A "factory floor" of between 60 and 80 human computers added and subtracted numbers to fill in line after line of the tables for the survey's *Tables du Cadastre* project. It was grunt work, demanding no special skills above basic numeracy and literacy. In fact, most computers were hairdressers who had lost their jobs—aristocratic hairstyles being the sort of thing that could endanger one's neck in revolutionary France.

The project took about 10 years to complete, but by then the war-torn republic did not have the funds necessary to publish the work. The manuscript languished in the *Académie des Sciences*



The Difference Engine

GEARS OF CHANGE: Charles Babbage produced a functioning prototype of his Difference Engine (*left* and *detail above*) in 1832. Although it demonstrated the feasibilty of his idea, it was too small to be of practical use. The first full version of a working Difference Engine would not be built until 1991, 159 years later, by the London Science Museum, which was guided by Babbage's detailed design notes.

COURTESY OF THE SCIENCE MUSEUM (*Difference Engine*); SCIENCE MUSEUM/SSPL (*inset*) for decades. Then, in 1819, a young British mathematician named Charles Babbage would view it on a visit to Paris. Babbage was 28 at the time; three years earlier he had been elected to the Royal Society, the most prominent scientific organization in Britain. He was also very knowledgeable about the world of human computers—at various times he personally supervised the construction of astronomical and actuarial tables.

On his return to England, Babbage decided he would replicate the French project not with human computers but with machinery. England at the time was in the throes of the Industrial Revolution. Jobs that had been done by human or animal labor were falling to the efficiency of the machine. Babbage saw the power of mechanization and realized that it could replace not just muscle but the work of minds.

He proposed the construction of his Calculating Engine in 1822 and secured government funding in 1824. For the next decade he immersed himself in the world of manufacturing, seeking the best technologies with which to construct his engine.

The year 1832 was Babbage's annus mirabilis. That year he not only produced a functioning model of his calculating machine (which he called the Difference Engine) but also published his classic *Economy of Machinery and Manufactures,* establishing his reputation as the world's leading industrial economist. He held Saturday evening soirees at his home in Dorset Street in London, which were attended by the front rank of society. At these gatherings the model Difference Engine was placed on display as a conversation piece.

A year later Babbage abandoned the Difference Engine for a grander vision that he called the Analytical Engine. Whereas the Difference Engine had been limited to the single task of table making, the Analytical Engine would be capable of any mathematical calculation. Like a modern computer, it would have a processor that performed arithmetic (the "mill"), memory to hold numbers (the "store"), and the ability to alter its function via user input, in this case by punched cards. In short, it was a computer conceived in Victorian technology.

Babbage's decision to abandon the unfinished Difference Engine was not well received, however, and the government demurred to supply him with additional funds. Undeterred, he produced thousands of pages of detailed notes and machine drawings in the hope that the government would one day fund construction. It was not until the 1970s, well into the computer age, that scholars studied these papers for the first time. The Analytical Engine was, as one of those scholars remarked, almost like looking at a computer designed on another planet.

The Dark Ages

Babbage's vision, in essence, was digital computing. Like today's devices, such machines manipulate numbers (or digits) according to a set of instructions and produce a precise numerical result.

Yet after Babbage's failure, computation entered what English mathematician L. J. Comrie called the Dark Age of digital computing—a period that lasted into World War II. During this time, machine computation was done primarily with so-called analog computers. These devices model a system using a mechanical analog. Suppose, for example, one wanted to predict the time of a solar eclipse. To do this digitally, one would numerically solve Kepler's laws of motion. Before digital computers, the only practical way to do this was hand computation by human computers. (From the 1890s to the 1940s the Harvard Observatory employed just such a group of all-female computers.) One could also create an analog computer, a model solar system made of gears and shafts that would "run" time into the future [*see box on next page*].

Before World War II, the most important analog computing instrument was the Differential Analyzer, developed by Vannevar Bush at the Massachusetts Institute of Technology in 1929. At that time, the U.S. was investing heavily in rural electrification, and Bush was investigating electrical transmission. Such problems could be encoded in ordinary differential equations, but these were very time-consuming to solve. The Differential Analyzer allowed for an approximate solution without any numerical processing. The machine was physically quite large—it filled a laboratory—and was something of a Rube Goldberg construction of gears and rotating shafts. To "program" the machine, researchers connected the various components of the device using screwdrivers, spanners and lead hammers. Though laborious to set up, once done the apparatus could solve in minutes equations that would take several days by hand. A dozen copies of the machine were built in the U.S. and England.

One of these copies belonged to the U.S. Army's Aberdeen Proving Ground in Maryland, the facility responsible for readying field weap-

TEAMWORK

The Harvard Observatory's human computers, seen here circa 1890, examined hundreds of thousands of photographic plates between the 1880s and the 1920s, classifying stars based on color, position and brightness.

[THE AUTHOR]

Martin Campbell-Kelly is a professor in the department of computer science at the University of Warwick in England, where he specializes in the history of computing. He is author of *Computer: A History of the Information Machine* (along with William Aspray) and of *From Airline Reservations to Sonic the Hedgehog: A History of the Software Industry*. He is editor of *The Works of Charles Babbage*.

COURTESY OF CURATOR OF ASTRONOMICAL PHOTOGRAPHS AT HARVARD COLLEGE OBSERVATORY (*human computers*); COURTESY OF MARTIN CAMPBELL-KELLY (*author*) ons for deployment. To aim artillery at a target of known range, soldiers had to set the vertical and horizontal angles (the elevation and azimuth) of the barrel so that the fired shell would follow the desired parabolic trajectory—soaring skyward before dropping onto the target. They selected the angles out of a firing table that contained numerous entries for various target distances and operational conditions.

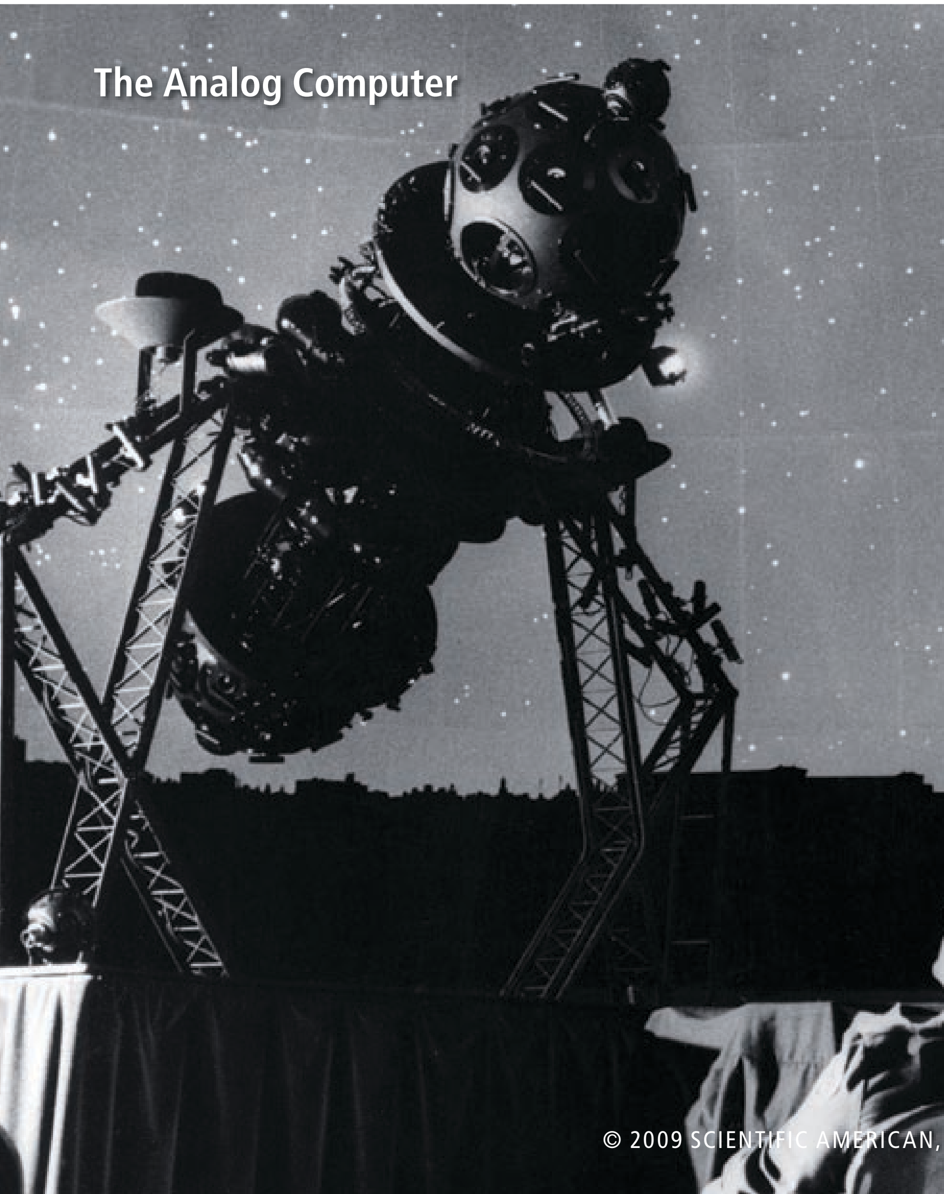
Every entry in the firing table required the integration of an ordinary differential equation. A human computer would take two to three days to do each calculation by hand. The Differential Analyzer, in contrast, would need only about 20 minutes.

Everything Is Change

On December 7, 1941, Japanese forces attacked the U.S. Navy base at Pearl Harbor. The U.S. was at war. Mobilization meant the army needed ever more firing tables, each of which contained about 3,000 entries. Even with the Differential Analyzer, the backlog of calculations at Aberdeen was mounting.

Eighty miles up the road from Aberdeen, the Moore School of Electrical Engineering at the University of Pennsylvania had its own differential analyzer. In the spring of 1942 a 35-year-old instructor at the school named John W. Mauchly had an idea for how to speed up calculations: construct an "electronic computor" [sic] that would use vacuum tubes in place of the mechanical components. Mauchly, a theoretically-minded individual, found his complement in an energetic young researcher at the school named J. Presper ("Pres") Eckert, who had already shown sparks of engineering genius.

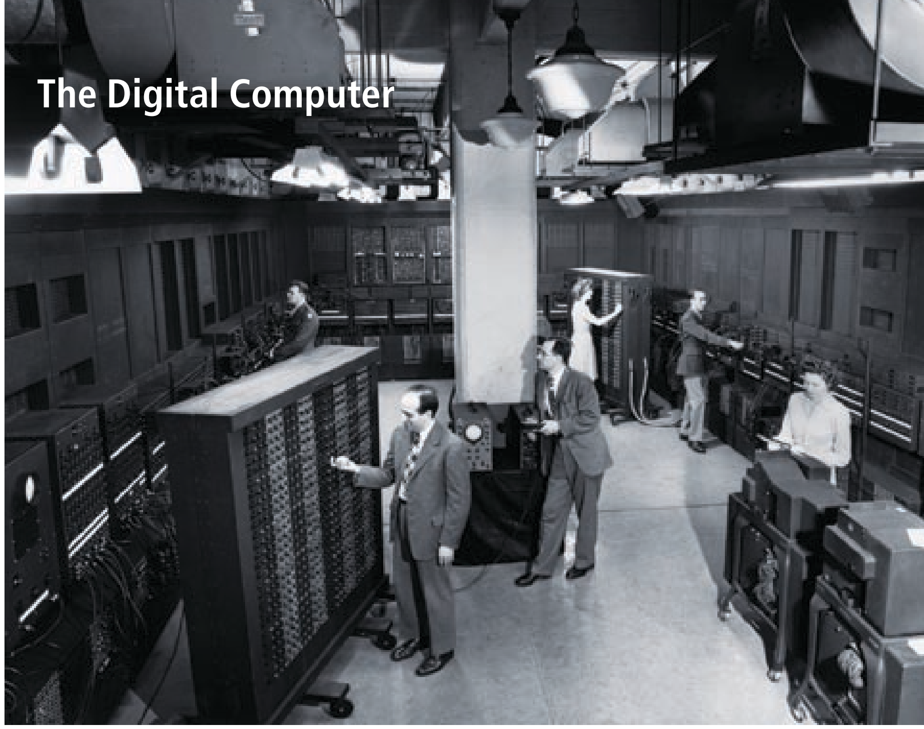
The Analog Computer



SEEING STARS: An example of the analog computer is the planetarium projector, which is designed to produce a physical analog of the motion of the stars and planets. The Adler Planetarium in Chicago installed the first American example in 1930 (*left*). Although the projectors are not accurate enough for practical computing, the planetarium still thrives. The latest projectors can be seen at New York City's Hayden Planetarium (*above*).

COURTESY OF THE ADLER PLANETARIUM (*Zeiss projector*);
COURTESY OF D. FINNIN *American Museum of Natural History* (*inset*)

The Digital Computer



POWER ON: Computing entered the electronic age with the ENIAC, invented by J. Presper Eckert and John W. Mauchly of the Moore School of Electrical Engineering at the University of Pennsylvania. The ENIAC used vacuum tubes to hold numbers in storage and consumed 150 kilowatts of power, equivalent to more than 1,000 modern PCs.

BETTMANN/CORBIS

A year after Mauchly made his original proposal, following various accidental and bureaucratic delays, it found its way to Lieutenant Herman Goldstine, a 30-year-old Ph.D. in mathematics from the University of Chicago who was the technical liaison officer between Aberdeen and the Moore School. Within days Goldstine got the go-ahead for the project. Construction of the ENIAC—for Electronic Numerical Integrator and Computer—began on April 9, 1943. It was Eckert's 23rd birthday.

Many engineers had serious doubts about whether the ENIAC would ever be successful. Conventional wisdom held that the life of a vacuum tube was about 3,000 hours, and the ENIAC's initial design called for 5,000 tubes. At that failure rate, the machine would not function for more than a few minutes before a broken tube put it out of action. Eckert, however, understood that the tubes tended to fail under the stress of being turned on or off. He knew it was for that reason radio stations never turned off their transmission tubes. If tubes were operated significantly below their rated voltage, they would last longer still. (The total number of tubes would grow to 18,000 by the time the machine was complete.)

Eckert and his team completed the ENIAC in two and a half years. The finished machine was an engineering tour de force, a 30-ton behemoth that consumed 150 kilowatts of power. The machine could perform 5,000 additions per second and compute a trajectory in less time than a shell took to reach its target. It was also a prime example of the role that serendipity often plays in invention: although the Moore School was not then a leading computing research facility, it happened to be in the right location at the right time with the right people.

Yet the ENIAC was finished in 1945, too late to help in the war effort. It was also limited in its capabilities. It could store only up to 20 numbers at a time. Programming the machine took days and required manipulating a patchwork of cables that resembled the inside of a busy telephone exchange. Moreover, the ENIAC was designed to solve ordinary differential equations. Some challenges—notably, the calculations required for the Manhattan Project—required the solution of partial differential equations.

John von Neumann was a consultant to the Manhattan Project when he learned of the ENIAC on a visit to Aberdeen in the summer of 1944. Born in 1903 into a wealthy Hungarian banking family, von Neumann was a mathematical prodigy who tore through his education. By 23 he had become the youngest ever privatdozent (the approximate equivalent of an associate professor) at the University of Berlin. In 1930 he emigrated to the U.S., where he joined Albert Einstein and Kurt Gödel as one of first faculty members of the Institute for Advanced Study in Princeton, N.J. He became a naturalized U.S. citizen in 1937.

Von Neumann quickly recognized the power of electronic computation, and in the several months after his visit to Aberdeen, he joined in meetings with Eckert, Mauchly, Goldstine and Arthur Burks—another Moore School instructor—to hammer out the design of a successor machine, the Electronic Discrete Variable Automatic Computer, or EDVAC.

The EDVAC was a huge improvement over the ENIAC. Von Neumann introduced the ideas and nomenclature of Warren McCullough and Walter Pitts, neuroscientists who had developed a theory of the logical operations of the brain (this is where we get the term computer "memory"). Like von Neumann, McCullough and Pitts had been influenced by theoretical studies in the late 1930s by British mathematician Alan Turing, who established that a simple machine can be used to execute a huge variety of complex tasks. There was a collective shift in perception around this time from the computer as a mathematical instrument to a universal information-processing machine.

Von Neumann thought of the machine as having five core parts: *Memory* held not just numerical data but also the instructions for operation. An *arithmetic unit* performed calculations. An *input* "organ" enabled the transfer of

The Analytical Engine was almost like looking at a computer designed on another planet.

THE FUTURE OF COMPUTER ARCHITECTURE

The stored-program computer has formed the basis of computing technology since the 1950s. What may come next?

QUANTUM: The much touted quantum computer exploits the ability of a particle to be in many states at once. Quantum computations operate on all these states simultaneously.

NEURAL NET: These systems are formed from many simple processing nodes that connect to one another in unique ways. The system as a whole exhibits complex global behavior.

LIVING: Computers based on strands of DNA or RNA process data encoded in genetic material.

programs and data into memory, and an *output* organ recorded the results of computation. Finally, a *control unit* coordinated operations.

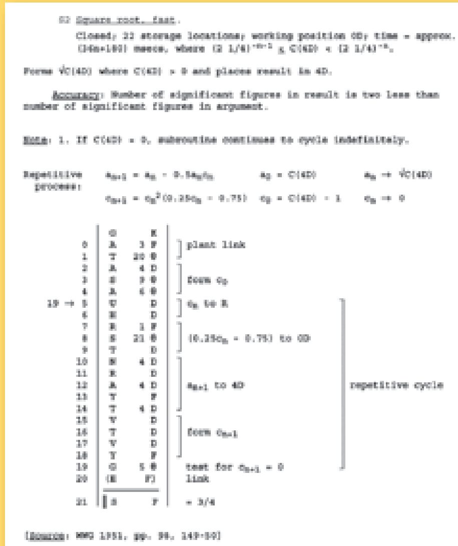
This layout, or architecture, makes it possible to change the computer's program without altering the physical structure of the machine. Moreover, a program could manipulate its own instructions. This feature would not only enable von Neumann to solve his partial differential equations, it would confer a powerful flexibility that forms the very heart of computer science.

In June 1945 von Neumann wrote his classic *First Draft of a Report on the EDVAC* on behalf of the group. In spite of its unfinished status, it was rapidly circulated among the computing cognoscenti with two consequences. First, there never was a second draft. Second, von Neumann ended up with most of the credit.

Machine Evolution

The subsequent 60-year diffusion of the computer within society is a long story that has to be told in another place. Perhaps the single most remarkable development was that the computer—originally designed for mathematical calculations—turned out to be infinitely adaptable to different uses, from business data processing to personal computing to the construction of a global information network.

We can think of computer development as



S2 Square root, fast.

Closed; 22 storage locations; working position 0D; time = approx.

Forms √C(4D) where C(4D) ≥ 0 and places result in 4D.

Accuracy: Number of significant figures in result is two less than number of significant figures in argument.

Note: 1. If C(4D) = 0, subroutine continues to cycle indefinitely.

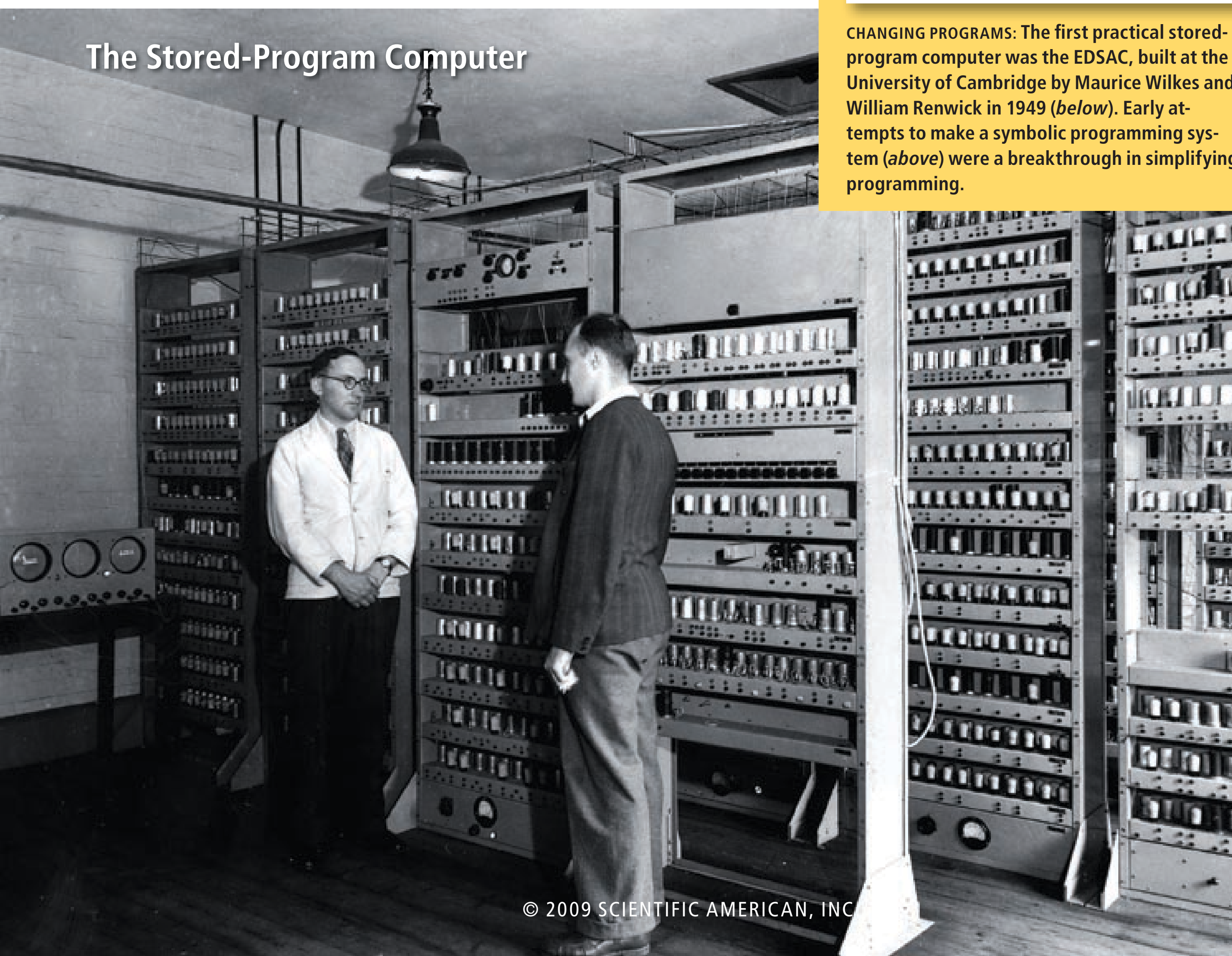
Repetitive process:

```
         |  G       K  |
     0   |  A     3 F  | plant link
     1   |  T    20 θ  |
     2   |  A     4 D  |
     3   |  S     9 θ  | form c0
     4   |  A     6 θ  |
19 → 5   |  U       D  | cn to R
     6   |  H       D  |
     7   |  R     1 F  |
     8   |  S    21 θ  | (0.25cn - 0.75) to 0D
     9   |  T       D  |
    10   |  N     4 D  |
    11   |  R       D  |
    12   |  A     4 D  | an+1 to 4D                 repetitive cycle
    13   |  T       F  |
    14   |  T     4 D  |
    15   |  V       D  |
    16   |  T       D  | form cn+1
    17   |  V       D  |
    18   |  T       F  |
    19   |  G     5 θ  | test for cn+1 = 0
    20   | (E       F) | link
    21   |  S       F  | = 3/4
```

[Source: WWG 1951, pp. 98, 149-50]

CHANGING PROGRAMS: **The first practical stored-program computer was the EDSAC, built at the University of Cambridge by Maurice Wilkes and William Renwick in 1949 (*below*). Early attempts to make a symbolic programming system (*above*) were a breakthrough in simplifying programming.**

The Stored-Program Computer



POPPERFOTO/GETTY IMAGES (*EDSAC*); SOURCE: "THE EDSAC SIMULATOR PROGRAM DOCUMENTATION," BY THE DEPARTMENT OF COMPUTER SCIENCE, UNIVERSITY OF WARWICK (*inset*)

having taken place along three vectors—hardware, software and architecture. The improvements in hardware over the past 60 years are legendary. Bulky electronic tubes gave way in the late 1950s to "discrete" transistors—that is, single transistors individually soldered into place. In the mid-1960s microcircuits contained several transistors—then hundreds of transistors, then thousands of transistors—on a silicon "chip." The microprocessor, developed in the early 1970s, held a complete computer processing unit on a chip. The microprocessor gave rise to the PC and now controls devices ranging from sprinkler systems to ballistic missiles.

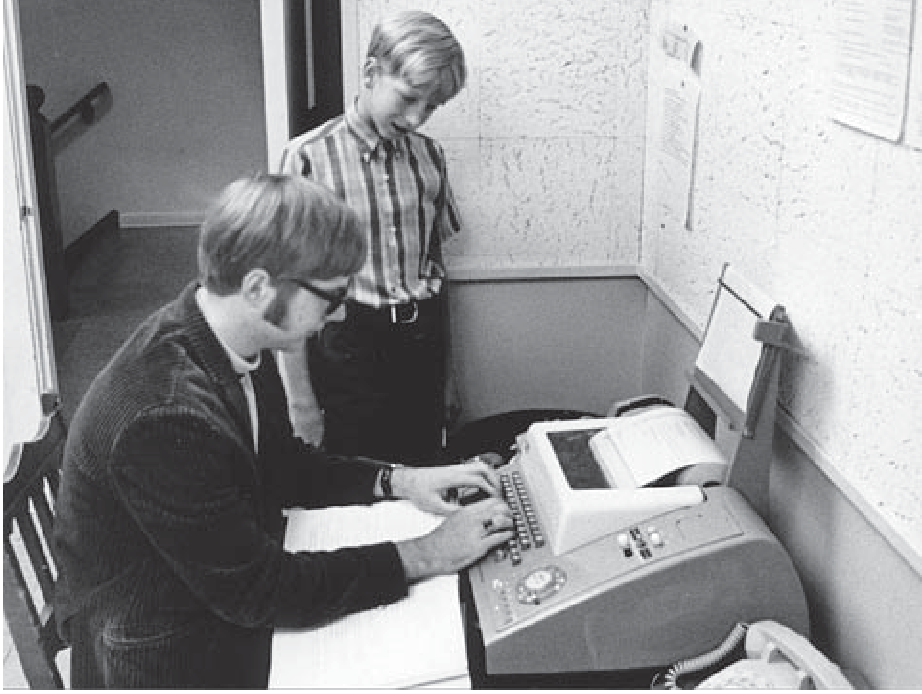
The challenges of software were more subtle. In 1947 and 1948 von Neumann and Goldstine produced a series of reports called *Planning and Coding Problems for an Electronic Computing Instrument*. In these reports they set down dozens of routines for mathematical computation with the expectation that some lowly "coder" would be able to convert them into working programs. It was not to be. The process of writing programs and getting them to work was excruciatingly difficult. The first to make this discovery was Maurice Wilkes, the University of Cambridge computer scientist who had created EDSAC, the first practical stored-program computer [*see box on opposite page*]. In his *Memoirs,* Wilkes ruefully recalled the moment in 1949 when "the realization came over me with full force that a good part of the remainder of my life was going to be spent in finding errors in my own programs."

He and others at Cambridge developed a method of writing computer instructions in a symbolic form that made the whole job easier and less error prone. The computer would take this symbolic language and then convert it into binary. IBM introduced the programming language Fortran in 1957, which greatly simplified the writing of scientific and mathematical programs. At Dartmouth College in 1964, educator John G. Kemeny and computer scientist Thomas E. Kurtz invented Basic, a simple but mighty programming language intended to democratize computing and bring it to the entire undergraduate population. With Basic even schoolkids—the young Bill Gates among them—could begin to write their own programs.

In contrast, computer architecture—that is, the logical arrangement of subsystems that make up a computer—has barely evolved. Nearly every machine in use today shares its basic architecture with the stored-program computer of 1945. The situation mirrors that of the gasoline-powered automobile—the years have seen many technical refinements and efficiency improvements in both, but the basic design is largely the same. And although it might be possible to design a radically better device, both have achieved what historians of technology call "closure." Investments over the decades have produced such excellent gains that no one has had a compelling reason to invest in an alternative [see "Internal-Combustion Engine," on page 97].

Yet there are multiple possibilities for radical evolution. In the 1980s interest ran high in so-called massively parallel machines, which contained thousands of computing elements operating simultaneously. This basic architecture is still used for computationally intensive tasks such as weather forecasting and atomic weapons research. Computer scientists have also looked to the human brain for inspiration. We now know that the brain contains specialized processing centers for different tasks, such as face recognition or speech understanding. Scientists are harnessing some of these ideas in "neural networks" for applications such as license plate identification and iris recognition.

More blue sky research is focused on building computers from living matter such as DNA [see "Bringing DNA Computers to Life," by Ehud Shapiro and Yaakov Benenson; Scientific American, May 2006] and computers that harness the weirdness of the quantum world [see "The Limits of Quantum Computers," by Scott Aaronson; Scientific American, March 2008]. No one knows what the computers of 50 years hence will look like. Perhaps their abilities will surpass even the powers of the minds that created them. ■



COURTESY OF THE LAKESIDE SCHOOL

CHILD'S PLAY: Simple programming languages such as Basic allowed the power of programming to spread to the masses. A young Paul Allen (*seated*) and his friend Bill Gates worked on a Teletype terminal attached by a phone line to a mainframe computer that filled a room.

➥ MORE TO EXPLORE

The Difference Engine: Charles Babbage and the Quest to Build the First Computer. Doron Swade. Penguin, 2002.

Computer: A History of the Information Machine. Martin Campbell-Kelly and William Aspray. Westview Press, 2004.

The Modern History of Computing. Stanford Encyclopedia of Philosophy. **http://plato.stanford.edu/entries/computing-history**

THE START OF EVERYTHING

Where do rainbows come from, Daddy? What about flying cars—and LSD? In the beginning, there was always the toddler's query, which led to the schoolchild's raised hand and, still later, the engineer's back-of-the envelope sketch of a new invention.

Everything started somewhere—and someone had to ask. Think of what you are about to read as a collection of queries rooted in childlike curiosity about the world around us and the still larger universe that stretches beyond.

After exploring the big questions in the articles that precede this section—the origins of the universe and the beginnings of life itself—we now turn to everything else. The origins of external ears, Scotch tape, the ethereal evolution of love and even artificial hearts are revealed in the pages that follow.

Of course, many of you were wondering what came before the big bang. But others ponder an even more urgent question. Read on, and you may find out who or what prevailed in the contest between the chicken and the ovum. *—The Editors*

PHILIP AND KAREN SMITH *Getty Images*

RAINBOWS

The simple magic of their shape and colors still puzzles

English poet John Keats famously worried that scientific explanations would "unweave a rainbow"—that by elucidating rainbows and other phenomena rationally, scientists would drain the world of its mystery. Yet if anything, the close study of rainbows enriches our appreciation of them. The multicolored arc is just the beginning. Look closely, and you will see that outside the main bow is a darkened band of sky and a second, dimmer arc, with its colors in reverse order. Inside the main bow are greenish and purplish arcs known as supernumerary bows. The rainbow can vary in brightness along its width or length, and it can split into multiple bows near the top. Viewed through polarizing sunglasses, the rainbow waxes and wanes as you tilt your head.

The basic scientific explanation for rainbows dates to Persian physicist Kamāi al-Dīn al-Fārisī and, independently, German physicist Theodoric of Freiberg in the 14th century. But scientists continued to work on the theory into the 1970s and beyond [see "The Theory of the Rainbow," by H. Moysés Nussenzveig; SCIENTIFIC AMERICAN, April 1977]. Many textbook explanations of rainbows are wrong, and a thorough description is still elusive. "The rainbow has the undeserved reputation of having a simple explanation," says atmospheric physicist Craig Bohren of Pennsylvania State University.

The central principle is that each water droplet in the air acts as a mirror, lens and prism, all in one. Droplets scatter sunlight in every direction but do so unevenly, tending to focus light 138 degrees from the incident direction. Those droplets that form this angle with the sun look brighter; together they produce a ring. Typically you see only the top half of this ring because there are not enough drops near the ground to fill out the bottom half. "The rainbow is just a distorted image of the sun," write atmospheric scientists Raymond Lee, Jr., and Alistair Fraser in their definitive book *The Rainbow Bridge.*

The angle of 138 degrees means you see the rainbow when standing with your back to the sun. The lensing angle varies slightly with wavelength, separating the white sunlight into colored bands. Multiple reflections within droplets create the outer bows; wave interference accounts for the supernumerary arcs; flattening of the droplets causes brightness variations along the arc; multiple droplet sizes produce split bows; and light is polarized much like the glare on any watery surface.

Even this physics does not touch on how our eyes and brains perceive the continuous spectrum as discrete colors. The weaving of the rainbow occurs in our heads as much as it does in the sky. *—George Musser*

FLYING CAR

A long-standing dream

If only my car could fly! Who has not uttered this cry in traffic? But what motivated the people who began designing flying cars near the turn of the 20th century?

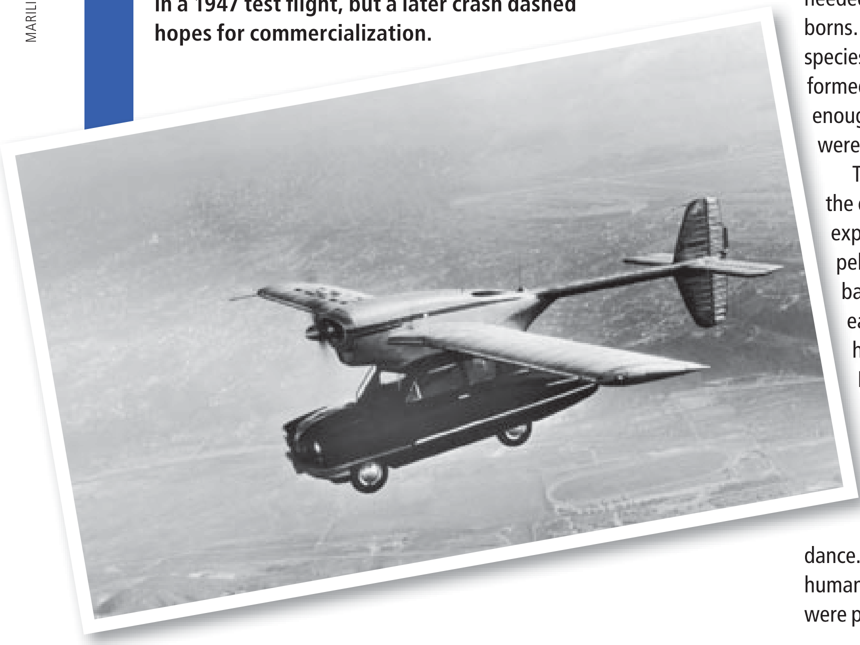
Most aviation pioneers of the time were thinking not in terms of flight alone but of "personal mobility" and getting cars to take wing, according to John Brown, editor of the Internet magazine *Roadable Times.* In fact, he notes, "the true brilliance" of the Wright Brothers—who demonstrated sustained, controlled powered flight at Kitty Hawk, N.C., in 1903—was their decision to concentrate solely on flying and "forget about the roadability part."

Of course, over time, additional reasons for pursuing flying cars came into play. Near the end of World War I, for instance, a Chicagoan named Felix Longobardi had military flexibility in mind. In his patent application, submitted in June 1918, he detailed a contraption that was a flying car as well as a gunboat—"for anti-air-craft purposes"—and a submarine. (It saw neither light of day nor eye of fish.)

Even before World War I ended, Glenn H. Curtiss, the legendary aircraft designer, submitted a patent for an "autoplane" that he intended to be a "pleasure craft." And Moulton B. Taylor, whose Aerocar was famously used by actor Robert Cummings, wrote in his 1952 patent application that he wanted his invention to be suitable "for air or highway travel, and inexpensive enough to appeal to a potentially large market."

To date, dozens of patents for flying cars have been issued, and more than 10, including a successor to the Aerocar, are under serious development. One developer, Terrafugia in Woburn, Mass., is perfecting (and taking $10,000 deposits for) the Transition, a light sport plane that is not meant for everyday driving. After landing at an airport, though, pilots should be able to fold the wings electronically and just drive the rest of the way to their destination. Test flights in March went well, but whether the company will take off as hoped remains to be seen. —*Ricki Rusting*

ConVairCar, Model 118, designed by Theodore P. Hall, did well in a 1947 test flight, but a later crash dashed hopes for commercialization.



MARILI FORASTIERI *Getty Images (clasped hands)*; GETTY IMAGES *(flying car)*

LOVE

Large brains may have led to the evolution of amour

For most creatures, procreation is an emotionally uncomplicated affair. In humans, however, it has a tricky accomplice: romantic love, capable of catapulting us to bliss or consigning us to utmost despair. Yet capricious though it may seem, love is likely to be an adaptive trait, one that arose early in the evolution of our lineage.

Two of the hallmarks of human evolution—upright walking and large brains—may have favored the emergence of love, according to a theory advanced by anthropologist Helen Fisher of Rutgers University. Bipedalism meant that mothers had to carry their babies, rather than letting them ride on their back. Their hands thus occupied, these moms needed a partner to help provision and protect them and their newborns. Ancient bipedal hominids such as *Australopithecus afarensis,* the species to which the 3.2-million-year-old Lucy fossil belongs, probably formed only short-term pair bonds of a few years, however—just long enough for the babies to be weaned and walking, after which females were ready to mate anew.

The advent of large brains more than a million years ago extended the duration of these monogamous relationships. As brain size expanded, humans had to make an evolutionary trade-off. Our pelvis, built for bipedalism, places a constraint on the size of a baby's head at birth. As a result, human babies are born at an earlier stage of development than are other primate infants and have an extended childhood during which they grow and learn. Human ancestors would thus have benefited from forming longer-term pair bonds for the purpose of rearing young.

Fisher further notes that the ballooning of the hominid brain (and the novel organizational features that accompanied this growth) also provided our forerunners with an extraordinary means of wooing one another—through poetry, music, art and dance. The archaeological record indicates that by 35,000 years ago, humans were engaging in these sorts of behaviors. Which is to say, they were probably just as lovesick as we are. —*Kate Wong*

ORIGINS

DIGITAL AUDIO PLAYER

Mobile music rocked the record industry

Sony's Walkman portable audio cassette player in 1979 improved on the transistor radio by allowing people to take their preferred music wherever they went (engineer Nobutoshi Kihara supposedly invented the device so that Sony co-chairman Akio Morita could listen to operas during long flights). But the digital revolution in personal audio technology was another two decades in the making and had implications beyond both the personal and audio.

Portable music went digital in the 1980s with the rise of devices built around CDs, mini discs and digital audiotape. In the 1990s the Moving Picture Experts Group (MPEG) developed a standard that became the MP3, a format that highly condenses audio files by discarding imperceptible sounds (although discriminating audiophiles tend to disagree with that description).

The Eiger Labs MPMan F10, which hit the market in 1998, was the first MP3 player to store music on digital flash memory—a whopping 32 megabytes, enough for about half an hour of audio. A slew of similar gadgets followed, some of which replaced the flash memory with compact hard drives capable of holding thousands of songs. The breakthrough product was Apple's 2001 iPod. Technologically, it was nothing new, but the combination of its physical sleekness, its spacious five-gigabyte hard drive and its thumbwheel-based interface proved compelling. Today digital players are as likely to hold photographs, videos and games as music, and they are increasingly often bundled into mobile phones and other devices.

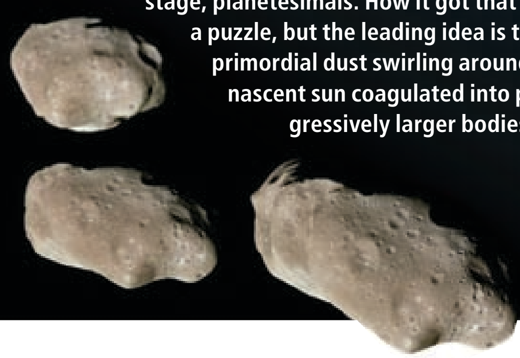
MP3s—immaterial and easily copied—freed music from the physical grooves in vinyl or plastic media. They also dealt a severe blow to the recording industry, which long resisted selling MP3s, prompting music lovers to distribute files on their own. Since 2000, CD sales plummeted from $13 billion to $5 billion, according to the Recording Industry Association of America. Meanwhile digital downloads rose from $138 million in 2004 to $1 billion last year; however, says Russ Crupnick, a senior industry analyst at NPD Entertainment, peer-to-peer shared files outnumber legal downloads by at least 10 to one. Looking ahead, he believes music will not be something to possess at all: the industry's salvation (if any) may come from paid access to songs streaming from the Web. —*Christie Nicholson*

ASTEROIDS

The small fry of the solar system have troubled pasts

For many people, asteroids are big rocks that drift menacingly through space and are great places to have a laser cannon dogfight. Conventional scientific wisdom holds that they are the leftover scraps of planet formation. Their full story, though, is rather more complex and still only dimly glimpsed. What planetary scientists lump together as asteroids are far too diverse—from boulders to floating heaps of gravel to mini planets with signs of past volcanic activity and even liquid water—to have a single common origin.

Only the largest, more than about 100 kilometers across, date to the dawn of our solar system 4.6 billion years ago. Back then, the system was basically one big swarm of asteroids or, as researchers call them at this early stage, planetesimals. How it got that way is a puzzle, but the leading idea is that primordial dust swirling around the nascent sun coagulated into progressively larger bodies.



Some of those bodies then agglomerated into planets; some, accelerated by the gravity of larger bodies, were flung into deep space; some fell into the sun; and a tiny few did none of the above. Those survivors linger in pockets where the planets have left them alone, notably the gap between the orbits of Mars and Jupiter. Gradually they, too, are being picked off. Fewer than one in 1,000, and perhaps as few as one in a million, of the asteroids originally in the main belt remain.

Smaller asteroids are not relics but debris. They come in an assortment of sizes that indicate they are products of a chain reaction of collisions: asteroids hit and shatter, the fragments hit and shatter, and so on. Some are rocky; some are metal—suggesting they came from different layers within the original bodies. About a third of asteroids belong to families with similar orbits, which can be rewound in time to a single point in space, namely, the location of the collision that birthed them. Because families should disperse after 10 million to 100 million years, asteroid formation by collision must be an ongoing process.

Indeed, so is planet formation. Whenever an asteroid hits a planet, it helps to bulk it up. Asteroids are not the leftovers of planet formation so much as they are the finishing touches. —*George Musser*

COURTESY OF APPLE, INC. (*iPod*); PHOTO RESEARCHERS, INC. (*asteroids*)

BATTERIES

Their inventor may not have known how they actually work

A battery's power comes from the tendency of electric charge to migrate between different substances. It is the power that Italian scientist Alessandro Volta sought to tap into when he built the first battery at the end of 1799.

Although different designs exist, the basic structure has remained the same ever since. Every battery has two electrodes. One, the anode, wants to give electrons (which carry a negative electric charge) to the other, the cathode. Connect the two through a circuit, and electrons will flow and carry out work—say, lighting a bulb or brushing your teeth.

Simply shifting electrons from one material to another, however, would not take you very far: like charges repel, and only so many electrons can accumulate on the cathode before they start to keep more electrons from joining. To keep the juice going, a battery balances the charges within its innards by moving positively charged ions from the anode to the cathode through an electrolyte, which can be solid, liquid or gelatinous. It is the electrolyte that makes the battery work, because it allows ions to flow but not electrons, whereas the external circuit allows electrons to flow but not ions.

For example, a charged lithium-ion battery—the type that powers cell phones and laptop computers—has a graphite anode stuffed with lithium atoms and a cathode made of some lithium-based substance. During operation, the anode's lithium atoms release electrons into the external circuit, where they reach the more electron-thirsty cathode. The lithium atoms stripped of their electrons thus become positively charged ions and are attracted toward the electrons accumulating in the cathode. They can do so by flowing through the electrolyte. The ions' motion restores the imbalance of charges and allows the flow of electricity to continue—at least until the anode runs out of lithium.

Recharging the battery reverses the process: a voltage applied between the two electrodes makes the electrons (and the lithium ions) move to the graphite side. This is an uphill struggle, energetically speaking, which is why it amounts to storing energy in the battery.

When he built his first battery, Volta was trying to replicate the organs that produce electricity in torpedoes, the fish also known as electric rays, says Giuliano Pancaldi, a science historian at the University of Bologna in Italy.

Volta probably went by trial and error before settling on using metal electrodes and wet cardboard as an electrolyte. At the time, no one knew about the existence of atoms, ions and electrons. But whatever the nature of the charge carriers, Volta probably was not aware that in his battery, the positive charges moved in opposition to the "electric fluid" moving outside. "It took a century before experts reached a consensus on how the battery works," Pancaldi says. *—Davide Castelvecchi*

LISA SPINDLER *Getty Images* (ear); CORBIS (battery)

EXTERNAL EARS

They guide sound to the sensitive middle ear

Looking more like a baby salamander than anything else, a six-week-old human embryo has tiny paddles for hands, dark dots for eyes and on either side of its shallow mouth slit, half a dozen small bumps destined to form an ear. By nine weeks, these "hillocks" will migrate up the face as the jaw becomes more pronounced and start taking on the recognizable shell shape so handy for holding up eyeglasses. Because development often reprises stages of evolution, the growth of embryonic ears in tandem with the jaw is no accident: the sound-transmitting middle ear bones that are a distinguishing feature of mammals evolved from what used to be gill arches in fish and jawbones in reptiles.

The tympanic membrane, or eardrum, that sits just outside the middle ear evolved separately and repeatedly in the ancestors of frogs, turtles, lizards, birds and mammals. Reptilian eardrums can do no more than crudely transmit low-frequency vibrations. To mammals, which have a fancier middle-ear setup, higher-frequency sounds are also audible; external skin and cartilage flaps, called pinnae, are thought to have evolved to capture and funnel those sounds more effectively. The entire human ear structure amplifies sounds by only about 10 to 15 decibels, but our pinnae also usefully modulate the frequency of sounds entering the ear canal. As the contours of the pinnae reflect incoming vibrations, they slightly delay the higher-frequency sounds in a way that cancels out some of them. This so-called notch-filtering effect preferentially delivers sounds in the range of human speech to the inner ear.

Pinnae also help to detect where a sound comes from. Perhaps no animal has a keener directional hearing sense than bats, whose pinnae range in shapes and sizes tailored to the frequencies of each species' own sonar signals. Another night hunter that relies heavily on hearing, the barn owl, instead uses its large ruff of facial feathers to capture sound and clues to its source. Studies of how human pinnae filter and reflect sounds are informing the design of hearing aids to better reproduce natural aural mechanics. Robots and automated surveillance cameras that turn toward the sound of a disturbance are also being modeled on the human head and external ears. *—Christine Soares*

ORIGINS

INSURANCE

Its probability-based view of misfortunes helped to shape the scientific outlook

The first "insurance policy" on record is probably the Codex Hammurabi, circa 1780 B.C., which you can still read in the original at the Louvre Museum in Paris if you are nimble with ancient Sumerian legalese. It avers that shippers whose goods were lost or stolen in transit would be compensated by the state. (How did shippers prove their claims? A sworn declaration before a god was good enough for the king of Babylon.)

Another 3,500 years or so passed before a catastrophe—the Great Fire of London in 1666—begat the first instance of "modern" insurance: a formal setup whereby people paid premiums to companies to bail them out in an emergency; actuaries for the companies set the premium rates based on risk of payout. Such insurance depended on advancements in higher mathematics—namely, probability theory. That development has been insurance's lasting and profound legacy for modern life, coloring the way we think about so many things, including ourselves.

Mathematical probability theory began in the mid-16th century, when European scholars first applied hard analysis to gambling games. The goal, a hallmark of the Enlightenment, was to lay reason on randomness. Deadly storms, plagues and other misfortunes were understood to be merely unfortunate but natural (and rare) events, not portents—less scourges to be feared and more mysteries to be solved.

Thus did probability crunching find its way into modern science. Geneticists use it to divine the likelihood that parents will have children with a particular birth defect. Particle physicists use it to allay fears that the new supercollider will produce an Earth-swallowing black hole. We organize our lives—from indulgences to duties—with the probabilistic expiration date of our life span in mind. At every turn, we subconsciously intuit that this or that outcome is likely to happen, but those intuitions are pliable. It is the real-world testing of our biases—the scientific method—that confirms or kills them.

The legacy of insurance industry risk crunching is not all positive: its fingerprints are all over the recent massive upheaval on Wall Street. A formula published in 2000 by actuary David X. Li, who went on to head research divisions at Citigroup and Barclays Capital, and widely used by economists and bankers to estimate the risk of asset-backed securities borrowed a key component from life insurance. The formula, called a Gaussian cupola function, was not so much an application of actuarial science as a misapplication of it. As it turns out, the default risk of financial instruments cannot be predicted in the same way that, say, the death risk of spouses can.

Oops. *—Bruce Grierson*

HAMMURABI'S CODE, inscribed on a black basalt slab about 1780 B.C., holds a record of the first "insurance policy."

SCOTCH TAPE

Most new inventions quickly fall into oblivion; some stick

In 1930 food-packing companies were enthralled with the relatively new and improved film called cellophane, a transparent polymer made from cellulose. Cellophane wrappers could help keep packaged food fresh yet would still allow customers a view of the contents. Sealing cellophane packages satisfactorily was a problem, however, until the 3M Company invented and trademarked Scotch tape—a name that the public nonetheless widely uses for all adhesive-backed cellophane tapes. (The analogous product Sellotape, introduced seven years later in Europe, has the same problems with generic use of its name.)

Engineers call the glue in Scotch tape a pressure-sensitive adhesive. It does not stick by forming chemical bonds with the material it is placed on, says Alphonsus Pocius, a scientist at the 3M Corporate Research Materials Laboratory in St. Paul, Minn. Instead applied pressure forces the glue to penetrate the tiniest microscopic irregularities on the material's surface. Once there, it will resist coming back out, thus keeping the tape stuck in place. The glue "has to be halfway between liquid and solid," Pocius explains: fluid enough to spread under pressure but viscous enough to resist flowing.

Concocting the right kind of glue is only part of the invention, however. The typical adhesive tape contains not just two materials (glue and backing, which can be cellophane or some other plastic) but four. A layer of primer helps the glue stick to the plastic, while on the other side a "release agent" makes sure that the glue does not stick to the top. Otherwise, Scotch tape would be impossible to unroll.

Adhesive tape recently caught the attention of physicists. Researchers showed that unrolling tape in a vacuum chamber releases x-rays, and they used those x-rays to image the bones in their fingers as a demonstration. The discovery could lead to cheap, portable (and even muscle-powered) radiography machines. The unrolling creates electrostatic charges, and electrons jumping across the gap between tape and roll produce x-rays. In the presence of air the electrons are much slower and produce no x-rays. But try unrolling tape in a completely dark room, and you will notice a faint glow. *—Davide Castelvecchi*

JAUNTY JUNTO *Getty Images (tape)*; GRANGER COLLECTION *(Hammurabi's Code)*

ANTIBIOTICS

These wonder-drug molecules might have evolved to help bacteria speak with their neighbors, not kill them

Most medically important antibiotics come from soil bacteria. Conventional wisdom holds that dirt microbes evolved these compounds as lethal weapons in the fierce battle waged beneath our feet for food and territory. For more than 15 years microbiologist Julian Davies of the University of British Columbia has been arguing otherwise. "They're talking, not fighting," Davies says.

His respected if not wholly accepted theory is that bacteria use most of the small molecules we call antibiotics for communication. As evidence, Davies points out that in nature, soil bacteria secrete antibiotics at trace levels that do not come close to killing their microbial neighbors. "Only when we use them at unnaturally high concentrations do we find that these chemicals inhibit bacteria," he explains.

Moreover, in Davies's Vancouver laboratory, his staff has been eavesdropping on the flurry of gene activity in bacteria exposed to low-dose antibiotics. The researchers equip their bacteria with glow-in-the-dark lux genes that provide a fluorescent signal when other linked genes are active; then they watch those genetic "switchboards" light up in a chorus of responses to antibiotic exposure. The call-and-response activity resembles that of cells responding to hormones, Davies observes, or of "quorum-sensing" bacteria that assess their own numbers.

"I'm not saying that some of these compounds couldn't be used as weapons in nature," Davies says. "But that's not what we're seeing." He notes that a gram of soil contains more than 1,000 different types of bacteria. "They're all thriving there together and clearly not killing one another." Davies proposes that many antibiotics may help coordinate bacterial activities such as swarming, biofilm formation and diverse interactions with their multicellular hosts.

Davies's theory implies both good news and bad for the world of medicine. Bacterial communities (and not just those in dirt) might be treasure troves of chemicals with microbe-killing drug potential. Davies and his colleagues have already found candidate molecules among gut bacteria such as *Escherichia coli*. But for every new antibiotic, there may also already be plenty of corresponding resistance genes. After all, the same bacteria that regularly produce and respond to antibiotics need mechanisms for protecting themselves from potentially toxic effects. And in the gene-swapping world of bacteria, it doesn't take long for such DNA instructions to jump from one species to many once a new antibiotic comes into widespread medical use.

—Jessica Snyder Sachs

ARTIFICIAL HEART

Did the wrong man get credit for the world's first permanent pump?

HANK MORGAN *Photo Researchers, Inc.*

In January 1982 surgeons at the University of Utah implanted the first permanent artificial heart into Barney Clark, a 61-year-old dentist from Seattle who was hours from death as he went into the operating room. He would live another 112 days. The work was a triumph for Willem Kolff, founder of the university's Division of Artificial Organs and head of the team that developed Clark's new heart. Yet in the weeks that followed the surgery, Kolff's name began to be left out of the frantic media coverage. Nearly three decades later he has been all but forgotten. Perhaps he should have named the heart after himself.

Kolff was already one of the world's foremost inventors of artificial organs when he moved in 1967 from the Cleveland Clinic to Utah. Ten years earlier he had invented the first working artificial kidney; that same year he began work on a heart. At Utah, Kolff led a team of more than 200 doctors and scientists who were pushing to advance the field of artificial organs. In 1971 he hired Robert Jarvik, a budding researcher in biomechanics who seemed to have a knack for engineering. Jarvik began medical school the next year and continued to work on improving the heart through his graduation in 1976.

Kolff had a tradition of naming new versions of the heart after young investigators in his lab to keep them motivated and prevent them from moving elsewhere. Jarvik was project manager for the iteration that came to be named Jarvik-7. That device was approved for use by the Food and Drug Administration in 1981.

Jarvik was 35 years old when Clark received the heart that bore his name. He appeared at the press conference that announced the implant in scrubs, although he did not take part in the surgery. Jarvik continued to attend press conferences at the center, while Kolff kept a low profile. Perhaps it is not surprising that the world came to associate a seminal piece of engineering—the work of hundreds, over a course of years—with one man. After all, it had his name on it.

—Michael Moyer

CORIOLIS EFFECT

The earth's spin influences hurricanes but not toilets

In the final year of World War I, when the German military pointed its largest artillery at Paris from a distance of 75 miles, the troops adjusted the trajectory for many factors that could be ignored with less powerful guns. In particular, a subtle influence from the rotation of the earth—the Coriolis effect or force—would have shifted all their shots by about half a mile.

Decades earlier a Parisian scientist by the name of Gaspard-Gustave de Coriolis had written down the equations describing that effect as a part of his 1835 paper analyzing machines with rotating parts, such as waterwheels. The Coriolis effect can arise in any situation involving rotation. If you stand anywhere on a counterclockwise-turning carousel, for instance, and throw a ball in any direction, you will see the ball's trajectory curve to its right. Someone standing next to the carousel will see the ball move in a straight line, but in your rotating frame of reference the ball's direction of motion swings around clockwise. A new force appears to act on the ball. On the spinning earth, we see a similar (but much weaker) force acting on moving objects.

As well as deflecting the paths of long-range artillery shells and ballistic missiles, the Coriolis effect is what causes cyclones (which includes hurricanes and typhoons) to spin clockwise south of the equator and counterclockwise north of it. Indeed, the Coriolis effect is the reason that winds in general tend to flow *around* regions of high and low pressure, running parallel to the lines of constant pressure on a weather map ("isobars"), instead of flowing directly from high to low pressure at right angles to the isobars. In the Northern Hemisphere, air flowing radially inward across the isobars toward the low pressure would be deflected to the right. The motion reaches a steady state with the wind encircling the low-pressure area—the pressure gradient pushing inward and the Coriolis force outward.

A popular factoid claims that water running down a drain turns in one direction in the Southern Hemisphere and the opposite way in the Northern Hemisphere. That idea is a myth: although the Coriolis force is strong enough to direct the winds of hurricanes when acting over hundreds of miles for days, it is far too weak to stir a small bowl of water in the scant seconds the water takes to run down the drain. —*Graham P. Collins*

TITAN II MISSILE fired across 7,000 miles typically would be deflected hundreds of miles by the Coriolis force.

BALL BEARINGS

Cheap steel was key to allowing the routine design of parts that rolled against one another

If the utility of an invention were somehow derived from the genius of its inventor, it would be pardonable that so many sources trace the idea for the ball bearing to a 1497 drawing by Leonardo da Vinci. But good ideas, like useful evolutionary traits, tend to emerge more than once, in diverse times and places, and the idea of arranging for parts to roll against one another instead of sliding or slipping is very old indeed. The Egyptians already had the basic idea when they moved great blocks of stone on cylindrical rollers. Similar ideas occurred to the builders of Stonehenge as early as 1800 B.C. and to the craftsmen who constructed the cylindrical-shaped bearings on the wheel hubs of wagons around 100 B.C. (On these wagons the axle turned with the wheels, so the bearings enabled the axle to roll against the wagon chassis.)

The first design for a ball bearing that would support the axle of a carriage did not appear until 1794, in a patent filed by a Welsh ironmaster named Philip Vaughan. Ball bearings between the wheel and the axle enabled the axle to remain fixed to the carriage chassis. But cast iron ball bearings were brittle and tended to crack under stress. It took the invention of the Bessemer process for making inexpensive steel, plus the invention of the bicycle, to fix the ball bearing permanently in the minds of engineers everywhere. Jules-Pierre Suriray, a Parisian bicycle mechanic, patented his steel ball-bearing design in 1869, and in that same year a bicycle outfitted with Suriray's ball bearings won an international cycling race.

The demand for ball bearings—on automobiles, tanks or guidance systems—has pushed manufacturers ever closer to the ideal of shaping a perfect sphere. No turning wheel will survive for long on its axle without ball bearings machined to a tolerance of less than a thousandth, or even a 10-thousandth, of an inch.

Many sources claim that the most perfect spheres occur in the bearings of computer hard drives, but in fact that honor goes to the ping pong–size spheres of fused quartz that serve as gyroscopic bearings for the satellite Gravity Probe B. Its gyroscopes are 30 million times more accurate than any other gyroscope ever built. —*Peter Brown*

MICHAEL DUNNING *Corbis (missile)*; WOLFRAM SCHROLL *Corbis (ball bearing)*

TEETH

They long predate the smile

Paleontologists used to wonder whether the first teeth were on the inside or the outside of prehistoric bodies. Sharks are covered in thousands of tiny denticles–toothlike nubs of dentine and collagen that make sharkskin coarse to the touch. If the denticles of some very early vertebrate had migrated into the jaw, grown larger and gained new functions, the speculation went, they could have given rise to modern choppers. But over the past decade fossil and genetic evidence has confirmed that teeth are much older than even the ancient shark lineage—indeed, older than the jaw or the denticle. And they originated inside the body, though not in the mouth.

The first sets of teeth belonged to eel-like swimmers that lived some 525 million years ago and ranged from four to 40 centimeters long. Collectively they are known as conodonts for the ring of long, conical teeth in their pharynx. Some fish species still have a set of vestigial teeth in their throat, but pharyngeal teeth for the most part are believed to have migrated forward into the mouth, perhaps as the jaw was evolving.

Supporting that idea, the programmed gene activity that builds teeth differs from the instructions that build a jaw, even though both types of structure grow in tandem. The marriage of tooth and jaw, however, likely gave rise to specialized tooth shapes. By the 10th day of a human embryo's development, molecular signaling that initiates tooth formation is taking place between two basic embryonic tissue layers. At the same time, signals from the growing jaw imprint a shape onto the primordial tooth that cannot be changed. Even when the bud of a future molar, for instance, is transplanted into a different area of the jaw, the final tooth will become whatever its original location fated it to be.

Unfortunately, dental researchers are finding it difficult to recapitulate half a billion years of evolution in the laboratory. Because burgeoning teeth depend on information from the budding embryonic jaw, work toward generating replacement teeth from dental stem cells focuses on growing them in the desired location in the recipient's mouth–but scientists are not yet sure the adult jaw can provide the necessary signals to shape made-to-order teeth.

—Christine Soares

EGG

The answer to the age-old riddle is biologically obvious

In March 2006, on the occasion of the release of *Chicken Little* on DVD, Disney convened a panel to put an end to the long-standing riddle: Which came first, the chicken or the egg? The verdict was unanimous. "The first chicken must have differed from its parents by some genetic change [that] caused this bird to be the first ever to fulfill our criteria for truly being a chicken," said John Brookfield, an evolutionary biologist at the University of Nottingham in England. "Thus the living organism inside the eggshell would have had the same DNA as the chicken that it would develop into, and thus would itself be a member of the species of chicken." What we recognize as the DNA of a chicken exists first inside an egg. Egg came first.

Yet despite the unified front of the three-person panel—David Papineau, a philosopher of science, and Charles Bourns, a chicken farmer, agreed in spirit with Brookfield's analysis—the question is at best incomplete, at worst misleading. If we take "chicken" to mean a member of *Gallus gallus domesticus* (a subspecies of junglefowl that evolved in Southeast Asia and has been domesticated for perhaps 10,000 years), we could ask at what point the first member of this species appeared (and whether it was in bird or egg form). Yet speciation is not a process that happens in an instant or in an individual. It takes generations on generations of gradual change for a group of animals to cease interbreeding with another group; only then can we say that speciation has occurred. Viewed in this way, it does not make sense to talk about the first chicken or the first egg. There was only the first group of chickens—some of whom, presumably, were in egg form.

And if one relaxes the species qualification, then the race is not even close. Invertebrates as simple as sponges rely on some form of egg for reproduction, which means that eggs probably predate the Cambrian explosion in biodiversity of 530 million years ago. Fish and amphibians lay gelatinous eggs; ancestors of reptiles and birds laid the first shelled eggs 340 million years ago, and that innovation, which allowed their eggs to survive and mature on dry land, enabled the rise of land vertebrates long before the first rooster crowed.

—Michael Moyer

GK AND VIKKI HART *Getty Images*

CANCER

When a cell’s controls break down, chaos is unleashed

Multicellularity has its advantages, but they come at a price. The division of labor in a complex organism means that every cell must perform its job and only its job, so an elaborate regulatory system evolved to keep cells in line. Nearly every one of the trillion or so cells in the human body, for instance, contains a full copy of the genome – the complete instruction set for building and maintaining a human being. Tight controls on which genes are activated, and when, inside any given cell determine that cell’s behavior and identity. A healthy skin cell executes only the genetic commands needed to fulfill its role in the skin. It respects neighboring cells’ boundaries and cues, and when the regulatory system permits, it divides to generate just enough new cells to repair a wound, never more.

Greek physician Hippocrates first used the term *karkinos,* or “crab,” in the fourth century B.C. to describe malignant tumors because their tendril-like projections into surrounding tissue reminded him of the arms of the crustacean. In Latin, the word for crab was *cancer,* and by the second century B.C. the great Roman physician Galen knew those spiny arms were just one sign that normal body tissues had gone out of control. He attributed the dysfunction to an excess of black bile. Modern scientists see a breakdown of the cellular regulatory system in the hallmarks of cancer: runaway growth, invasion of neighboring tissue and metastasis to far-off parts of the body.

The proteins and nucleic acids that control gene activity are themselves encoded by genes, so cancers begin with mutations that either disable key genes or, conversely, cause them to be overactive. Those changes initiate a cascade of imbalances that knock out downstream regulatory processes, and soon the cell is careening toward malignancy. So far efforts to identify the exact combination of mutations necessary to ignite a particular type of cancer—in the brain, the breast or elsewhere—have not yielded clear patterns. Once regulatory networks are destabilized, they can break down in ways as complex and diverse as the molecular pathways they regulate, making the precise origin of each instance of cancer unique. For all their internal chaos, though, cancer cells share some characteristics with stem cells—those primal body-building cells that are exempt from many constraints on normal cells. One important difference is that in stem cells, the full potential of the genome is controlled; in cancer, it is unleashed. *—Christine Soares*

THE STIRRUP

Invention of the stirrup may rival that of the longbow and gunpowder

A slight alteration to the custom of riding a horse may have dramatically changed the way wars were fought. Humans rode bareback or mounted horses with a simple blanket after they first domesticated the animals, thousands of years after the dawn of agriculture. The leather saddle first straddled a horse’s back in China perhaps as far back as the third century B.C. But the saddle was only one step toward transforming the use of cavalry as a means of waging war. Climbing onto a horse while bearing weapons had long presented its own precarious hazards. Cambyses II, a Persian king in the sixth century B.C., died after stabbing himself as he vaulted onto a horse.

By the fourth century A.D., the Chinese had begun to fashion foot supports from cast iron or bronze. What made the stirrup (derived from the Old English word for a climbing rope) such an important innovation was that it allowed the rider immensely greater control in horsemanship: rider and animal became almost extensions of each other. It was possible to shoot arrows accurately while the horse dashed ahead at full gallop. A cavalryman could brace himself in the saddle and, with a lance positioned under his arm, use the tremendous force of the charging horse to strike a stunned enemy. The horse's sheer mass and quickness became an implement of the cavalry's weaponry—and a powerful intimidation factor.

The fierce Avar tribe may have brought stirrups to the West when it arrived in Byzantium in the sixth century A.D. The Byzantine Empire soon adopted the stirrup—and later the Franks embraced it as well. The societal impact of this saddle accoutrement has intrigued historians for decades. Some scholars suggested that feudalism emerged in Europe because mounted warfare, facilitated by the stirrup, became vastly more effective for the cavalry of the Franks. An aristocratic class emerged that received land for its service in the cavalry.

Others, on the opposite side of what is known as the Great Stirrup Controversy, argue that this interpretation of events is baseless. Whether the stirrups were the single enabling technology that brought about the rise of feudalism remains in doubt. Unquestionably, though, this small extension from a saddle was an innovation that transformed the craft of war forever. *—Gary Stix*

GETTY IMAGES

BLOTTER ART decorates LSD-infused absorbent paper with color palettes reminiscent of the psychedelic era of the 1960s.

LSD

An inquisitive Swiss chemist sent himself on the first acid trip

The medical sciences can invoke a long and storied tradition of self-experimentation. Typhoid vaccine, cardiac catheterization, even electrodes implanted in the nervous system came about because scientists recruited themselves as their own guinea pigs.

One of the most memorable instances happened on April 16, 1943, when Swiss chemist Albert Hofmann inadvertently inhaled or ingested a compound derived from a crop fungus that went by the chemical name of lysergic acid diethylamide, or LSD-25. He subsequently entered into "a not unpleasant intoxicated-like condition, characterized by an extremely stimulated imagination," he recalled in his 1979 autobiography, *LSD, My Problem Child.* "In a dreamlike state, with eyes closed ..." he continued, "I perceived an uninterrupted stream of fantastic pictures extraordinary shapes with intense, kaleidoscopic play of colors."

Ever the intrepid researcher, Hofmann decided to probe further the psychotropic properties of the substance, which Sandoz Laboratories had previously developed and then abandoned as a possible stimulant for breathing and circulation. A few days after his first trip, he carefully apportioned a 0.25-milligram dose; within a short time the Sandoz laboratory where he worked again became distorted and strange. The words "desire to laugh" were the last ones scrawled in his research journal that day. His inebriated state prompted him to leave work early. The bicycle ride home—in which he could not tell that he was moving—has given April 19 the designation of "bicycle day" among LSD aficionados everywhere.

Hofmann went on to use LSD hundreds of times more—and his creation became a ticket into the altered mental states embraced by the counterculture. Though subsequently banned, the drug continues to attract intense interest by investigators who are examining therapeutic uses, including the possibility that it may help the terminally ill reconcile themselves to their mortality. *—Gary Stix*

SINCLAIR STAMMERS *Photo Researchers, Inc.* (LSD); GETTY IMAGES (*relief*)

COOKING

Preparing foods with fire may have made us humans what we are

In a world without cooking, we would have to spend half our days chewing raw food, much as the chimpanzee does. Cooking not only makes food more delicious, it also softens food and breaks starches and proteins into more digestible molecules, allowing us to enjoy our meals more readily and to draw more nutrition from them. According to Harvard University biological anthropologist Richard Wrangham, cooking's biggest payoff is that it leaves us with more energy and time to devote to other things—such as fueling bigger brains, forming social relationships and creating divisions of labor. Ultimately, Wrangham believes, cooking made us human.

Archaeological evidence is mixed as to when our ancestors started building controlled fires—a prerequisite for cooking—but Wrangham argues that the biological evidence is indisputable: we must have first enjoyed the smell of a good roast 1.9 billion years ago. That is when a species of early human called *Homo erectus* appeared—and those hominids had 50 percent larger skulls and smaller pelvises and rib cages than their ancestors, suggesting bigger brains and smaller abdomens. They also had much smaller teeth. It makes sense that cooking "should have left a huge signal in the fossil record," Wrangham says, and, quite simply, "there's no other time that fits." Never before and never again during the course of human evolution did our teeth, skull and pelvis change size so drastically. If cooking had arisen at a different point, he says, we would be left with a big mystery: "How come cooking was adopted and *didn't* change us?"

Wrangham also has a theory as to how controlled fires, and thus cooking, came about. He speculates that *H. erectus*'s closest ancestors, the australopithecines, ate raw meat but hammered it to make it flatter and easier to chew, rather like steak carpaccio. "I've tried hammering meat with rocks, and what happens? You get sparks," he says. "Time and time again this happens, and eventually you figure out how to control the fire." *—Melinda Wenner*

BREAD MAKING relief image decorates an Egyptian tomb dating back more than 4,000 years.

CLOCKS

Their origin is one of the deepest questions in modern physics

Sundials and water clocks are as old as civilization. Mechanical clocks—and, with them, the word "clock"—go back to 13th-century Europe. But these contraptions do nothing that nature did not already do. The spinning Earth is a clock. A dividing cell is a clock. Radioactive isotopes are clocks. So the origin of clocks is a question not for history but for physics, and there the trouble begins.

You might innocently think of clocks as things that tell time, but according to both of the pillars of modern physics, time is not something you can measure. Quantum theory describes how the world changes in time. We observe those changes and infer the passage of time, but time itself is intangible. Einstein's theory of general relativity goes further and says that time has no objective meaning. The world does not, in fact, change in time; it is a gigantic stopped clock. This freaky revelation is known as the problem of frozen time or simply the problem of time.

If clocks do not tell time, then what do they tell? A leading idea is that what we perceive as "change" is not variation in time but a pattern among the universe's components—the fact, for example, that if Earth is at a certain position in its orbit, the other planets are at specific positions in theirs. Physicist Julian Barbour developed this relational view of time in the winning entry for the Foundational Questions Institute essay contest last year. He argued that because of the cosmic patterns, each piece of the universe is a microcosm of the whole. We can use Earth's orbit as a reference for reconstructing the positions of the other planets. In other words, Earth's orbit serves as a clock. It does not tell time but rather the positions of the other planets.

By Barbour's reasoning, all clocks are approximate; no single piece of a system can fully capture the whole. Any clock eventually skips a beat, runs backward or seizes up. The only true clock is the universe itself. In a sense, then, clocks have no origin. They have been here all along. They are what make the concept of "origin" possible to begin with. —*George Musser*

LEGS, FEET AND TOES

The essential parts for walking on land evolved in water

The evolution of terrestrial creatures from aquatic fish with fins may have begun with the need for a breath of fresh air. Animals with limbs, feet and toes—a group known as the tetrapods (literally, "four-footed")—arose between 380 million and 375 million years ago. Scientists long believed that limbs evolved as an adaptation to life on terra firma. But recent discoveries have revealed that some of the key changes involved in the fin-to-limb transition occurred while the ancestors of tetrapods were still living in the water.

Tetrapod evolution experts such as Jennifer Clack of the University of Cambridge hypothesize that these early modifications to the bones and joint surfaces of the pectoral fins might have benefited tetrapod ancestors in two key ways. First, they could have allowed the creatures, which lived in the plant-choked shallows, to perform a push-up that raised their heads out of the oxygen-poor water for a breather. (Changes in other parts of the skeleton, such as the skull and neck, also facilitated air breathing.) The protolimbs could have also helped these animals to propel themselves along the bottom and to steady themselves against the current while waiting to ambush prey.

Researchers once thought that the bones making up feet and toes were an evolutionary innovation unique to the tetrapods. But over the past few years analyses of tetrapod forerunners, such as the *Tiktaalik* fossil unveiled in 2006, have revealed that these bones derive directly from bones in the fish fin. Curiously, the earliest tetrapods and tetrapodlike fish had feet with between six and eight digits, rather than the five of most modern tetrapods. Why tetrapods ultimately evolved a five-digit foot is uncertain, but this arrangement may have provided the ankle joint with the stability and flexibility needed for walking. —*Kate Wong*

RAÚL MARTÍN

PAPER MONEY

A substitute for coins turned into a passport for globalization

Blame it on paper currency. The development of banknotes in China more than a millennium ago accelerated wealth accumulation, deficit spending and credit extension—paving the way for our present-day financial crisis.

When Chinese merchants started using paper money in the Tang Dynasty (which spanned A.D. 618 to 907), they could have hardly foreseen such difficulties. At the time, the introduction of notes that could be redeemed for coins at the end of a long journey was a boon. Paper cut down on traders' loads, enabling them to transport large sums of money over sizable distances.

The practice caught on nationwide in the 10th century, when a copper shortage prompted the emperor of the Song Dynasty to issue the world's first circulating notes. A string of earlier Chinese inventions—including paper, ink and block printing—made it all possible.

When Marco Polo visited the Mongol Empire in the 1200s, he was impressed by Kublai Khan's sophisticated mints, connecting them to an apparently booming economy. (The explorer did not pick up on signs of the inflation brought on by the rapid printing of notes.) Later, faster circulation of currency allowed European nations to siphon resources out of Asia and Africa, fundamentally altering the global balance of power.

Today paper money means that wealth flows back to the developing world as well. Financial convertibility makes it possible for China to buy up U.S. bonds, financing debts that may never be paid back. But it also escalates the pace of wealth accumulation. Paper currency—and its modern heir, electronic trading—lay behind the recent commodities and housing bubbles, contributing to last year's financial crash.

In today's recession, things have come full circle. Amid concerns about financial stability, some investors are holding on to precious metals. A backlash against more abstract forms of currency means a return to our economic roots: centuries after our conversion to paper, the price of gold has soared.

—Mara Hvistendahl

THE VIBRATOR

One of the first electrical appliances made its way into the home as a purported medical device

For a sex toy, the vibrator's roots seem amazingly antiseptic and clinical. Prescribed as a cure for the curious disease hysteria, the device for decades found clinical application as a supposed medical therapy.

Derived from the Greek word for "uterus," hysteria occurred in women with pent-up sexual energy—or so healers and early physicians believed. Nuns, widows and spinsters were particularly susceptible, but by the Victorian era many married women had fallen prey as well. In the late 19th century a pair of prominent physicians estimated that three quarters of American women were at risk.

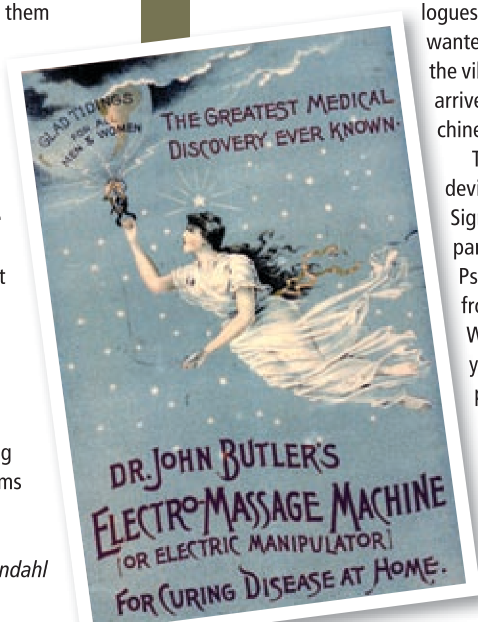
The prescription of clitoral orgasm as a treatment for hysteria dates to medical texts from the first century A.D. Hysterical women typically turned to doctors, who cured them with their hands by inducing a "paroxysm"—a term that hides what we now know as a sexual climax. But manual stimulation was time-consuming and (for the doctors at least) tedious. In *The Technology of Orgasm: "Hysteria," the Vibrator and Women's Sexual Satisfaction,* science historian Rachel P. Maines reports that physicians often passed the job off to midwives.

The invention of electricity made the task easier. Joseph Mortimer Granville patented an electromechanical vibrator in the early 1880s to relieve muscle aches, and doctors soon realized it might be used on other parts of the body. That innovation shortened treatment time for hysteria, fattening doctors' wallets.

Patients were happy, too. The number of health spas offering vibration therapy multiplied, and the service was so popular vibrator manufacturers warned doctors not to overdo it with the modern appliance: if they met relentless patient demand, even mechanical vibration could be tiring. By the turn of the century needlework catalogues advertised models for women who wanted to try the treatment at home, making the vibrator the fifth electric appliance to arrive in the home—after the sewing machine, the fan, the teakettle and the toaster.

The vibrator's legitimacy as a medical device declined after the 1920s, when Sigmund Freud correctly identified paroxysm as sexual. In 1952 the American Psychiatric Association dropped hysteria from its list of recognized conditions. When the vibrator was again popularized years later, women no longer needed the pretense of illness to justify a purchase.

—Mara Hvistendahl



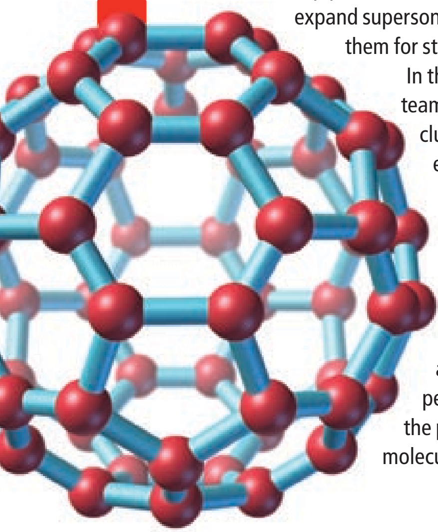
SEX TOYS started off as medical devices for treating hysteria in women, becoming a substitute for manual stimulation by physicians.

GETTY IMAGES *(money)*; COURTESY OF BAKKEN MUSEUM *(advertisement)*

BUCKYBALLS AND NANOTUBES

A once overlooked form of carbon may represent the future of technology

Fullerenes, a form of solid carbon distinct from diamond and graphite, owe their discovery to a supersonic jet—but not of the airplane variety. At Rice University in 1985 the late Richard E. Smalley, Robert F. Curl and Harold W. Kroto (visiting from the University of Sussex in England), along with graduate students James R. Heath and Sean C. O'Brien, were studying carbon with a powerful tool that Smalley had helped pioneer: supersonic jet laser spectroscopy. In this analytical system, a laser vaporizes bits of a sample; the resulting gas, which consists of clusters of atoms in various sizes, is then cooled with helium and piped into an evacuated chamber as a jet. The clusters expand supersonically, which cools and stabilizes them for study.



In their experiments with graphite, the Rice team recorded an abundance of carbon clusters in which each contained the equivalent of 60 atoms. It puzzled them because they had no idea how 60 atoms could have arranged themselves so stably. They pondered the conundrum during two weeks of discussion, frequently over Mexican food, before hitting on the solution: one carbon atom must lie at each vertex of 12 pentagons and 20 hexagons arranged like the panels of a soccer ball. They named the molecule "buckminsterfullerene," in tribute to Buckminster Fuller's similar geodesic domes. Their discovery sparked research that led to elongated versions called carbon nanotubes, which Sumio Iijima of NEC described in a seminal 1991 paper.

Both "buckyballs" and nanotubes could have been found earlier. In 1970 Eiji Osawa of Toyohashi University of Technology in Japan postulated that 60 carbon atoms could adopt a ball shape, but he did not actually make any. In 1952 two Russian researchers, L. V. Radushkevich and V. M. Lukyanovich, described producing nanoscale, tubular carbon filaments; published in Russian during the cold war, their paper received little attention in the West.

As it turned out, buckminsterfullerene is not hard to make. It forms naturally in many combustion processes involving carbon (even candle burning), and traces can be found in soot. Since the Rice discovery, researchers have devised simpler ways to create buckyballs and nanotubes, such as by triggering an electrical arc between two graphite electrodes or passing a hydrocarbon gas over a metal catalyst. Carbon nanotubes have drawn much scrutiny; among their many intriguing properties, they have the greatest tensile strength of any material known, able to resist 100 times more strain than typical structural steel.

During an interview with Scientific American in 1993, Smalley, who died in 2005 from leukemia, remarked that he was not especially interested in profiting from fullerenes. "What I want most," he said, "is to see that *x* number of years down the road, some of these babies are off doing good things." Considering that nanotubes in particular are driving advances in electronics, energy, medicine and materials, his wish will very likely come true. *—Philip Yam*

GEORGE RETSECK

ECONOMIC THINKING

Even apparently irrational human choices can make sense in terms of our inner logic

Much economic thinking rests on the assumption that individuals know what they want and that they make rational decisions to achieve it. Such behavior requires that they be able to rank the possible outcomes of their actions, also known as putting a value on things.

The value of a decision's outcome is often not the same as its nominal dollar value. Say you are offered a fair bet: you have the same chance of doubling your $1 wager as you have of losing it. Purely rational individuals would be indifferent to the choice between playing or not playing: if they play such a bet every day, on average they will be no better or no worse off.

But as Captain Kirk might tell Mr. Spock, reality often trumps logic. Or as Swiss mathematician Gabriel Cramer wrote in a 1728 letter to his colleague Nicolas Bernoulli, "The mathematicians estimate money in proportion to its quantity, and men of good sense in proportion to the usage that they may make of it." Indeed, many people are "risk-averse": they will forfeit their chance of winning $1 to be guaranteed of keeping the $1 they have, especially if it is their only one. They assign more value to the outcome of not playing than to the outcome of potentially losing. A risk-oriented person, on the other hand, will go for the thrill.

Cramer's idea was later formalized by Bernoulli's statistician cousin Daniel into the concept of expected utility, which is an implicit value given to the possible outcomes of a decision, as revealed by comparing them with the outcomes of a bet. Risk-averse and risk-oriented persons are not irrational; rather they make rational decisions based on their own expected utility. Economists generally assume that most people are rational most of the time, meaning that they know which decisions will maximize the expected utility of their choices. (Of course, doing so requires knowing how to evaluate risk wisely, which people do not always do well. AIG, anyone?)

Some experiments, however, have shown that people are occasionally unable to rank outcomes in a consistent way. In 1953 American mathematician Kenneth May conducted an experiment in which college students were asked to evaluate three hypothetical marriage candidates, each of whom excelled in a different quality. The students picked intelligence over looks, looks over wealth and wealth over intelligence. *—Davide Castelvecchi*

CARBON

Synonymous with life, it was born in the heart of stars

Although carbon has recently acquired a bad rap because of its association with greenhouse gases, it has also long been synonymous with biology. After all, "carbon-based life" is often taken to mean "life as we know it," and "organic molecule" means "carbon-based molecule" even if no organism is involved.

But the sixth element of the periodic table—and the fourth most abundant in the universe—has not been around since the beginning of time. The big bang created only hydrogen, helium and traces of lithium. All other elements, including carbon, were forged later, mostly by nuclear fusion inside stars and supernovae explosions.

At the humongous temperatures and pressures in a star's core, atomic nuclei collide and fuse together into heavier ones. In a young star, it is mostly hydrogen fusing into helium. The merger of two helium nuclei, each carrying two protons and two neutrons, forms a beryllium nucleus that carries four of each. That isotope of beryllium, however, is unstable and tends to decay very quickly. So there would seem to be no way to form carbon or heavier elements.

But later in a star's life, the core's temperature rises above 100 million kelvins. Only then is beryllium produced fast enough for there to be a significant amount around at any time—and some chance that other helium nuclei will bump into those beryllium nuclei and produce carbon. More reactions may then occur, producing many other elements of the periodic table, up to iron.

Once a star's core runs out of nuclei to fuse, the outward pressure exerted by the nuclear fusion reaction subsides, and it collapses under its own weight. If a star is large enough, it will produce one of the universe's most spectacular flares: a supernova explosion. Such cataclysms are good, because supernovae are what disperse carbon and the other elements (some of them forged in the explosions themselves) around the galaxy, where they will form new stars but also planets, life … and greenhouse gases. *—Davide Castelvecchi*

THE PLACENTA

An eggshell membrane evolved into the organ that lets fetuses grow in the womb

More than 120 million years ago, while giant dinosaurs crashed through the forests in fearsome combat, a quieter drama unfolded in the Cretaceous underbrush: some lineage of hairy, diminutive creatures stopped laying eggs and gave birth to live young. They were the progenitors of nearly all modern mammals (the exceptions, platypuses and echidnas, still lay eggs to this day).

GETTY IMAGES

What makes mammals' live birth possible is the unique organ called the placenta, which envelops the growing embryo and mediates the flow of nutrients and gases between it and the mother via the umbilical cord.

The placenta seems to have evolved from the chorion, a thin membrane that lines the inside of eggshells and helps embryonic reptiles and birds draw oxygen. Kangaroos and other marsupials have and need only a rudimentary placenta: after a brief gestation, their bean-size babies finish their development while suckling in the mother's pouch. Humans and most other mammals, however, require a placenta that can draw nutrients appropriately from the mother's blood throughout an extended pregnancy.

Recent studies have shown that the sophistication of the placenta stems in part from how different genes within it are activated over time. Early in embryonic development, both mouse and human placentas rely on the same set of ancient cell-growth genes. But later in a pregnancy, even though the placenta does not obviously change in appearance, it invokes genes that are much newer and more species-specific. Thus, placentas are fine-tuned for the needs of mammals with different reproductive strategies: witness mice, which gestate for three weeks with a dozen or more pups, versus humans, who deliver one baby after nine months.

To last more than a week or two, the placenta, which is primarily an organ of the fetus, must prevent the mother's immune system from rejecting it. To do so, the placenta may deploy a mercenary army of endogenous retroviruses—viral genes embedded in the mammal's DNA. Scientists have observed such viruses budding from the placenta's cell membranes. Viruses may play crucial roles in pacifying the mother's immune system into accepting the placenta, just as they do in helping some tumors survive. ***—Davide Castelvecchi***

GRAPHICAL PERSPECTIVE

"Realistic" imagery depends on relatively recent cultural assumptions and technical skills

The Pioneer 10 and 11 deep-space probes carry a plaque for the benefit of any aliens they might run into. On it is a line drawing of a man and a woman. Will it make any sense to its intended audience? Even if extraterrestrials notice the markings and recognize them as a picture, will they apprehend the 3-D figures?

Many of the artistic conventions we take for granted had to be invented, and they reflect a specific cultural (let alone planetary) context. The perspective view used on the Pioneer plaque is one example. It produces the illusion of depth by showing distant objects smaller than nearby ones and by ensuring that parallel lines converge on a vanishing point. Many software packages now automate these techniques and enable artists to create photorealistic images with relative ease.

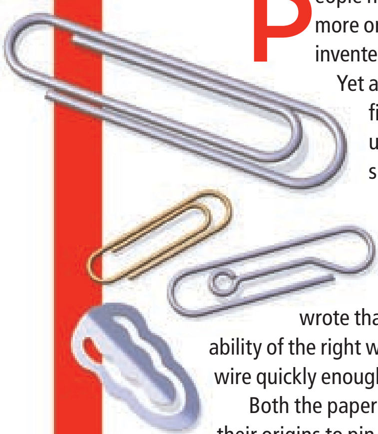
Yet realism has not always been an ambition of artists. Although elements of perspective go at least as far back as Greek painter Agatharchus in the fifth century B.C., it became popular only with the Italian Renaissance. In early 15th-century Florence, architect Filippo Brunelleschi performed a public demonstration with mirrors (then a new technology) to show how faithfully his paintings depicted building facades. He inspired painters such as Donatello, Masaccio and Domenico di Bartolo (*painting above*); Leon Battista Alberti worked out the math. Their rigorous geometric constructions ensured that natural depth cues such as size, vertical position and tile patterns were mutually consistent for maximum verisimilitude.

Learning to view a perspective drawing requires accepting and overlooking its limitations, such as its assumption of a single viewpoint. In computer graphics, perspective is well suited to first-person shooter games, but games such as SimCity that show a bird's-eye view use a different technique, axonometric projection, elements of which go back to Chinese painters in the second century B.C. Not only should we wonder whether aliens will be able to decipher our drawings, we should also ask whether we would recognize alien artwork if we saw it. *—George Musser*

ALFREDO DAGLI ORTI *The Art Archive*

THE PAPER CLIP

Despite its shortcomings, the iconic design will likely stick around

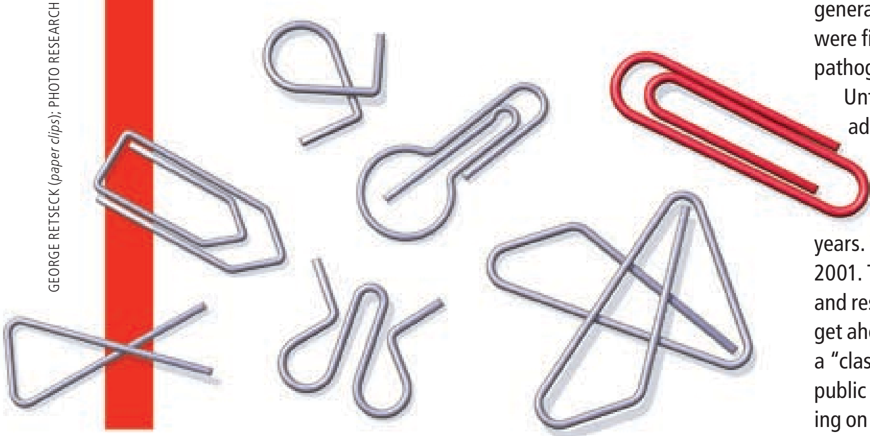


People have fastened sheets of paper together more or less permanently ever since the Chinese invented the stuff in the first or second century A.D. Yet according to the Early Office Museum, the first bent wire paper clip wasn't patented until 1867, by one Samuel B. Fay. The iconic shape of the Gem paper clip (the namesake of Gem Office Products Company) that we know today did not appear until around 1892, and it was never patented. Henry Petroski, the technology historian, wrote that its development had to await the availability of the right wire as well as machinery that could bend wire quickly enough for a box of clips to be sold for pennies.

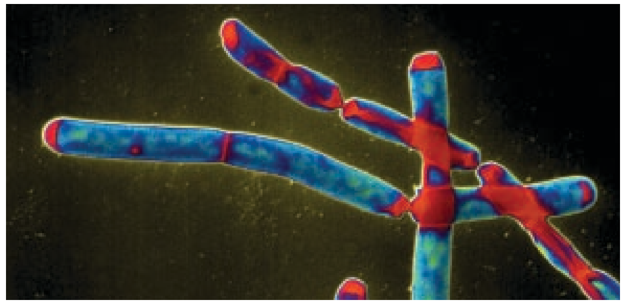
Both the paper clip and the machine that makes it trace their origins to pin making. Office workers in the early 19th century stuck their papers together—literally—with pins; a pin design known as the T-pin is still advertised in office products catalogues today. Victorian-era pin-making machinery had already solved the problem of cheaply mass-converting wire to pins; adapting the machine's talents to shaping wire was a relatively minor adjustment that made it possible for hosts of creative wire benders to dream of cashing in big.

Today paper clips made out of molded plastic, wire clips coated with colored plastic, and even semicircular sheets of aluminum that fold the top corners of the papers (and are thereby able to carry a logo or a favorite design) have come on the market. And you can still readily buy T-pins, owl clips, binder clips and ideal clips. Taken together, they have even made some inroads in the traditional Gem paper clip business.

But before you send a sketch of your new, improved design to Gem Office Products, consider this: the Gem paper clip can scratch or tear paper, catches on others of its kind in a box and, if spread too wide, slips off the papers it is intended to hold. The company once estimated that it received at least 10 letters a month suggesting alternative designs. Yet to most people, the Gem simply *is* the paper clip. It's as frozen into office culture as the "qwerty" keyboard. —*Peter Brown*



GEORGE RETSECK (*paper clips*); PHOTO RESEARCHERS, INC. (*anthrax*)



ANTHRAX

Solving the riddle of its lethal contagion modernized the understanding of disease

Among diseases of man and beast, anthrax stands as one of the oldest known and certainly one of the most storied. (It is thought to be what Homer meant by the "burning plague" in the *Iliad*.) Once a common killer of grazing animals, it was also a lethal occupational hazard for humans who worked with infected hides and livestock. Yet the cause of anthrax remained a menacing enigma until well into the 19th century, when an unassuming German country doctor entered the picture to help name it and tame it.

In the 1870s Robert Koch set out to confirm that firecracker-shaped bacterial cells in the syrupy blood of anthrax-felled livestock (first isolated by French scientists a decade earlier) were what was killing the herds and flocks. Despite a lack of scientific equipment, Koch ran painstaking trials out of his home on possible routes of transmission. In 1876 he packed up his slides and took the train to Breslau (then in Germany) to present convincing evidence to a packed room of skeptical experts that spores shed by the bacterial rods (now known as *Bacillus anthracis*) could survive in dirt and launch infections in new hosts. Proceeding from that knowledge, Louis Pasteur in France, on whose work Koch had built, created an anthrax vaccine within four years.

In a historical moment, medical science changed. Bolstered by similar successes against tuberculosis and cholera, the new model replaced the prevailing view that diseases were spontaneously generated (by forces unknown—vengeful gods, perhaps). Diseases were finally better thought of as the signature of contaminants and pathogenic interlopers.

Unfortunately, starting in the 1930s, various nations' experimental adaptation of anthrax spores as weapons renewed the dread over the ancient scourge. An international treaty banned all bioweapons development in 1972, but the Soviet Union at least seems to have continued to work on anthrax weaponization for some years. Then came the unsolved mail-based post-9/11 anthrax attacks of 2001. They sent vaccine labs in the U.S. into heavy production mode, and researchers burned through some five billion R&D dollars trying to get ahead of what the Centers for Disease Control and Prevention call a "class A" agent—the bioterror category deemed the highest threat to public health. Scientific knowledge can thus take life or give it, depending on whether it is in the hands of a brilliant loner with grace or a

INTERMITTENT WINDSHIELD WIPERS

A now routine automotive feature pitted an individual inventor against the entire industry

The origins of even the simplest technology are sometimes best remembered not for the ingenuity of the inventor's imagination but rather for the endless legal disputes it engendered. In the annals of famous patent litigation, the intermittent windshield wiper holds a pride of place. The genesis of this useful but seemingly incidental feature of the modern automobile even attracted Hollywood scriptwriters in search of a latter-day David and Goliath tale that became a 2008 release called *Flash of Genius.*

The story revolves around a brilliant, idiosyncratic college professor named Robert Kearns. Almost blinded by a champagne cork on his wedding night in 1953, Kearns later found that the monotonous back-and-forth movement of wiper blades vexed his diminished vision, as recounted in the most commonly cited version of events.

Kearns used off-the-shelf electronic parts in 1963 to devise windshield wipers that would clean the surface and then pause. The engineer demonstrated his system to Ford and ended up revealing details of how it worked. The automaker decided not to buy wipers from a Detroit tool-and-die company to which Kearns had licensed his patent rights— and it subsequently developed its own system.

In 1976 Kearns, then working with the National Bureau of Standards, disassembled a commercial wiper system and discovered that the company had apparently adopted his own design. He promptly had a nervous breakdown and, once recovered, began a struggle that lasted until the 1990s to gain redress. Kearns recruited several of his children to help in preparing lawsuits against the world's major auto companies, sometimes even serving as his own legal counsel. Juries ultimately determined that Ford and Chrysler had infringed Kearns's patents, resulting in about $30 million in awards.

Critics have argued that Kearns's inventions violated a key criterion of patentability, that an invention should not be "obvious" to one skilled in making widgets similar to the type being patented. An electronic timer—the essence of Kearns's invention—was, if anything, obvious, Ford contended. Still, Kearns prevailed in these two cases (but not later ones), and he will live on indefinitely as a hero to small inventors. —*Gary Stix*

THE EYE

What was half an eye good for? Quite a lot, actually

One of creationists' favorite arguments is that so intricate a device as the eye—with a light-regulating iris, a focusing lens, a layered retina of photosensitive cells, and so on—could not have arisen from Darwinian evolution. How could random mutations have spontaneously created and assembled parts that would have had no independent purpose? "What good is half an eye?" the creationists sneer, claiming the organ as prima facie proof of the existence of God.

Indeed, even Charles Darwin acknowledged in *On the Origin of Species* that the eye seemed to pose an objection to his theory. Yet by looking at the fossil record, at the stages of embryonic development and at the diverse types of eyes in existing animals, biologists since Darwin have outlined incremental evolutionary steps that may have led to the eye as we know it.

The basic structure of our eyes is similar in all vertebrates, even lampreys, whose ancestors branched away from ours about 500 million years ago. By that time, therefore, all the basic features of the eye must have existed, says Trevor Lamb of the Australian National University. But vertebrates' next closest kin, the slippery hagfish—animals with a cartilaginous cranium but no other bones—has only rudimentary eyes. They are conical structures under the skin, with no cornea, no lens and no muscles, whose function is probably just to measure the dim ambient light in the deep, muddy seabeds where hagfish live.

Our eyes are thus likely to have evolved after our lineages diverged from those of hagfish, perhaps 550 million years ago, according to Lamb. Earlier animals might have had patches of light-sensitive cells on their brain to tell light from dark and night from day. If those patches had re-formed into pouchlike structures as in hagfish, however, the animals could have distinguished the direction from which light was coming. Further small improvements would have enabled the visualization of rough images, as do the pinhole-camera eyes of the nautilus, a mollusk. Lenses could eventually have evolved from thickened layers of transparent skin. The key is that at every stage, the "incomplete" eye offered survival advantages over its predecessors.

All these changes may have appeared within just 100,000 generations, biologists have calculated, which in geologic terms is the blink of an eye. Such speedy evolution may have been necessary, because many invertebrates were developing their own kinds of eyes. "There was a real arms race," Lamb says. "As soon as somebody had eyes and started eating you, it became important to escape them." —*Davide Castelvecchi*

FABRICE LEROUGE *Getty Images*

DIAMOND

Its hardness is natural; its value is not

A diamond is forever. So are sapphire, silica and Styrofoam. It is the hardest known naturally occurring substance, which explains why diamonds are excellent industrial cutting materials, not emblems of romance. They are no more rare than any number of minerals, no more dazzling. So although diamonds may have their genesis in the heat and pressure of the earth's mantle billions of years ago, what a diamond represents is a very modern tale.

In 1870 British mining efforts in South Africa uncovered massive diamond deposits. Until then, as commodities, diamonds had been extremely rare; the new finds threatened to flood the market with stones and obliterate their price. Investors in the mines realized they had to consolidate their interests to control the flow of diamonds into the open market, and so in 1888 they formed the De Beers Consolidated Mines Ltd. consortium. By stockpiling its goods to keep prices high, De Beers controlled the worldwide diamond supply for the next century.

Its next trick was to control demand. In 1938 De Beers hired the American public-relations firm N. W. Ayer to begin the first advertising campaign that aimed not to sell a specific item, nor to bring customers into a specific store, but rather to sell an idea: that a diamond is the only acceptable symbol of everlasting love—and the larger the diamond, the greater the love. The company planted stories in newspapers and magazines that emphasized the size of the diamonds movie stars gave one another; four-color advertisements of celebrities conspicuously flashing their rocks helped to cement the connection. The slogan "A Diamond Is Forever" entered the lexicon in 1949, and by the time the postwar generation grew old enough to wed, the diamond engagement ring had become a nonnegotiable symbol of courtship and prestige.

Antitrust rulings earlier this decade broke De Beers's choke hold on the diamond market and forced an end to its practice of stockpiling. Yet it has effectively been replaced by Alrosa, a firm 90 percent owned by the Russian government that became the world's largest diamond producer earlier this year. Alrosa, worried about a drop in prices during a global recession, has not sold a stone on the open market since December 2008. As Andrei V. Polyakov, a spokesperson for Alrosa, explained to the *New York Times*, "If you don't support the price, a diamond becomes a mere piece of carbon." —*Michael Moyer*

THE PILL

Infertility treatments led to reproductive liberation

The oral contraceptive so universally embraced it became known simply as "the pill" was a decades-long dream of family-planning advocate Margaret Sanger, although none of the men who realized her vision started out with that purpose. In the 1930s scientists began discovering the roles of steroid hormones in the body and contemplated their therapeutic potential, but extracting hormones from animals was prohibitively expensive for most medical uses. Then, in 1939, Penn State chemist Russell Marker devised a method for making steroids from plants that remains the basis of hormone production even today. The company he founded, Syntex, soon developed an injectable synthetic progesterone derived from a wild yam.

Progesterone was an attractive drug candidate for treating menstrual irregularities that contributed to infertility because its natural role is to prevent ovulation during pregnancy and parts of a woman's menstrual cycle. In 1951 Syntex chemist Carl Djerassi—who would later become famous for his prodigious literary output—synthesized a plant-derived progestin that could be taken in convenient oral form.

When Sanger and her wealthy benefactor, Katharine Dexter McCormick, approached steroid researcher Gregory Pincus about creating a contraceptive pill in 1953, he was working for the small and struggling Worcester Foundation for Experimental Biology in Massachusetts. But 20 years earlier at Harvard University, Pincus had scandalized polite society by carrying out successful in vitro fertilization of rabbits; Sanger believed he had the daring and know-how to produce her long-sought pill.

Pincus in turn recruited an infertility doctor, John Rock, who was already using progesterone to suspend his patients' ovulation for a few months in the hope that their fertility would rebound. Still under the guise of fertility research, Rock and Pincus conducted their first human trial in 1954, injecting 50 women with synthetic progestins over the course of three months. All 50 stopped ovulating for the duration of the trial and resumed when the drugs were withdrawn. After several more years of experimentation, the first contraceptive pill was approved by the U.S. Food and Drug Administration in June 1960. —*Christine Soares*

DON FARRALL *Getty Images (diamond)*; CORBIS *(birth-control pills)*

THE MECHANICAL LOOM

Programmable textile machinery provided inspiration for the player piano and the early computer

A master weaver in 18th-century Lyon, France, Jean-Charles Jacquard was able to fabricate no more than six inches of silk brocade a week. Even that production rate was feasible only with the aid of an apprentice to sit atop his wooden drawloom, raising individual warp threads by hand while the maître slid through brightly colored threads of weft. The unrelenting tedium of weaving a pattern line by line may explain why his son, Joseph-Marie, avoided it even before the French Revolution briefly put brocade out of fashion. Only after squandering his family inheritance did Joseph-Marie reconsider—and even then, instead of becoming a master weaver, he invented a machine to save himself the labor.

Jacquard's key idea was to store brocade patterns on perforated cards that could be fed through the loom, with one card per line of weaving. The loom would read the arrangement of holes punched on a card with a lattice of spring-activated pins connected to hooks that would each individually lift a warp thread wherever a pin entered a hole. In this way, the loom could be programmed, and patterns could be modified or switched by rearranging or replacing the card deck.

Patented in 1804, an expertly operated Jacquard loom could produce two feet of brocade a day, a feat impressive enough, given France's dependence on textile exports, to merit the device a visit from Napoleon. Yet not even the notoriously ambitious emperor could have appreciated the significance that Jacquard's invention would have to future generations.

As it turned out, holes punched in paper provided a ready-made solution for developing any kind of programmable machine. Inside the pneumatic mechanism of a pianola, one punched roll would play a Bach toccata, while another would play a Gershwin rag. Vastly greater was the versatility inside a computer, as 19th-century British scientist Charles Babbage imagined with his unbuilt Analytical Engine and as American engineer Howard Aiken realized in the 1930s when he constructed the Harvard Mark I at IBM. Following Babbage's lead, Aiken made stacks of Jacquard punch cards operate in tandem, with one stack setting the operation applied to read data from another.

In modern computers the cards are gone (as are Aiken's electromechanical switches), but computers still embody essentially the same architecture. And although industrial looms are no longer manned by masters of the craft such as Jacquard's father, Joseph-Marie's innovation brings even weaving to ever higher levels of efficiency through the computer consoles that control the patterning of modern textiles.—*Jonathon Keats*

JACQUARD LOOM, invented as labor-saving equipment and patented in 1804, produces textiles in a Mongolian factory during the mid-1960s. Procession of punch cards (*left*) stores instructions of patterns to be woven.

MAD COW DISEASE

Cannibalism takes its revenge on modern farms

The story behind the brain-destroying mad cow disease vividly illustrates why it's not a good idea to eat your own species. For cattle, cannibalism had nothing to do with survival or grisly rituals and everything to do with economics.

The first so-called mad cows (the sickness is formally called bovine spongiform encephalopathy) were identified in 1984 in the U.K. They were probably infected a few years earlier by eating feed derived from the parts of sheep, cows and pigs that people avoided—diaphragms, udders, hooves, spinal cords, brains, and the like. The process of separating the ground-up components of slaughtered animals to make feed—and other products such as soap and wax—is called rendering and has existed for hundreds of years. In the mid-20th century in the U.K., rendering demanded the use of solvents and hours of boiling. The procedures presumably destroyed any pathogens that might have come from diseased creatures—pathogens that include the prion, a dangerous, malformed version of a protein found in all mammals.

In the 1970s the price of oil rose sharply, shooting up 10-fold by 1980. High crude prices, coupled with stagnant economic times, led renderers to seek ways to cut energy costs. So they did away with the solvents and the extended heating, opting instead to separate the parts in a centrifuge. The elimination of the extra cooking steps apparently enabled prions to persist.

Perhaps the first prions came from a cow that spontaneously developed the disease. Or perhaps scrapie, a prion disease of sheep that had been endemic in the U.K. for centuries but did not seem to pose a threat to human health, jumped species to infect bovines. In any case, subsequent rendering of infected cows—and then giving the resulting feed to other cows to eat as a cheap source of protein—amplified the outbreak. The situation echoed the devastation of the Fore people of Papua New Guinea: when the group practiced cannibalistic funerary rites in the early 20th century, it spread a fatal prion disease called kuru.

For the cows of the U.K. and elsewhere—the export of contaminated feed spread the disease globally—the epidemic subsided after regulations banned cannibalistic feed. Animal-health officials last year registered 125 cases worldwide, down from the peak of 37,000 in 1992. The rules came too late to save some 200 people who contracted the human form of the ailment—a small number, thankfully, considering that tens of millions have probably dined on mad cow beef. *—Philip Yam*

PHOTOSYNTHESIS

The reaction that makes the world green is just one of many variants

When the sun shines, green plants break down water to get electrons and protons, use those particles to turn carbon dioxide into glucose, and vent out oxygen as a waste product. That process is by far the most complex and widespread of the various known versions of photosynthesis, all of which turn the light of particular wavelengths into chemical energy. (Studies have even suggested that certain single-celled fungi can utilize the highly energetic gamma rays: colonies of such fungi have been found thriving inside the post-meltdown nuclear reactor at Chernobyl.) Using water as a photosynthetic reactant instead of scarcer substances such as hydrogen sulfide eventually enabled life to grow and thrive pretty much everywhere on the planet.

Water-splitting photosynthesis was "invented" by the ancestors of today's cyanobacteria, also known as blue-green algae. The organisms that now do this type of photosynthesis, including plants, green algae and at least one animal (the sea slug *Elysia chlorotica*), carry organelles called chloroplasts that appear to be the descendants of what once were symbiotic cyanobacteria. All of them use some form of the pigment chlorophyll, sometimes in combination with other pigments. Photosynthesis starts when arrays of chlorophyll molecules absorb a photon and channel its energy toward splitting water.

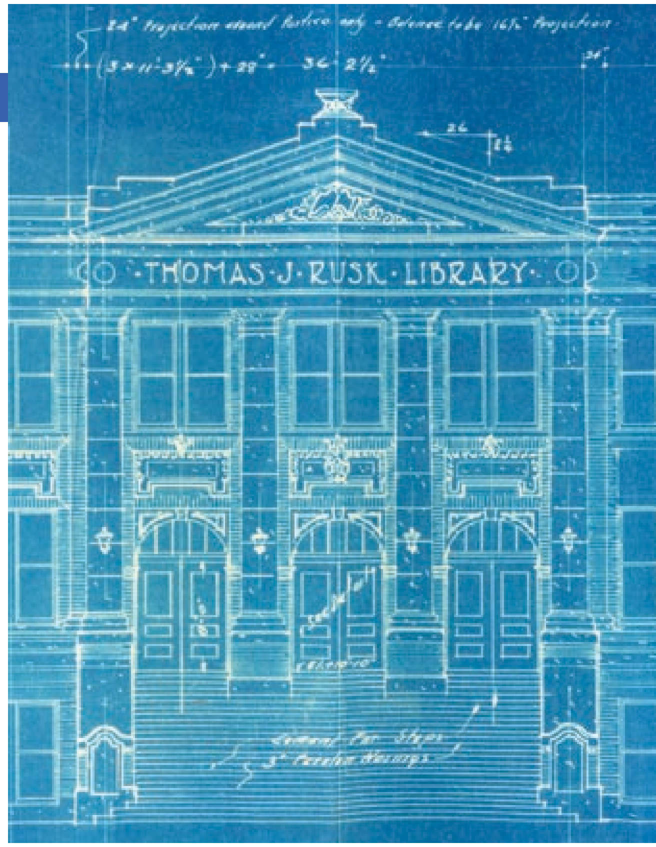
But water is a uniquely hardy molecule to be involved in photosynthesis. Taking electrons from water and giving them enough energy to produce glucose requires two separate assemblies of slightly different chlorophyll molecules (and an apparatus of more than 100 different types of proteins). Simpler forms of photosynthesis use one or the other version, but not both. The mystery is, Which one appeared first in evolution, and how did the two end up combined? "It's a question we don't really know the answer to," says Robert Blankenship of Washington University in St. Louis.

Scientists also do not know when cyanobacteria learned to split water. Some evidence suggests that it may have been as early as 3.2 billion years ago. It surely must have happened at least 2.4 billion years ago, when oxygen shifted from being a rare gas to being the second most abundant one in the atmosphere—a change without which complex multicellular animals that can formulate scientific questions could never have existed. *—Davide Castelvecchi*

GETTY IMAGES (*loom*); VINCENZO LOMBARDO *Getty Images* (*leaves*)

THE BLUEPRINT

A failure for photography, it was long irreplaceable for duplicating house plans



"This paper will prove valuable," wrote John Herschel in a scientific memorandum on April 23, 1842, noting the effect of sunlight on a sample he had treated with "ferrocyanate of potash." The light turned the chemical blue, leading Herschel to believe he had found a basis for the invention of color photography. He had not—nor would he live long enough to witness the true usefulness of his discovery.

A British astronomer and chemist, Herschel had already played a crucial role in the 1839 invention of the black-and-white salt print—the first photographic negative—by finding a way to fix, or set, the fugitive image with sodium thiosulfate. His obsessive search for other photosensitive chemicals led him to try out everything from vegetable extracts to dog urine, as well as the then new pharmaceutical known as ferrocyanate of potash, a substance now called potassium ferricyanide. The ferrocyanate produced a strong image, particularly when combined with another pharmaceutical called ammonio (ammonium ferric citrate), and the image proved permanent after washing. Herschel dubbed his invention the "cyanotype," but he was deeply dissatisfied with it, because he could not coax the chemistry to produce a stable positive image—only a negative. Most photographers shared his opinion, shunning the strange cyan hue in favor of conventional black-and-white pictures.

Only in 1872, one year after Herschel died, was the cyanotype revived, when the Paris-based Marion and Company renamed his invention "ferroprussiate paper" and began marketing it for the replication of architectural plans. (Previously, they had been copied by hand, which was expensive and prone to human error.) At the 1876 Philadelphia Centennial Exposition, the process reached American shores, where it finally met success as the blueprint, the first inexpensive means of duplicating documents. All that was required was a drawing traced on translucent paper. Pressed against a second sheet coated with Herschel's chemical under glass, the drawing was exposed to sunlight, then washed in water. The blueprint paper recorded the drawing in reverse, black lines appearing white against a cyan background.

Occupying the top floors of office buildings where there was ample sunlight, blueprint shops thrived for nearly a century, only gradually phasing out Herschel's chemistry for less labor-intensive processes such as the diazo print and the photocopy from the 1950s to the 1970s. Today most architectural plans are digitally rendered, and Herschel would have marveled at the color gamut of the modern laser printer. Yet he would have been puzzled, given his failed efforts to print in full color, to see that when we want to communicate an innovative new plan, we call it a blueprint and output it in cyan. —*Jonathon Keats*

FEATHERS

Barbs became plumes long before birds took wing—in fact, long before birds

The scaly, green *Tyrannosaurus rex* of monster movies is history. The real *T. rex* was probably covered in a fine feathery fuzz, as were most of the dinosaurs in its family, known as the theropods, which later gave rise to birds. Rich fossil beds in northeastern China have yielded specimens confirming that a wide variety of strictly earthbound dinosaurs sported feathers during the Cretaceous period, some 125 million years ago.

Studying those fossils along with feather development in modern birds has allowed researchers to reconstruct the likely steps in feather evolution. The earliest protofeathers were little more than hollow barbs of keratin, the tough protein that makes up scales, hooves and hair. At some point the barbs developed horizontal ridges that separated into filaments, then split open vertically, resulting in a tassel-like feather. Long, filamentous tail feathers were recently found in a fossil belonging to a dinosaur lineage known as the ornithischians, which diverged from the dinos that would become theropods 70 million years before the Cretaceous—suggesting that feathers could be a very ancient and widespread feature.

The original purpose of plumage might have been simply to provide lightweight warmth, but the vivid hues and patterns seen in modern birds also play a critical role in mating display. Not all feather colors are produced by pigment, however. Nanoscale keratin structures within the feathers trap air and scatter light of certain wavelengths, depending on their shapes—the dark blues of the Eastern bluebird, for instance, result from twisted air channels and keratin bars. Further studies of how these nanostructures self-assemble could yield new techniques for making colored and light-emitting materials. —*Christine Soares*

COURTESY OF THE CENTER FOR EAST TEXAS STUDIES, STEPHEN F. AUSTIN STATE UNIVERSITY (*blueprint*); CORBIS (*feather*)

BONE

Structure, strength and storage in one package

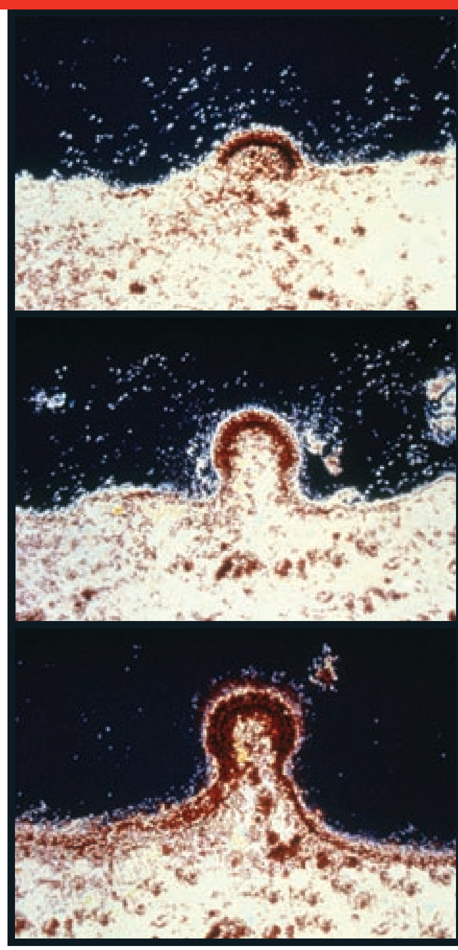
A social gathering in the Cambrian era, beginning some 540 million years ago, might have resembled an underwater war game—all life resided in the ocean then and almost every creature present would have been wearing some sort of external armor, complete with spiked helmets. The ancestors of insects and crustaceans wore full exoskeletons, probably made from a mixture of protein and chitin like the shells of modern lobsters. Starfishlike organisms and mollusks manufactured their body armor from calcium carbonate extracted from seawater. Even one fishlike evolutionary dead-end, the ostracoderm, managed somehow to swim while encased in scales and heavy plates made of true bone—that is, mineralized cartilage rich in calcium and phosphates.

It was the mild-mannered softies of the period, however, that would first develop internal bones. Wormlike organisms, such as the conodonts [see "Teeth," on page 75], started to mineralize the cartilage surrounding their primitive spinal cords, becoming the first vertebrates. Bony cranial coverings came next, and other creatures with more extensive cartilaginous internal skeletons soon followed suit. Because these swimmers used muscle contractions to propel themselves, having muscles anchored to solid bone would have provided greater strength. The hardened skeleton also offered a more solid scaffold for bodies to grow larger and to diversify, adding limbs to their repertoires.

Serving as a massive and highly responsive storage depot for critical minerals, particularly calcium, is a role that likely evolved later but is now one of the most important functions of human bone. Without calcium, the heart cannot beat and brain cells cannot fire, so far from being inert, bone is in constant flux between growth and self-demolition to meet the body's needs and to maintain its own structure. Cells called osteoclasts ("bone breakers") destroy old or dead bone tissue, and osteoblasts ("bone growers") give rise to new bone cells. Working together, these cells replace about 10 percent of the skeleton every year. In the shorter term, if blood calcium levels are too low, osteoclasts destroy bone to release the mineral. Conversely, if exercise produces larger muscles, osteoblasts get to work building new bone to withstand their pull. *—Christine Soares*

AIDS AND HIV

The viral infection's origin among apes might hold a key for someday taming it



A cquired immunodeficiency syndrome (AIDS) received its utilitarian name in 1982, a year after U.S. doctors recognized an epidemic of pneumonias, rare cancers and assorted bacterial infections among mostly male, mostly young and mostly previously healthy adults. The next year French researchers isolated the cause of the immune system collapse that defined the syndrome: a virus that selectively infects and destroys immune cells themselves.

The human immunodeficiency virus (HIV), which today resides in more than 30 million people and seemed to come out of the blue in the early 1980s, is now known to have been infecting humans for at least a century. Recent studies of preserved tissue samples show HIV present in the former Belgian Congo in 1959, in Haiti by 1966 and possibly in the U.S. as early as 1969. The historic specimens also let scientists calibrate "molecular clocks" to trace the evolution of the virus back to its first appearance in humans.

Those analyses place the emergence of the most widespread HIV strain, known as group M, in southern Cameroon around 1908. Its ancestor was likely a virus that has been infecting West African chimpanzees since 1492, according to another recent molecular clock study. If so, many rural people were surely exposed to simian immunodeficiency syndrome (SIV) over the centuries through live chimps or in bush meat before the infection caught hold in the human population. Scientists are consequently keen to figure out what allowed "successful" SIV strains to adapt to our species and begin spreading as HIV.

AIDS researchers are also intensively studying the behavior of SIV in its native host because although the simian virus is nearly identical to HIV, in wild chimps it is generally benign. The immune cells of our closest primate cousins get infected, too, but eventually manage to rally and reconstitute their numbers. The origin of the devastating syndrome that is AIDS therefore lies in some combination of minute changes in HIV itself—and the human body's responses to it—and remains a mystery. *—Christine Soares*

NEWLY FORMED HIV particle buds from a cell membrane. The virus hijacks immune cells to copy itself, killing them in the process.

PHOTO RESEARCHERS, INC.

RELIGIOUS THOUGHT

Belief in the supernatural may have emerged from the most basic components of human cognition

God may or may not exist, but His followers certainly do. Nearly every civilization worships some variety of supernatural power, which suggests that humans are hard-wired to believe in something that, by definition, is not of this world. But why? Evolutionarily speaking, how could belief in something in the absence of physical evidence have aided the survival of early *Homo sapiens*?

Evolutionary biologists Stephen Jay Gould and Richard Lewontin of Harvard University proposed that religious thinking is a side effect of tendencies that more concretely help humans to thrive. Perhaps the most primitive is our "agency detector," the ability to infer the presence of others. If the grass rustles in the distance, our first instinct is that someone or something may be lurking. This propensity has obvious evolutionary advantages: if we are right, we have just alerted ourselves to a nearby predator. (And if we are wrong, no harm done and we can get back to picking berries.)

In addition, humans instinctually construct narratives to make sense of what may be a disconnected jumble of events. Nassim Nicholas Taleb, author of *The Black Swan* and a professor of risk engineering, calls this the "narrative fallacy"—we invent cause-and-effect stories to explain the world around us even if chance has dictated our circumstances. Gods, empowered with omnipotence and shielded from natural inquiry, can be used to explain any mysterious event.

Finally, humans can imagine the thoughts and intentions of others and imagine that they are different from our own, a trait known as theory of mind. The condition, which is severely diminished in autistic children, is so fundamental to what it is to be human that it might be a necessary precondition for civilization. It is a small step from imagining the mind of another person—even if you have no direct access to it—to imagining the mind of a deity.

Taken together, the evolutionary adaptations that made the garden of human society flourish also provided fertile ground for belief in God. Of course, it is impossible to transport ourselves back to early civilization to rigorously test these ideas, so perhaps one more idea about the divine will have to wait for verification. *—Michael Moyer*

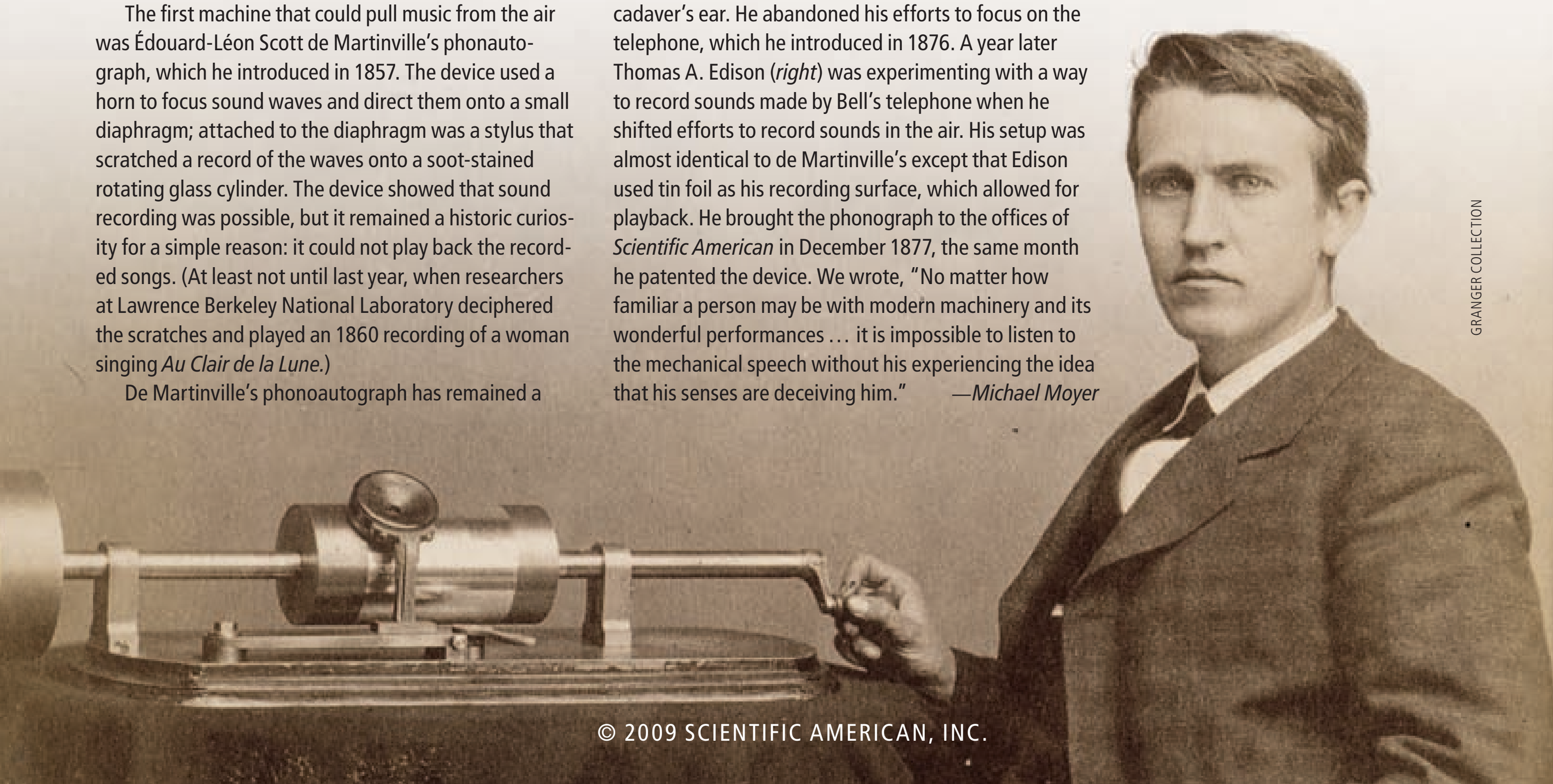
RECORDED MUSIC

The first recordings remained silent for 150 years

In the ninth century Persian scholars invented the first known mechanical instrument, a hydropowered organ that played music preprinted onto a rotating cylinder. It would be 1,000 years before inventors cracked the reverse process—printing sounds onto a storage device.

The first machine that could pull music from the air was Édouard-Léon Scott de Martinville's phonautograph, which he introduced in 1857. The device used a horn to focus sound waves and direct them onto a small diaphragm; attached to the diaphragm was a stylus that scratched a record of the waves onto a soot-stained rotating glass cylinder. The device showed that sound recording was possible, but it remained a historic curiosity for a simple reason: it could not play back the recorded songs. (At least not until last year, when researchers at Lawrence Berkeley National Laboratory deciphered the scratches and played an 1860 recording of a woman singing *Au Clair de la Lune.*)

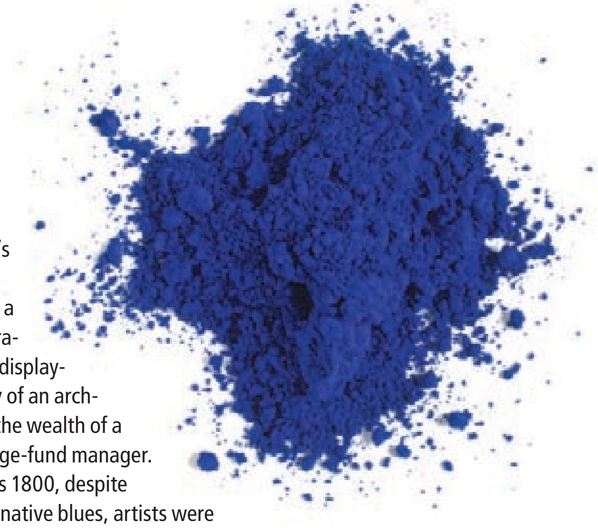
De Martinville's phonoautograph has remained a quaint footnote, but his basic architecture of a horn, diaphragm, stylus and cylinder provided the foundation for all sound recording for the next 70 years. In 1874 Alexander Graham Bell experimented with sound recording using de Martinville's architecture, except he used a cadaver's ear. He abandoned his efforts to focus on the telephone, which he introduced in 1876. A year later Thomas A. Edison (*right*) was experimenting with a way to record sounds made by Bell's telephone when he shifted efforts to record sounds in the air. His setup was almost identical to de Martinville's except that Edison used tin foil as his recording surface, which allowed for playback. He brought the phonograph to the offices of *Scientific American* in December 1877, the same month he patented the device. We wrote, "No matter how familiar a person may be with modern machinery and its wonderful performances … it is impossible to listen to the mechanical speech without his experiencing the idea that his senses are deceiving him." *—Michael Moyer*



GRANGER COLLECTION

THE COLOR BLUE

The natural pigment was once a "precious" color



Looking for the perfect blue? You'll have to specify. Cobalt, Prussian, azurite or ultramarine? According to Philip Ball's book *Bright Earth,* if you were an artist living in the 14th century, the finest blue could cost you a king's ransom. We can't even reproduce it in this magazine—it's not part of the gamut, or achievable range of colors, that can be rendered by the four "process colors" of ordinary printing.

The oldest man-made blue—the oldest synthetic pigment, period—is "Egyptian" blue. Color makers fired a mixture of one part lime, one part copper oxide and four parts quartz in a kiln, which left an opaque blue material that can be ground to a fine powder for making paint. The stuff occurs on Egyptian artifacts dating to around 2500 B.C. and was still in use when Mount Vesuvius buried Pompeii in A.D. 79.

In the Middle Ages color became central to the alchemists' obsession with transmutation. And the alchemists' great contribution to artists' blue was ultramarine. It is made from blue lapis lazuli, a semiprecious stone then mined in Afghanistan. The costly raw material and elaborate preparation—which involved endless kneading of the lapis powder and washing in lye—led to the deep, rich, dark blue seen, as Ball points out, in paintings of the robe of the Virgin Mary. The medieval painter's patron who could afford a Virgin in ultramarine was displaying the piety of an archbishop and the wealth of a modern hedge-fund manager.

As late as 1800, despite several alternative blues, artists were still seeking a less costly substitute to ultramarine. In 1824 the French Society for the Encouragement of National Industry offered 6,000 francs for an industrial process that could make a synthetic ultramarine for less than 300 francs a kilogram. A color manufacturer named Jean-Baptiste Guimet claimed the prize, and by the 1870s the snob appeal of the natural pigment had died out—killed by time and a price between 100 and 2,500 times higher than the synthetic variety. Industrial ultramarine became the blue of choice in the work of Impressionists such as Renoir, Cézanne and van Gogh. —*Peter Brown*

SUSANNA PRICE *Getty Images*

FACIAL EXPRESSIONS

Our unique expressiveness may have a three-million-year-old pedigree

Two eyes positioned above a pair of nostrils that are themselves perched above a mouth—such is the layout of the face for vertebrate creatures ranging from sharks to humans. However well that arrangement may be optimized for finding and eating food, among mammals the face has taken on another critical role: communication. Nowhere is this function more apparent than in the human visage.

Primates in general have complex social lives, and they commonly use facial expressions in their interactions with one another. We humans have particularly expressive faces with which we convey such emotions as fear, happiness, sadness and anger. Researchers once chalked up the rich repertoire of human expressions to our having uniquely specialized facial muscles. But physical anthropologist Anne Burrows of Duquesne University has found that, in fact, the chimpanzee—the next most dramatic primate—differs little from humans in the musculature of its mug.

Two features, though, do separate human facial expressions from those of the rest of the primate pack. First, we have distinctive sclerae, or whites, around our irises. Second, our lips protrude from our faces and are darker than the surrounding skin. These traits provide our countenances with strong visual contrasts that may well better telegraph our feelings.

Exactly when and how humans evolved such animated faces is unknown, but clues might be found in the fossilized skulls of our ancestors. Endocasts—casts of the impression the brain leaves on the interior of the skull—offer insights into the changing capabilities of brain regions over time. In 2000 paleoneurologist Dean Falk, now at Florida State University, led an analysis of endocasts from the ancient hominid *Australopithecus africanus,* which lived between three million and two million years ago. The results showed that parts of that creature's anterior temporal region were larger than those of apes. That enhancement might have made this human predecessor better at processing information about visages. If so, our propensity for making and reading faces may have very deep roots indeed. —*Kate Wong*

JASON HETHERINGTON *Getty Images*

GAMMA RAYS

To create one typically means you have to destroy something, be it a single particle or an entire star

Gamma rays are like cheetahs: they are the charismatic megafauna of the particle world. They are light of the maximum possible potency, usually defined as a wavelength shorter than 10^{-11} meter—a realm where light's wave nature is hard to observe and its particulate nature stands out. Each gamma photon has an energy of more than 100 kilo-electron-volts (keV), 100,000 times more than a photon of visible light. The mightiest gamma ever recorded packed a punch of 100 tera-electron-volts (TeV), far outgunning anything particle physicists can blast out with their most powerful instrument, the Large Hadron Collider.

Creating such extreme particles takes commensurately extreme processes: the collision of particles moving at nearly the speed of light; the annihilation of matter and antimatter, which converts their mass entirely into energy, per Einstein's famous equation $E = mc^2$; the leakage of energy out of black holes; and the release of nuclear energy in radioactive decay or fusion reactions. (Technically, all photons emitted by atomic nuclei are classified as gamma rays, even the rare ones of less than 100 keV.) As extreme as these processes may be, we bask in their glow every day: sunlight started off as gamma radiation in the sun's core and degraded into visible light during its tortuous passage through the overlying layers of gas.

The gammas of greatest interest to astronomers, though, come from things that are dead, dying or deadly. When a massive star blows up in a supernova explosion, its debris sparkles with gamma rays, and the stellar corpse left behind—a neutron star or black hole—has such intense gravity that it drives the ongoing generation of gammas. At the centers of galaxies, black holes with the mass of a billion stars suck in material, some of which does not fall all the way in but squirts back out as jets that set off shock waves and generate gammas. Some gammas have yet to be traced to a source and might come from the decay or annihilation of particles not yet known to science. If the starry night sky seems tranquil and gentle, gamma rays betray the true violence of the universe. —*George Musser*

LIGHT

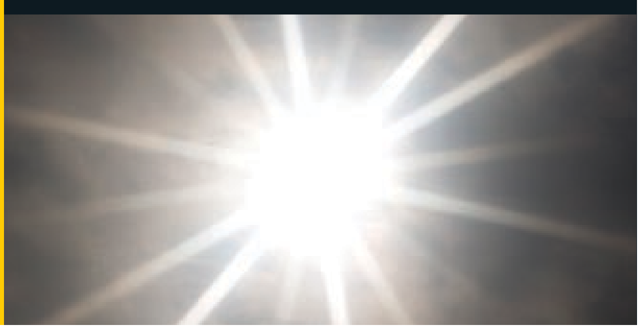
It emerged not with a quick flip of the switch but with a slow breaking of the dawn

In the book of Genesis, all God had to do was say the word. In modern cosmology, the creation of light took rather more effort. The familiar qualities of light—an electromagnetic wave, a stream of particles called photons, a source of information about the world—emerged in stages over the first millennia of cosmic history.

In the very earliest moments, electromagnetism did not operate as an independent force but was interwoven with the weak nuclear force that governs radioactive decay. Those combined electroweak forces produced a phenomenon recognizable as light, but more complicated. For instance, there was not one but two forms of ur-light, made up of particles known as *B* and *W* bosons. By 10^{-11} second, the universe had cooled enough for electromagnetism to make a clean break from the weak force, and the bosons reconfigured themselves to give rise to photons.

The photons were thoroughly mixed in with material particles such as quarks. Together they formed an undifferentiated soup. Had you been alive, you would have seen a blinding, featureless glow all around you. Lacking color or brightness variations, it was as unilluminating as absolute darkness. The first objects with some internal structure did not emerge until 10 microseconds, when quarks agglomerated into protons and neutrons, and 10 milliseconds, when protons and neutrons began to form atomic nuclei. Only then did matter start to leave a distinctive imprint on light.

At about 380,000 years, the soup broke up and light streamed across space in more or less straight lines. At last it could illuminate objects and form images. As this primordial light dimmed and reddened, the universe passed through a gloomy period known as the Dark Ages. Finally, at an age of 300 million years or so, the first stars lit up and the universe became able to generate new light. In Genesis, light emerged before matter, but in physics, the two emerged together. *—George Musser*



CHOCOLATE

Mixing the bitter treat with milk was the popular breakthrough

Chocolate was a favorite drink of the Maya, the Aztecs and other Mesoamerican peoples long before the Spaniards "discovered" it and brought it back to Europe. Archaeological evidence suggests that chocolate has been consumed for at least 3,100 years and not just as food: the Maya and other pre-Columbian cultures offered cacao pods to the gods in a variety of rituals, including some that involved human sacrifice.

But it was an Irish Protestant man who had what might be the most pivotal idea in chocolate history. In the 1680s Hans Sloane, a physician and naturalist whose estate—a vast collection of books and natural specimens—kick-started the British Museum, was in service to the British governor of Jamaica, collecting human artifacts and documenting local plants and animals. Sloane realized that the bitter local chocolate beverage would become much more palatable to his taste when mixed with milk. He later patented his invention. Although many had been enjoying chocolate made with hot water, Sloane's version quickly became popular back in England and elsewhere in Europe. Milk also became a favorite addition to solid chocolate, and today around two thirds of Americans say they prefer milk chocolate to dark chocolate.

Chocolate's positive health effects are by now well documented. Antioxidants such as polyphenols and flavonoids make up as much as 8 percent of a cacao bean's dry weight, says Joe Vinson, a chemist at the University of Scranton. Antioxidants neutralize highly reactive molecules called free radicals that would otherwise damage cells. And it is not a coincidence that the cacao tree (and other antioxidant-rich plants such as coffee and tea) would originate from low latitudes. "Things that have high levels of antioxidants tend to grow in places near the equator, with lots of sun," Vinson says. The sun's ultraviolet rays break up biological molecules into free radicals, and these plants may produce antioxidants to better endure the stress.

Although eating too much chocolate results in excessive calorie intake, human and animal studies have shown that moderate chocolate consumption can have beneficial effects on blood pressure, slow down atherosclerosis and lower "bad" cholesterol. Chocolate may also be good for the mind: a recent study in Norway found that elderly men consuming chocolate, wine or tea—all flavonoid-rich foods—performed better on cognitive tests. *—Davide Castelvecchi*

ELLINOR HALL *Getty Images (sun)*; GETTY IMAGES *(chocolate)*

INTERNAL-COMBUSTION ENGINE

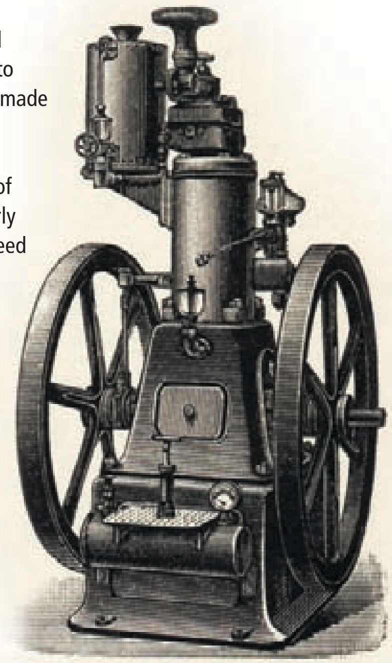
Still powering the world's vehicle fleet 130 years on

Nearly every vehicle on the road today is powered by some version of the four-stroke internal-combustion engine patented by Nikolaus Otto in 1876 (*right*). Otto exploited the findings of French physicist Sadi Carnot, who in 1824 showed that the efficiency of an engine depends critically on the temperature differential between a hot "source" of energy and a cold "sink." The four-stroke engine compresses an air-fuel mixture and ignites it with a spark, thus creating a fleeting but intense source of heat. Its portable efficiency has not been matched since.

Yet some consider the internal-combustion engine an anachronism, a dangerously out-of-date vestige of a world that assumed oil was unlimited and the climate stable. The best hope for displacing the engine appears to be an electric motor powered by an energy store such as chemical batteries or a hydrogen-powered fuel cell. What many forget is that electric vehicles had their chance—indeed, they were far more popular than gasoline-powered cars in the late 19th and early 20th century. They could go all day on a single charge and move a driver around a city with ease. They did not require a hand crank to start and did not have gears to shift, both of which made gas-powered vehicles of the day as user-friendly as heavy machinery.

Electric vehicles were more suited to the world of the 19th century than the 20th, however. Those early vehicles could go all day on one charge because speed limits were set between seven to 12 miles per hour to accommodate horse-drawn carriages. When those limits rose after World War I and travel between cities and towns became the norm, gasoline-powered vehicles began to dominate the auto market.

Since then, automakers have invested untold billions into increasing the efficiency of the modern four-stroke engine. Until electric cars can surpass the power and range of vehicles afforded by gas, expect the internal-combustion engine to continue its long reign. —*Michael Moyer*



SHEILA TERRY *Photo Researchers, Inc.*

ORIGINS

CUPCAKES

The yummy baked good is one of America's first and finest contributions to world cuisine

Like many acts of pure genius, the invention of the cupcake is lost in the creamy fillings of history. According to food historian Andrew Smith, the first known recipe using the term "cupcake" appeared in an American cookbook in 1826. The "cup" referred not to the shape of the cake but to the quantity of ingredients; it was simply a downsized English pound cake. Lynne Olver, who maintains a Web site called the Food Timeline, has tracked down a recipe for cakes baked in cups from 1796. But we will probably never know the name of the first cook to take the innovative leap or whether it had anything to do with a six-year-old's birthday party. "Just like other popular foods—the brownie comes to mind—it's impossible to pinpoint a date of origin for the cupcake," says culinary historian Andrea Broomfield.

That cook almost certainly lived on the left bank of the Atlantic. Broomfield says that the earliest known cupcake recipes in England date to the 1850s and that their popularization was slow. One writer in 1894 had evidently never heard of cupcakes: "In Miss [Mary E.] Wilkins's delightful New England Stories, and in other tales relating to this corner of the United States, I have frequently found mention of cup-cake, a dainty unknown, I think, in this country. Will some friendly reader … on the other side of the Atlantic kindly answer this query, and initiate an English lover of New England folks and ways into the mysteries of cup-cake?" Even to this day true cupcakes—as opposed to muffins or cakes cut up into cup-size portions—are sadly uncommon in Europe.

In recent years the U.S. has had something of a great cupcake awakening, as blogs and bakeries have devoted themselves to its pleasures. Some attribute this renewed popularity to the cupcake-indulging characters of HBO's *Sex and the City,* and food historian Susan Purdy also credits dietary awareness: you can have your low-calorie cake and eat it, too. But true connoisseurs needed no moment of rediscovery. They never forgot what it was like to be six. —*George Musser*

APPENDIX

Not needed, but not useless

Many have speculated that it exists to keep surgeons in business. Leonardo da Vinci thought it might be an outlet for "excessive wind" to prevent the intestines from bursting. The great artist and anatomist was not entirely off base in that the human appendix does appear to have originated at a time when primates ate plants exclusively, and all that fiber was tougher to digest.

The intestinal offshoot formally known as the vermiform appendix is a long, slender cavity, closed at its tip. It branches off the cecum, which is itself a big pouch at the beginning of the large intestine that receives partly digested food emptying from the small intestine. While food stalls in the cul de sac of the cecum, friendly gut microbes help to break it down further. Some of today's herbivorous animals, such as rabbits and koalas, have a large appendix, filled with specialized cellulose-digesting bacteria for the same purpose. Yet plenty of plant-eating mammals, including some monkeys, have no appendix at all, relying on an enlarged cecum to break down plants. Because the appendix seems to be optional even among primates, biologists cannot simply infer that ours is a shrunken legacy from a common ancestor with the bunny. Rather the primate appendix and the appendices of other herbivorous mammals appear to have evolved independently as extensions of the cecum—perhaps for the same digestive purpose—but the human appendix has long since lost that function.

Serving as a repository for food and benign digestive bugs, though, may have created a secondary role for the appendix, at least early in life. Its inner lining is rich in immune cells that monitor the intestinal environment. During the initial weeks of infancy, the human gut is first populated with its normal, healthy complement of symbiotic microbes; the appendix may be a training center to help naive immune cells learn to identify pathogens and tolerate harmless microbes. If it hasn't already been removed in early adulthood, the opening of the appendix cavity closes entirely sometime in middle age. But by that time its purpose may have been served. —*Christine Soares*

GETTY IMAGES (*cupcake*); SCOTT CAMAZINE *Photo Researchers, Inc.* (*appendix*)

THE WEB

The global information resource spun out of research into fundamental physics

When Tim Berners-Lee sketched out what we now know as the World Wide Web, he offered it as a solution to an age-old but prosaic source of problems: documentation. In 1989 the computer scientist was working at CERN, the particle physics laboratory near Geneva, just as a major project, the Large Electron Positron collider, was coming online. CERN was one of the largest Internet sites in Europe at the time, home to thousands of scientists using a variety of computer systems. Information was stored hierarchically: a treelike central repository held documents at the end of its branches. Finding a file meant crawling up the trunk and out to the right leaf. Scientists who were new to CERN (and there were a lot of them—most researchers stayed only for brief, two-year stints) had a hard time figuring out which branches to venture onto to find the right information for their project.

In a proposal to CERN management that March, Berners-Lee suggested constructing a system that operated more like the working structure of the organization itself: "A multiply connected 'web' whose interconnections evolve with time," he wrote in *Information Management: A Proposal.* Information would no longer be stored on hierarchal trees; instead a forest of nodes would be connected by links. "When describing a complex system," he wrote, "many people resort to diagrams with circles and arrows.... The system we need is like a diagram of circles and arrows, where circles and arrows can stand for anything."

It was this agnosticism regarding content that gave what became the Web the power it has today. The system Berners-Lee finished on Christmas Day in 1990 was imbued with flexibility at every level: any file could be identified by its unique address, or Universal Resource Locator (URL). Behind the scenes, the Hypertext Transfer Protocol (HTTP) provided a uniform language for different types of computer systems to communicate with one another. And simple Hypertext Markup Language (HTML) linked documents together and specified how they should appear. Equally important, the components were made available free of charge to anyone who wanted them. Two decades later the World Wide Web has proven itself to be the most effective information dissemination platform ever created.

—*Michael Moyer*

TECTONIC PLATES

The long, strange trip of continental drift

Alfred Wegener's idea of continental drift wandered in the wilderness for the first few decades after he wrote about it in his 1915 book, *The Origin of Continents and Oceans.* Although some geologists marshaled further evidence for the theory, most remained skeptical because no plausible mechanism seemed capable of sending huge landmasses plowing through the ocean crust on long journeys across the surface of the earth.

The modern concept of moving tectonic plates emerged in 1962, proposed by Harry H. Hess of Princeton University. Hess had captained a U.S. Navy transport ship during World War II and used the vessel's sonar to map the Pacific Ocean floor along his travels. He hypothesized that all the earth's crust—oceanic as well as continental—was mobile, driven by convective motions in the underlying layer known as the mantle. New crust forms at mid-ocean ridges, where hot magma from the mantle wells up and crystallizes. The young crust spreads from the ridges, and old crust sinks back down at deep ocean trenches. In this way, the crust and the uppermost, solid portion of the mantle (together known as the lithosphere) are divided into moving plates.

Hess's ideas became accepted after studies found the magnetism of rock on the ocean floor matched predictions: the earth's magnetic field, which sporadically reverses polarity, leaves its imprint in solidifying rock, producing bands of alternating magnetism parallel to ocean ridges.

Continental drift thus has its roots in the immense heat coming from the planet's interior. Radioactive decay still produces the heat today. Yet scientists estimate that three billion years ago twice as much heat was emerging, leading to numerous hotspots with magma welling up, fragmenting the early lithosphere into many small tectonic plates. The first continents may have been not much larger than Iceland and a lot like it in other ways, too: for 16 million years or so Iceland (*below*) has been forming above a hotspot on the Mid-Atlantic Ridge. —***Graham P. Collins***

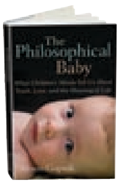
GETTY IMAGES

Babies' Brains ■ Naming Life ■ Fictional Reads

BY KATE WONG

➜ THE PHILOSOPHICAL BABY: WHAT CHILDREN'S MINDS TELL US ABOUT TRUTH, LOVE, AND THE MEANING OF LIFE

by Alison Gopnik. Farrar, Straus and Giroux, 2009 ($25)



Alison Gopnik, a professor of psychology at the University of California, Berkeley, argues that far from being irrational and limited in their ability to think, babies are smarter, more imaginative and more conscious than adults. Along the way, she examines such fascinating topics as why children pretend, how they discover the truth, the origins of love and morality, and how early life shapes later life. Understanding how children think can help adults become better parents—another subject Gopnik explores.

➜ VESUVIUS: A BIOGRAPHY

by Alwyn Scarth. Princeton University Press, 2009 ($29.95)

Writer Alwyn Scarth traces the violent history of Mount Vesuvius—from its destruction of Pompeii in A.D. 79 to its most recent eruption in 1944. What might the future hold for this, the most dangerous volcano in all of Europe? Scarth discusses the warning signs of an eruption and considers current contingency plans for the 600,000 people who live in the 236-square-kilometer area around the summit of this ferocious force of nature.

EXCERPT

➜ NAMING NATURE: THE CLASH BETWEEN INSTINCT AND SCIENCE

by Carol Kaesuk Yoon. W. W. Norton, 2009 ($27.95)

Biologist and journalist Carol Kaesuk Yoon explores humanity's long-standing obsession with naming living things. Here she describes how the modest barnacle—which 16th-century scholars believed came from plants known as "Barnakle Trees" and themselves concealed miniature geese called barnacle geese—tricked even 18th-century father of systematic classification Carl Linnaeus.

"Picture a barnacle. You probably envision something hard, white, salt-encrusted, sharp, and stuck onto something else, like a boat bottom. And though they seem more rocklike than lifelike at first glance, at second glance they may begin to remind you of a limpet perhaps, or a mussel, or some other sea creature with a formidable hard outer shell, softer more vulnerable parts tucked inside, and zero mobility. The barnacle, most people would say, belongs with what are clearly its like kind, the clams, snails and so on; that is, it would appear to be a mollusk. And this is exactly how Linnaeus ordered it.

"… It was the group he called 'The Worms.' So the barnacles fell in, at the master's hand, as they would likely have at any one of ours, with the mollusks. And there barnacles remained, more or less, for another half century or so.

"Not that anyone was terribly worried about them. Compared with trumpeting elephants or towering oak trees, barnacles were just kind of hard for naturalists to get worked up about. If there were a living creature whose understanding would shake the very foundations of the ordering of life, the barnacle seems the least likely candidate. But there was much more to those tiny shuttered creatures than anyone suspected."

ALSO NOTABLE

NONFICTION

- **Darwin's Armada: Four Voyages and the Battle for the Theory of Evolution**
  by Iain McCalman. W. W. Norton, 2009 ($29.95)
- **Not a Chimp: The Hunt to Find the Genes That Make Us Human**
  by Jeremy Taylor. Oxford University Press, 2009 ($27.95)
- **The Nature of Technology: What It Is and How It Evolves**
  by W. Brian Arthur. Free Press, 2009 ($27)

- **Smithsonian Atlas of Space Exploration**
  by Roger D. Launius and Andrew K. Johnston. Bunker Hill Publishing, 2009 ($34.99)
- **Crow Planet: Essential Wisdom from the Urban Wilderness**
  by Lyanda Lynn Haupt. Little, Brown, 2009 ($23.99)

FICTION FOR ADULTS

- **Pythagoras' Revenge: A Mathematical Mystery**
  by Arturo Sangalli. Princeton University Press, 2009 ($24.95)
- **Ultimatum**
  by Matthew Glass. Grove/Atlantic, 2009 ($24)

FICTION FOR KIDS

- **The Evolution of Calpurnia Tate**
  by Jacqueline Kelly. Henry Holt, 2009 ($16.99)
- **The Unknowns: A Mystery**
  by Benedict Carey. Amulet Books, 2009 ($16.95)

EXHIBITS

- **Lucy's Legacy: The Hidden Treasures of Ethiopia and Titanic: The Artifact Exhibition**
  June 24–October 25 at the Discovery Times Square Exposition in New York City.
- **Farmers, Warriors, Builders: The Hidden Life of Ants**
  May 30–October 10 at the Smithsonian National Museum of Natural History in Washington, D.C.

COURTESY OF DEBORAH SMAIL *Houston Museum of Natural Science (Lucy)*

Cache and Carry

The best answer yet to what's black and white and read all over

BY STEVE MIRSKY

I'm not your classic "early adopter" when it comes to new electronic gizardry (a word I just made up that means a combination of gizmo and wizardry, with a secondary definition of bird digestion). I'm not even what one ersatz electronics guru referred to as an "early adapter," although I do sometimes wonder if my purpose in life has been reduced to making sure my various devices are all plugged in correctly.

So I'm a bit surprised to be a longtime owner (since February!) of a second-generation Amazon Kindle. The e-reader looks both futuristic and pedestrian, like something Harrison Ford in *Blade Runner* might be reading from and then bleeding on.

My sister, who travels a great deal for work and is fond of airplane fiction of the Dan Brown and Robin Cook schools, adopted a first-generation model early. Borrowing hers, I was thus able to experiment when I had some travel of my own. I usually take a bunch of books on the road. So I weighed the Kindle against the books—seriously, I put them on a scale—and promptly decided to get one of them there newfangled, thin, low-mass reading machines of my own.

Amazon sells Kindle versions of many new books at a discount. But one of the first things I discovered is how much stuff you can cram on it that is totally free. Project Gutenberg, which is trying to get everything that's now off copyright onto the Web, has posted thousands of classics, and it's easy to download them in seconds on a home computer and then move them over to the Kindle. Three decades ago I bought (but still have not read) a copy of *The Brothers Karamazov,* which sits on a shelf at home. Now, with the Kindle, in less than five months I already have not read the electronic edition of *The Brothers Karamazov* on three continents.

(By the way, the 1958 movie version of that book stars a very young, very subdued William Shatner, who later, as Captain Kirk, was often handed a Kindle-looking device, which he then invariably glanced at, signed and returned. So rather than being an e-reader, it was probably a deep-space requisition-generating machine with which to authorize the purchase of red Starfleet shirts, which are tough to keep in stock.)

Users can also easily move PDF and text documents over to the device. So instead of printing out the 125 pages of manuscripts and proposals that we may go over in a given editorial meeting, I just load the whole PDF onto the Kindle. At the meeting, it's then a snap to shuttle between the editorial notes and a Dan Jenkins golf novel called *Slim and None,* which unfortunately also describes the chances that I will read *The Brothers Karamazov* before you read this column.

But the Kindle is not without its drawbacks. The ease with which one can sample a book's first chapter for free and then buy the complete work can lead the less careful reader astray. That was how, before a recent flight to London, I wound up getting a Dean Koontz best seller called *Relentless*. The plot was man-bites-dog intriguing: a novelist gets a bad review, after which the reviewer appears to be intent on tracking down and killing the writer.

But then (SPOILER ALERT!, although "spoiler" suggests there is something that could be ruined), I unexpectedly descended into a Bizarro world of good-guy survivalists, bad-guy intellectuals and a six-year-old physics supergenius named Milo who actually *does* read Dostoyevsky, albeit a comic book edition of *Crime and Punishment*. I was alternately shaking and scratching my head long before Milo builds a teleportation apparatus that can't handle the boy's weight but can deal with the 10-pounds-lighter family dog. Which quickly learns how to teleport itself without the device. You know, the way Pavlov's dogs learned to salivate without the food. With his new power, the dog foils a nefarious plot. Woof.

In the climactic confrontation, Milo saves the day with salt shakers that he's converted into localized, short-interval time-reversal machines (of the *Galaxy Quest* Omega 13 variety). The six-year-old undoes the murder of his father, the novelist, who, given a second chance, gets the jump on his assailant, the reviewer's mother, head of a giant conspiracy to lower American cultural standards. (I'm not kidding, that's the actual plot.) Which leads me to the biggest drawback of the Kindle: at $299, you can't really afford to hurl it into the Thames. ■

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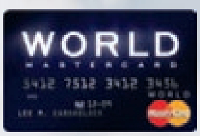

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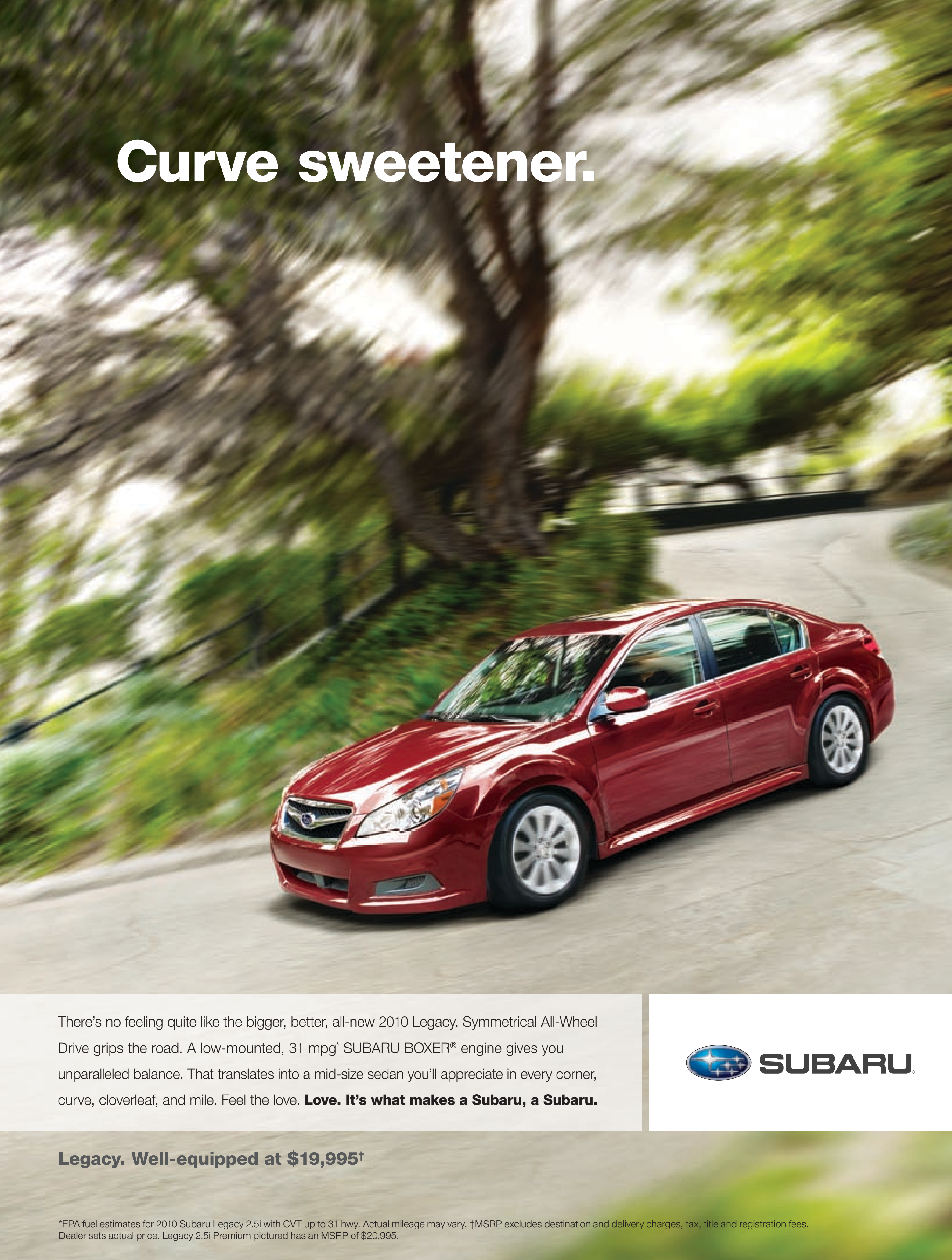
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