WORKING ON MARS
A Moon-Walking Scientist Tells How

SQUASHING SUPERBUGS
The Race for New Antibiotics

SCIENTIFIC AMERICAN

July 2009 $5.99 U.S. U.K. £4.10 www.ScientificAmerican.com

Forensic Tools Battle IVORY POACHERS
page 56

GRASSOLINE

Forget ethanol from corn. New fuels made from weeds and waste could halve U.S. oil needs

The Science of Economic Bubbles and Busts

Evolutionary Roots of Your Right and Left Brain

KENN BROWN

ON THE COVER

Grasses and other plants are rich in cellulose that can be converted into alternatives to gasoline—but at what price?
Image by Kenn Brown, Mondolithic Studios.

GO TO SCIENTIFICAMERICAN.COM

SLIDE SHOW: LIFE AT THE MARINE MONUMENTS ▼

The U.S.'s three new national marine monuments host a bounty of life that is now protected.
More at **www.ScientificAmerican.com/jul2009**

D. BRUMBAUGH *Center for Biodiversity and Conservation, American Museum of Natural History*

60-Second Science Blog
Monkey See, Monkey Regret

Researchers used a simian version of the game show *Let's Make a Deal* to test whether monkeys, like humans, wonder about what might have been.

Slide Show
Seven Artificial Valves That Lend Hearts a Helping Hand

Artificial designs have evolved over the past five decades to successfully replace natural valves.

60-Second Earth Podcast
Cash for Clunkers

Is the government's plan to pay people for trading in old, inefficient vehicles an environmental bane or boon?

News
Growth Industry: Honeybee Numbers Expand Worldwide as U.S. Decline Continues

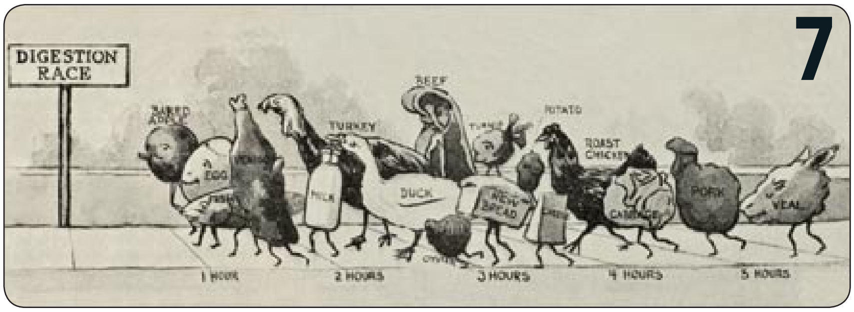
Populations in the U.S. and Europe have been hit hard, but honeybees are on the rise elsewhere.

60-Second Science Podcast
Elderly Who Forget Age Remember Better

In a study, senior citizens who were reminded of their age and of stereotypes about aging performed worse on memory tests than secure seniors did.

Scientific American (ISSN 0036-8733), published monthly by Scientific American, Inc., 75 Varick Street, 9th Floor, New York, N.Y. 10013-1917. Copyright © 2009 by Scientific American, Inc. All rights reserved. No part of this issue may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying and recording for public or private use, or by any information storage or retrieval system, without the prior written permission of the publisher. Periodicals postage paid at New York, N.Y., and at additional mailing offices. Canada Post International Publications Mail (Canadian Distribution) Sales Agreement No. 40012504. Canadian BN No. 127387652RT; QST No. Q1015332537. Publication Mail Agreement #40012504. Return undeliverable mail to Scientific American, P.O. Box 819, Stn Main, Markham, ON L3P 8A2. Subscription rates: one year $34.97, Canada $49 USD, International $55 USD. Postmaster: Send address changes to Scientific American, Box 3187, Harlan, Iowa 51537. **Reprints available:** write Reprint Department, Scientific American, Inc., 75 Varick Street, 9th Floor, New York, N.Y. 10013-1917; (212) 451-8877; fax: (212) 355-0408. **Subscription inquiries: U.S. and Canada (800) 333-1199; other (515) 248-7684. Send e-mail to sacust@sciam.com** Printed in U.S.A.

DEPARTMENTS



My Moon Landing

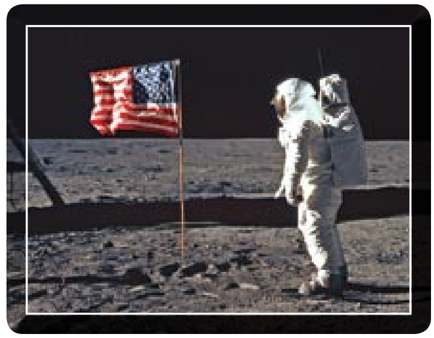
Forty years ago this month I walked on the moon with Neil Armstrong and Buzz Aldrin. The odds are good that you did, too, if you were within the reach of a television or radio on that July 20. My family and 10-year-old self were vacationing on Cape Cod at the time, but my attention was mostly 230,000 miles overhead. With whelk shells in the silky white dunes, I rehearsed the lunar module's landing dozens of times along audacious flight plans that NASA would no doubt have discouraged.

For days I watched news anchor Walter Cronkite take America on tours of mission control and interview scientists and engineers about what the astronauts might find in the Sea of Tranquillity. Film clips recalled past fantasies of lunar exploration, from the French 1902 short *Le Voyage dans la Lune* to the 1950 classic *Destination Moon*. To this day, I remember learning about the Great Moon Hoax of 1835, which claimed that telescopes had seen bat-winged humanoids flitting through lunar caverns.

But even without bat people on the moon, the universe we were expanding into felt glorious. And that was why my family and I (and probably you and yours) cheered on that late Sunday afternoon when the *Eagle* lander touched down safely. That night I stayed up past my bedtime to watch every second of grainy televised footage of Armstrong and Aldrin on the lunar surface. Every detail of what I heard and saw after the "That's one small step for man" speech is a blur today and might have been at the time, too, because the overwhelming thought in my head was that *we were on the moon*.

That is why I have always felt that part of the absolute best popular science writing can do is to bring audiences along with the scientists and help them share personally in the adventure of those explorations, even if the scientists never wander outside a laboratory and the readers never wander outside a comfortable chair.

Twenty years ago this month I walked in the door and found a desk at *Scientific American*. It was both intimidating and exciting to be working at the source of such classic, inspirational articles as Harry J. Jerison's 1976 piece on comparative brain size and evolution, Alan H. Guth and Paul J. Steinhardt's 1984 essay on the inflationary theory of cosmology and R. W. Sperry's 1964 description of split-brain studies. After nearly 15 years as editor in chief, I still find it intimidating and exciting.



REMEMBER how that felt?

That is time enough for racking up accomplishments (and mistakes); for my own sake and *Scientific American*'s, I am taking another walk. But I am overjoyed that Mariette DiChristina, our executive editor for the past eight years, will be taking over for me: she will do a stupendous job of moving this magazine forward while protecting what makes it unique and valuable. Even if I had written this farewell differently, I would have lacked the space to express my gratitude and love for the colleagues here, past and present, who have supported, taught and befriended me beyond all bounds of duty. My last, best advice for anyone who seeks it is simply this: never forget what it meant when we were on the moon. ■

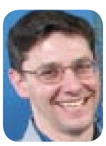
JOHN RENNIE
editor in chief

FLYNN LARSEN (*Rennie*); COURTESY OF NASA (*walking on moon*)

Among Our Contributors

BRUCE E. DALE is a leader of the Great Lakes Bioenergy Research Center and former chair of the chemical engineering department at Michigan State University.

MICHAEL A. FISCHBACH is assistant professor of bioengineering at the University of California, San Francisco, where he uses bioinformatics to identify genes for antibiotic peptides.

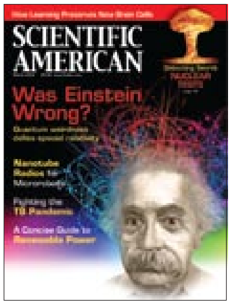


GEORGE W. HUBER is professor of chemical engineering at the University of Massachusetts Amherst and a pioneer in the innovative production of hydrogen fuel from biomass.

HARRISON H. SCHMITT is a geologist by training but piloted the lunar module for the last of the *Apollo* moon landings and later served as U.S. senator of New Mexico.

CHRISTOPHER T. WALSH is professor of biological chemistry and molecular pharmacology at Harvard Medical School, where he studies how cells synthesize antibiotics and other compounds.

Renewable Energy ▪ Tuberculosis ▪ Special Relativity



MARCH 2009

"Windmills on your roof need not generate anywhere near the number of volts required by big windmills."
—*Jeremy Gorman* WILMINGTON, VT.

Bigger Is Better?

I am concerned that, like most of our renewable efforts recently, Matthew L. Wald's overview of renewable energy technology, "The Power of Renewables," is oriented toward projects made by large corporations. This strategy will further entrench vested energy interests, when energy should be diffused to the general public. Windmills on your roof need not generate anywhere near the number of volts required by big windmills, which need to be matched and phased to the grid. And a rooftop windmill's output can be stored in batteries or large condensers that can be used as insulation. We should not miss an opportunity to capitalize on the ingenuity of individuals worldwide to provide local solutions.

Jeremy Gorman
Wilmington, Vt.

WALD REPLIES: *The dollars available for renewable energy equipment are finite and should be spent where they will produce the most energy and displace the most fossil fuels. Big windmills make more kilowatt-hours per dollar than small ones. Big solar installations cost less per megawatt than small ones (and big arrays in the deserts of the Southwest are a better investment of taxpayer subsidies than small rooftop arrays).*

Opposition to big corporations and opposition to global warming are two separate things; mixing them does not sit well with everybody.

Healthy Habitats

The narrow focus of Clifton E. Barry III and Maija S. Cheung's article "New Tactics against Tuberculosis" on "bugs and drugs" as the cause of and solution to TB infections misses the larger point of what works best to combat epidemic diseases. Only a small percentage of the decrease in TB infections can be attributed to microbe-specific interventions such as antibiotics and vaccines. Most of the decline has come from broader improvements in public health. That is not to say that pharmaceuticals are useless, but other factors are even more important. Moreover, nonspecific public health measures help with many unrelated diseases and are generally cheaper than medical care.

C. Andrew Aligne
University of Rochester

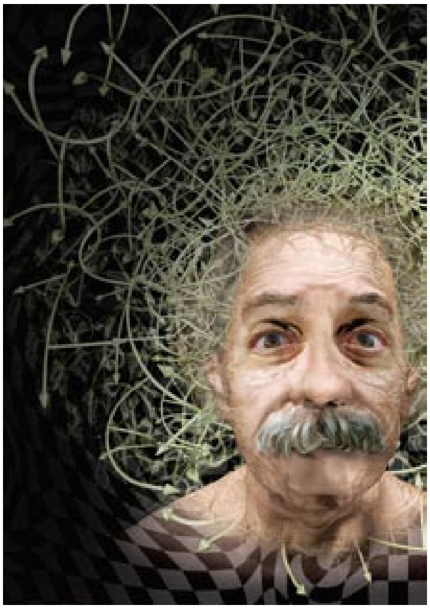
Electrodynamic Duo

In "A Quantum Threat to Special Relativity," David Z Albert and Rivka Galchen question the viability of special relativity because quantum mechanics demonstrates nonlocality, which special relativity does not allow. But the most successful physical theory we have—quantum electrodynamics—is a fully consistent amalgam of both theories that correctly predicts the results of practical experiments.

Lawrence R. Mead
University of Southern Mississippi

ALBERT AND GALCHEN REPLY: *Although quantum electrodynamics is mind-bogglingly good at predicting what the outcomes of a wide variety of experiments on quantum-mechanical systems are going to be, it is silent on the question of how such outcomes actually mechanically emerge. And this ques-*

tion is manifestly one to which any complete fundamental account of nature must provide an answer. Irish physicist John S. Bell's theorem discussed in our article demonstrates that any such answer must ineluctably introduce nonlocality into the world. And that nonlocality is the source of the tension with special relativity.



JEAN-FRANCOIS PODEVIN

QUANTUM ENTANGLEMENT, in which two particles behave synchronously with no intermediary, violates the locality required by Einstein's special theory of relativity.

The Conqueror Worm?

"Crawling to Oblivion," by Michael Tennesen [News Scan], presents the viewpoint that earthworms are detrimental to North American hardwood forests—a position that is not accepted by many earthworm scientists. The University of Minnesota research group of ecologist Cindy Hale referred to in the article has been making statements about the damaging invasion of U.S. forests by European earthworms over the past few years, but its claims are based on very little well-planned research.

Exotic earthworms in U.S. hardwood forests function similarly to those in Europe and many other places. They break down the undecomposed mat of organic matter (which in Europe is considered characteristic of relatively nonproductive soil), turning it into soil that promotes rapid tree growth. The conversion of leaf detritus to mineral compounds is a key process in the recycling and utilization of organic matter and does not rob plants of nutrients.

Clive A. Edwards
Ohio State University

HALE REPLIES: *Tennesen's article represents the consensus of many researchers and peer-reviewed publications, in particular a set of articles in the September 2006* Biological Invasions *with over a dozen authors.*

Edwards has built a career on the beneficial impacts of earthworms, based on research in agricultural systems, which we do not disagree with. I make a point of telling my audiences that everything they have heard about earthworms being good for agricultural systems is true. But our research is based on native forest ecosystems of North America. Edwards's contention that earthworms function basically the same in European forests as in North American forests is correct insofar as where earthworms are present they consume the litter layer, but beyond that the parallel falls apart. Earthworm-free, cold-temperate North American hardwood forests are diverse and naturally reproducing forests. Most hardwood forests in Western (and parts of Eastern) Europe, however, are beech-dominated. Earthworms are often absent in these forests because of very low pH. And when pH is increased, earthworms invade: the litter layer decreases, fertility and tree growth increases, but the increase in fertility is largely the result of the change in pH, not the earthworms.

ERRATUM "Monitoring for Nuclear Explosions," by Paul G. Richards and Won-Young Kim, should have stated that North Korea has reportedly separated plutonium, not uranium. And the box "How Monitoring for the Treaty Covers Earth" should have specified that the map is an estimate of the International Monitoring System's sensitivity, based on all 50 primary seismic stations being in operation (40 are now operating).

CLARIFICATION "Playing by Ear," by Steve Mirsky [Anti Gravity], states that the King Cobra LD driver is illegal in competition sanctioned by the U.S. Golf Association (USGA). Although the cited *British Medical Journal* report says the driver's coefficient of restitution exceeds the USGA limit, the USGA considers the driver to conform to its standards.

Letters to the Editor

Scientific American
75 Varick Street, 9th Floor
New York, NY 10013-1917
or editors@SciAm.com

Letters may be edited for length and clarity. We regret that we cannot answer each one. Post a comment on any article instantly at www.ScientificAmerican.com/sciammag

How to Contact Us

SUBSCRIPTIONS
For new subscriptions, renewals, gifts, payments, and changes of address: U.S. and Canada, 800-333-1199; outside North America, 515-248-7684 or www.ScientificAmerican.com

REPRINTS
To order reprints of articles: Reprint Department, Scientific American, 75 Varick Street, 9th Floor, New York, NY 10013-1917; 212-451-8877, fax: 212-355-0408; reprints@SciAm.com

PERMISSIONS
For permission to copy or reuse material: Permissions Department, Scientific American, 75 Varick Street, 9th Floor, New York, NY 10013-1917; 212-451-8877; www.ScientificAmerican.com/permissions or 212-451-8546 for procedures. Please allow three to six weeks for processing.

ADVERTISING
www.ScientificAmerican.com has electronic contact information for sales representatives of Scientific American in all regions of the U.S. and in other countries.

Electrons Clarified ▪ Baseball Illuminated ▪ Chess Excoriated

Compiled by Daniel C. Schlenoff

JULY 1959

WOLFGANG PAULI—"It is well known that theoretical physicists are quite inept in handling experimental apparatus; in fact, the standing of a theoretical physicist is said to be measurable in terms of his ability to break delicate devices merely by touching them. By this standard Wolfgang Pauli was a very good theoretical physicist; apparatus would fall, break, shatter or burn when he merely walked into a laboratory. Pauli's exclusion principle, on the other hand, acquired its importance because it helped to clarify the internal structure of the atom, according to Niels Bohr's model of the atom. —George Gamow"

➡ This article on Pauli's exclusion principle is at **www.ScientificAmerican.com/jul2009**

PLANT ALKALOIDS—"Since earliest times alkaloids (such as morphine and caffeine) have served man as medicines, poisons and the stuff that dreams are made of. Our self-centered view of the world leads us to expect that the alkaloids must play some comparably significant role in the plants that make them. It comes as something of a surprise, therefore, to discover that many of them have no identifiable function whatever. By and large they seem to be incidental or accidental products of the metabolism of plant tissues."

JULY 1909

DIGESTION—"We have prepared an engraving which shows the relative digestibility of foods of various kinds. It will be seen that the baked apple and the raw egg are near the winning post, the egg being tied by the fish. Then follows venison, all those being digested within an hour. The period of indigestibility is beautifully summed up in pork and veal, which require, under the most favorable conditions, five hours to digest. In the sixth hour and 'beyond' class, we find jam, crabs, and alcoholic beverages of various descriptions."

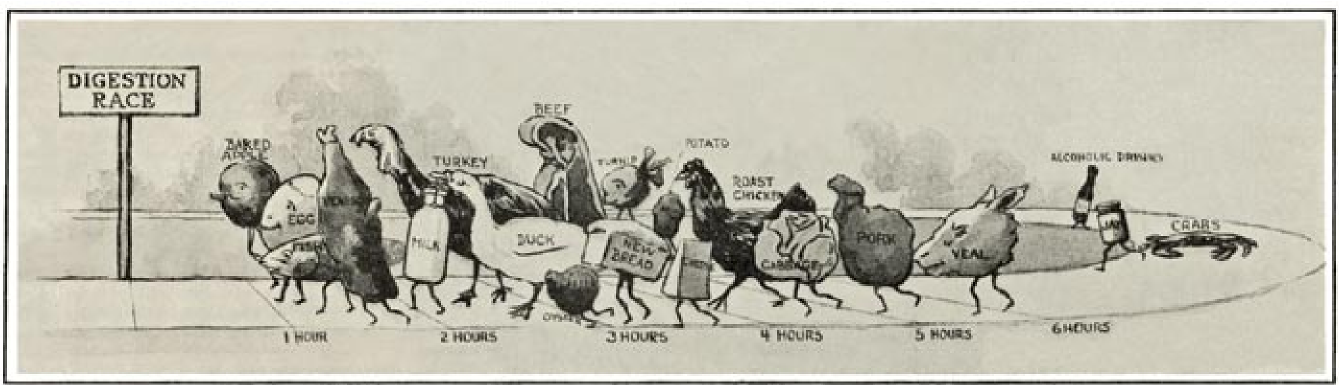
NIGHT GAMES—"The experiment of playing baseball by night was successfully made recently in Cincinnati. Powerful searchlights were employed to illuminate the baseball field. The Cincinnati National League Baseball Park, where the first night game was played [between the Elk Lodge of Cincinnati and the Elk Lodge of Newport, Ky.], was encircled with 100-foot steel towers, each carrying two extremely powerful carbon lamps. Every corner of the field was brightly illuminated by a total of fourteen lamps. The inventor of the lamps is George F. Cahill, who has taken a great interest in what may be termed the mechanical improvement of baseball playing."

[NOTE: The first night game in Major League Baseball was played on May 24, 1935, in Cincinnati.]

JULY 1859

FROTHY WATER—"The maelstrom is not a myth—the ancient accounts of the whirlpool on the coast of Norway were imposing for the terrors which were ascribed to it—a large boiling cauldron circling round in one great eddy, into which whales and ships were sometimes drawn and carried down forever beneath its horrid waters. That such a whirlpool does exist would appear to be true, but it is not such a terrific affair after all. M. Hagerup, the Minister of Norwegian Marine, states that the great whirl is caused by the setting in and out of the tides between Lofoden and Mosken, and is most violent half-way between ebb and flood tide."

DESCENT INTO CHESS—"A pernicious excitement to learn and play chess has spread all over the country, and numerous clubs for practicing this game have been formed in cities and villages. Why should we regret this? It may be asked. We answer, chess is a mere amusement of a very inferior character, which robs the mind of valuable time that might be devoted to nobler acquirements, while it affords no benefit whatever to the body. Chess has acquired a high reputation as being a means to discipline the mind, but persons engaged in sedentary occupations should never practice this cheerless game; they require out-door exercises—not this sort of mental gladiatorship."



FOOD RACE through the human body, according to a cartoon from 1909

SCIENTIFIC AMERICAN, VOL. CI, NO. 3; JULY 17, 1909

Mercury Cycle ■ Happiness and Choices ■ Gray Wolf Delisted ■ Hubble's Last Fix

Edited by Philip Yam

How Mercury Gets into Seafood

Scientists have known how mercury from industrial pollution affects local freshwater ecosystems and poses a human health threat [see "Mapping Mercury"; SciAm, September 2005]. New data reveal just how the mercury cycle functions in the ocean. Based on samples from 16 sites from Hawaii to Alaska and on computer simulations, researchers at the U.S. Geological Survey and other institutions conclude that bacterial decomposition of algae that have sunk from the surface to mid-depth plays a crucial role. In the presence of mercury, which in this study came from Asia via ocean currents, the decomposition process creates methylmercury, which works its way up the food chain and into predators such as tuna. The study, in the May 1 *Global Biogeochemical Cycles*, also finds that the North Pacific has seen a 30 percent rise in mercury contamination since the mid-1990s.

TUNA is a major source of mercury in the human diet.

More Choices, More Happiness?

Having too many options can leave people less happy with the decisions they ultimately make [see "The Tyranny of Choice"; SciAm, April 2004]. Experiments described in the March *Psychology and Marketing* attempt to reconcile those findings with theories from psychology and economics that equate more choices with greater satisfaction. In one test, participants had to pick a charity to which to donate money from a list of either five or 40 organizations. The study found no evidence of the too-much-choice effect even in the more plentiful option, except when participants were asked to justify their picks. Under those circumstances, they seemed less satisfied with their decisions, because they had to recall the choices they could have made. The researchers suggest that the too-much-choice effect may occur only under certain conditions and is less robust than previously thought.

—*Kathryn Wilcox*

EENY, MEENY: Dissatisfaction from many choices may occur only under certain conditions.

Off the List

Thanks to repopulation efforts during the past few decades, the gray wolf (*Canis lupus*) now thrives in the U.S., and since 2003 the U.S. Fish and Wildlife Service has been trying to move the top predator off the endangered species list—a plan opposed by groups that believe the wolves are susceptible to being overhunted [see "Out of the Woods"; SciAm, April 2003]. But this past April the service largely succeeded, determining that enough wolves live in key areas and that they can be managed by most state wildlife departments. The agency still plans to monitor the wolves for the next five years and can place them back on the list at any time.

—*Kathryn Wilcox*

Good for a Few More Years

The crew of the space shuttle *Atlantis* hauled in the Hubble Space Telescope on May 13 to service the venerable instrument for the fifth and final time. NASA originally scrapped the dangerous mission in the wake of the *Columbia* disaster in 2003, but public and political pressure won out. Besides maintenance and upgrades, Hubble got new instrumentation that will penetrate deeper into the void at near-infrared wavelengths, thereby providing a glimpse back in time to about when the universe was 500 million years old. If all the fixes work, Hubble should continue burnishing its impressive résumé of discoveries [see "Hubble's Top 10"; SciAm, July 2006] until at least 2014, by which time its successor, the James Webb Telescope, will also be in orbit.

HUBBLE SPACE TELESCOPE, with its aperture door open.

MARK NAVALES *Getty Images (tuna)*; MARK NEWMAN *Photo Researchers, Inc. (wolf)*; PORNCHAI KITTIWONGSAKUL *Getty Images (supermarket)*; PHOTO RESEARCHERS, INC. *(Hubble)*

PANDEMICS

Eyes on the Swine

Could animal surveillance have seen the new flu coming? BY CHRISTINE SOARES

Less than 24 hours after a commercial jet took a sudden detour into the Hudson River this past January, security camera video of the event from multiple vantage points began surfacing. In an age of ubiquitous surveillance, the public has come to assume that someone or something is always watching, ready to spot trouble as it is happening. Yet a novel strain of the influenza A (H1N1) virus jumped species and burst into the human population in March and April, and by late May health and agriculture officials were still trying to figure out where it came from.

The emergence of the new H1N1 flu strain has demonstrated the effectiveness of existing systems to watch for human flu outbreaks while also proving a long-standing theory that pigs could serve as mixing vessels for a pandemic virus. But it has also highlighted how disappointing progress has been in detecting where and how such viruses evolve in animals and in predicting their transmission to people—abilities that might have helped avert a pandemic or at least provide an early warning.

Despite years of attention and funding for flu research, however, health officials are no closer to having an efficient way to flag new animal pathogens that could harm people. For example, in 2007, when Jürgen A. Richt and his colleagues at the U.S. Department of Agriculture's National Animal Disease Center in Ames, Iowa, identified a new influenza A (H2N3) strain in pigs that they thought had pandemic potential, "there was no one to tell," he recalls. "So we asked ourselves, 'What do we do with it?' Nobody was interested—there was no rule or regulation in place." Richt and a group of collaborators published their assessment of the new strain in a scientific journal article that concluded that "it would be prudent to establish vigilant surveillance in pigs and in workers who have occupational exposure."

ANDY SACKS Getty Images

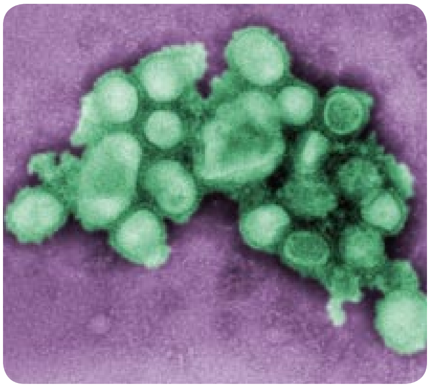
MIXING VESSEL: **The surveillance of animals, such as those on this Michigan hog farm, for new flu viruses has lagged behind preparations for human pandemics the flu bugs can cause.**

In the context of disease, surveillance means at a minimum that doctors and diagnostic laboratories report every instance of certain pathogens they detect. All human flu cases are "reportable" to the Centers for Disease Control and Prevention, for example, which tracks the incidence and movement of the illness. But for both people and animals, voluntary lab testing to diagnose flu captures only the small fraction of cases that ever involve a doctor visit. Systematic sampling and mandatory reporting of disease in swine herds are limited to a handful of commercially devastating illnesses, including classical swine fever and nipah virus.

Richt, now at Kansas State University, thinks veterinary diagnostic labs could play an important role in more active animal screening by testing every sample submitted for any reason for a full spectrum of pathogens. "We need a better network to look in animal populations for emerging infectious agents, with 21st-century technology," he says. Big state laboratories, including the ones in Iowa and North Carolina, home to the largest U.S. swine populations, already have the technical ability to screen for a range of pig diseases, Richt explains. Microarray chips able to test for pathogens specific to pigs, cattle or poultry could give smaller labs the same capacity and provide a more comprehensive, real-time picture of microbial threats to people, such as a new flu variant, brewing in livestock.

Identifying novel flu strains in animals is one thing; determining whether they pose a human danger is another. "I'm a lot more pessimistic about being able to predict these things," says Jeffery K. Taubenberger of the National Institute of Allergy and Infectious Diseases. In March he published an analysis of two swine branches of the H1N1 family tree—one of them a Eurasian strain that contributed segments of the novel H1N1 now infecting humans. The two strains had a common H1N1-type ancestor, but both have been evolving independently in pig populations, and the minute changes to viral genes that allowed the virus to adapt to a new host were different in each strain. Many other scientists looking for consistent signals that a virus is changing hosts or is becoming more transmissible or more virulent have also failed to find clear patterns.

As a result, no one can explain why the avian H5N1 flu virus has infected some 400 people worldwide, mainly in Asia and Africa, but failed so far to adapt completely to humans. Nor do scientists know where the original 1918 pandemic virus came from or where its distant descendant, the new H1N1 strain, is going. Having spread to 40 countries, infected nearly 10,000 people and killed 79 as of late May, it might still fizzle in the coming months or learn to transmit between people more easily. And this fall it could return to the Northern Hemisphere as a lion or a lamb.



H1N1 VIRUS, as imaged by an electron microscope, is adapting to people. Scientists cannot predict how it will continue to evolve.

COURTESY OF C. C. GOLDSMITH AND A. BALISH *Centers for Disease Control and Prevention*

Taubenberger, who with his colleagues at the Armed Forces Institute of Pathology first fished the 1918 H1N1 pandemic strain out of preserved samples of victims' tissue in 1996, says too much is still unknown about the basic biology and ecology of flu viruses. He thinks surveillance of an entire rural ecosystem—pigs, birds, people, as well as dogs, cats, horses, and other domesticated and wild animals—would finally yield some deeper insights into why and how flu viruses evolve.

Fortunately, money and research directed toward pandemic preparations have dramatically improved human flu surveillance and response systems. Richt points to how rapidly labs identified the first U.S. cases of the new flu in two children in southern California and alerted the CDC, allowing health officials to swing into action. Unfortunately, without closer monitoring of the animal sources of novel flu strains, human surveillance will have to remain the first line of defense.

RADIATION

Blasts from the Past

Did China's nuclear tests kill thousands and doom generations? BY ZEEYA MERALI

Enver Tohti remembers the week that it rained dust. That summer of 1973 he was in elementary school in Xinjiang Province, China's westernmost region, which is inhabited mostly by Uygurs, one of the country's minority ethnic groups. "There were three days that earth fell from the sky, without wind or any sort of storm. The sky was deadly silent—no sun, no moon," he recalls. When the kids asked what was happening, the teacher told them that there was a storm on Saturn (its Chinese name translates into "soil planet"). Tohti believed her. It was only years later that he realized it was radioactive dust raised by the test detonation of a nuclear bomb within the province.

Three decades on, Tohti, now a medical doctor, is launching an investigation into the toll still being taken—and one that the Chinese government steadfastly refuses to acknowledge. A few hundred thousand people may have died as a result of radiation from at least 40 nuclear explosions carried out between 1964 and 1996 at the Lop Nur site in Xinjiang, which lies on the Silk Road. Almost 20 million people reside in Xinjiang, and Tohti believes that they offer unique insight into the long-term impact of radiation, including the relatively little studied genetic effects that may be handed down over generations. He is establishing the Lop Nur project at Sapporo Medical University in Japan with physicist Jun Takada to evaluate these consequences.

"It is a sad opportunity, but it is an opportunity nonetheless to both learn something new and replicate what we think we are seeing elsewhere," observes Anders Møller, who co-directs the Chernobyl Research Initiative (CRI) and is based at the National Center for Scientific Research in Paris.

Takada has calculated that the peak radiation dose in Xinjiang exceeded that measured on the roof of the Chernobyl nuclear reactor after it melted down in 1986. Most damage to Xinjiang locals came from detonations during the 1960s and 1970s, which rained down a mixture of radioactive material and sand from the surrounding desert. Some were three-megaton explosions, 200 times larger than the bomb dropped on Hiroshima, says Takada, who published his findings in a book, *Chinese Nuclear Tests* (Iryoka-gakusha, 2009).

In the early 1990s Takada, who studied radiation effects from tests conducted by the U.S., the former Soviet Union and France, was invited by scientists in Kazakhstan, which borders Xinjiang, to evaluate the hazard from Chinese tests. He devised a computer model to estimate fallout patterns using Soviet records of detonation size and wind velocity as well as radiation levels measured in Kazakhstan from 1995 to 2002. Takada was not allowed into China, so he extrapolated his model and used information about the population density in Xinjiang to estimate that 194,000 people would have died as a result of acute radiation exposure. Around 1.2 million received doses high enough to induce leukemia, solid cancers and fetal damage. “My estimate is a conservative minimum,” Takada says.

The figures came as little surprise to Tohti. Ironically, as a teenager, he was proud that his province was chosen for tests marking China’s technological and military progress. His view changed when he became a physician and saw a disproportionate number of malignant lymphomas, lung cancers, leukemia cases, degenerative disorders and babies born with deformities. “Many doctors suspected this was connected to the tests, but we couldn’t say anything,” Tohti recalls. “We were warned away from researching by our superiors.”

Tohti was only able to speak out in 1998, when he moved to Turkey, ostensibly as part of his medical training. There he joined forces with a team of British documentary filmmakers whom he smuggled back into Xinjiang as tourists. Together they uncovered medical records showing that cancer rates were 30 to 35 percent higher in the province than the national average.

Tohti and Tanaka’s Lop Nur project could fill in many gaps left open by analyses of other mass radiation poisonings. In studying the Chernobyl aftermath, Møller and his colleagues found that animal populations in the area still show a significant decline in numbers and an increase in genetic mutations, in contrast to earlier reports of recovering wildlife.

BETTMANN/CORBIS

FIRST OF MANY: **China entered the nuclear club with this 1964 blast at Lop Nur. Such atmospheric tests continued to 1996, exposing millions to radioactive fallout.**

But pinning down generational effects in humans has proved difficult, because relatively little time has passed since the disaster and a small number of people were affected, explains Timothy Mousseau, a CRI co-director based at the University of South Carolina. Still, accumulating data suggest “that there is serious genetic damage in people living in these contaminated areas,” he says. For this reason, Mousseau is optimistic that the Lop Nur project will build up a dossier of genetic evidence. The difficulty, Møller and Tanaka agree, will be deciphering whether effects on second and third generations are inherited genetic mutations or are caused by exposure to contaminated water and soil.

For Tohti, the priority is helping the sick. In March the French government announced that it would compensate civilian victims of its nuclear tests, which were conducted in Polynesia. In 2008 the Chinese state news service Xinhua reported that its government is paying undisclosed subsidies to military personnel involved in the tests. Tohti wants aid extended to affected civilians, adding that 80 percent do not have health care. “Right now, they can’t afford treatment,” he says. “So all they can do is wait to die.”

The Lop Nur project is just the tip of an international iceberg, remarks Abel Gonzalez of the Argentine Nuclear Regulatory Authority in Buenos Aires. Radiation researchers have had easy access to only three sites where nuclear blasts occurred—the U.S.’s site Bikini Atoll, the Soviet Union’s Semipalatinsk site in Kazakhstan and France’s site in Polynesia—and these areas represent just a small fraction of the approximately 500 atmospheric tests the world has seen. “We have a moral responsibility to investigate all nuclear test sites,” Gonzalez says. Certainly for the Xinjiang people affected by the Lop Nur tests, truer words have never been spoken.

Zeeya Merali is a freelance science writer based in London.

When Population Bombs Go Nuclear

Does repeated exposure to radiation affect germ-line cells such that the same mutations get passed on, generation after generation? That is one question the Lop Nur project hopes to answer. The other two major instances of a large population exposure to radiation—the atomic bombs dropped over Hiroshima and Nagasaki—have produced no generational effects in survivors, points out Roy Shore, chief of research at the Radiation Effects Research Foundation in Hiroshima. But he adds that the exposure patterns vary. “The atomic bomb was an almost instantaneous exposure,” Shore explains. “We still need good data on radiation that has been delivered time and time again, over a long period—there may be different effects.” —***Z.M.***

ANTHROPOLOGY

Hitching a Ride

Crawling may be unnecessary for normal child development BY KATE WONG

Babies must crawl before they walk, parents and pediatricians agree. Crawling has also been held up as a prerequisite to the normal progression of other aspects of neuromuscular and neurological development, such as hand-eye coordination and social maturation. But new research may knock the legs out from under this conventional wisdom.

According to anthropologist David Tracer of the University of Colorado at Boulder, babies of the Au hunter-gatherers of Papua New Guinea do not go through a crawling stage. Instead their parents and other caregivers carry them until they can walk. Yet Au children do not appear to suffer any ill effects from skipping this phase. In a presentation given to the American Association of Physical Anthropologists in Chicago this past April, Tracer argued that, in fact, not crawling may be entirely normal and possibly even adaptive.

In his observations of 113 Au mother-child pairs, Tracer found that babies up to 12 months old were carried upright in a sling 86 percent of the time. On the rare occasions when the mothers put their infants on the ground, they propped them up in a sitting position, rather than placing them down on their stomachs. As a result of spending all of that time upright, Au kids never learn to crawl. (They do, however, go through a scoot phase in which they sit upright and propel themselves along on their bottoms. Tracer says the Au believe that this scooting, rather than crawling, is the universal human prewalking phase.)

The Au are not alone in discouraging their children from crawling. Tracer notes that babies in a number of other traditional societies—including ones in Paraguay, Mali and Indonesia—are raised this way.

CRAWLING may be a recently evolved stage of child development.

DENNIS HALLINAN *Getty Images*

Furthermore, he observes, neither do our closest living relatives, chimpanzees and gorillas, put their youngsters on the ground very often. Thus, it may well be that our early hominid ancestors toted their babies around, too, rather than letting them crawl.

Citing a study of Bangladeshi children showing that crawling significantly increases the risk of contracting diarrhea, Tracer proposes that carrying infants limits their exposure to ground pathogens. It also protects them from predators. He therefore contends that the crawling stage is a recent invention—one that emerged only within the past century or two, after humans began living in elevated houses with flooring, which would have been much more hygienic than dirt.

Wenda Trevathan, an anthropologist at New Mexico State University, agrees that babies were probably rarely placed on the ground in the past, adding glowing embers as another potential hazard. Tracer's work "highlights how narrowly we view normal infant development," she remarks, "and calls into question the tendency to judge all human infants on the basis of Western infants."

EVOLUTION

Juvenile Thoughts

Being more infantile may have led to bigger brains BY CHARLES Q. CHOI

For decades scientists have noted that mature humans physically resemble immature chimps—we, too, have small jaws, flat faces and sparse body hair. The retention of juvenile features, called neoteny in evolutionary biology, is especially apparent in domesticated animals—thanks to human preferences, many dog breeds have puppy features such as floppy ears, short snouts and large eyes. Now genetic evidence suggests that neoteny could help explain why humans are so radically different from chimpanzees, even though both species share most of the same genes and split apart only about six million years ago, a short time in evolutionary terms.

In animals, neoteny comes about because of delays in development, points out molecular biologist Philipp Khaitovich of the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany. For instance, humans sexually mature roughly five years after chimps do, and our teeth erupt later. "Changes in the timing of development are some of the most powerful mechanisms evolution can use to remodel organisms, with very few molecular events required," he explains.

To look for genetic evidence that neoteny played a role in the evolution of *Homo sapiens*, Khaitovich and his colleagues compared the expression of 7,958 genes in the brains of 39 humans, 14 chimpanzees and nine rhesus monkeys. They collected samples from the dorsolateral prefrontal cortex—a region linked with memory that is relatively easy to identify in the primate brain. These tissues came from deceased individuals at several stages of life, from infancy to middle age, enabling the researchers to see how genetic activity changed over time in each species.

In both humans and chimps, about the same percentage of genes changed in activity over time. But roughly half these age-linked genes in humans differed from chimps in terms of when they were active during development. Analysis of the 299 genes whose timings had shifted in all three species revealed that almost 40 percent were expressed later in life in humans, with some genetic activity delayed well into adolescence.

STEVE WINTER *Getty Images*

THERE THERE, NOW: Adult humans share features associated with immature chimpanzees, such as small jaws and flat faces. The retention of juvenile features, called neoteny, may explain why humans are so different from chimps despite a mostly similar genome.

Although the specific function of many of these neotenic genes remains uncertain, they are especially active in the gray matter of the human brain, where higher thought occurs, the researchers note in the April 7 *Proceedings of the National Academy of Sciences USA*. They are now probing other parts of the brain in humans, chimps and macaques to see where neoteny might play a role.

Actually proving that neoteny helped to drive human evolution and brain size is difficult. Khaitovich suggests analyzing genetic activity in cases of faster-than-normal development in people, "which past research already shows can lead to a reduction in cognitive abilities," he says.

Other experts certainly think that neoteny's role is reasonable. The ability of the brain to learn is apparently greatest before full maturity sets in, "and since neoteny means an extended childhood, you have this greater chance for the brain to develop," says molecular phylogeneticist Morris Goodman of Wayne State University, who did not participate in this study. In other words, human evolution might have been advanced by the possibilities brimming in youth.

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

POLICY

The Specter of Fraud

Stimulus funds for science raise concern about misconduct BY EUGENIE SAMUEL REICH

One unintended side effect of Congress's intense efforts to jump-start the U.S. economy is the threat of fraud. Earl Devaney, chair of a newly appointed federal watchdog agency, the Recovery Accountability and Transparency Board, has warned that without precautionary measures, as much as 7 percent of the stimulus package will end up in the hands of bad actors. Apply Devaney's math to the $31 billion being spent on science—by the National Institutes of Health, NASA, the Departments of Commerce and Energy, and the National Science Foundation (NSF) combined—and stimulus funds represent an unprecedented boost not only for science, but also, potentially, for science fraud.

Under the stimulus bill, formally known as the American Recovery and Reinvestment Act, various science-funding agencies will enjoy a substantial uptick in their budgets. But they are under pressure to dole out the new funds quickly on "beaker ready" projects. The risk of scientific misconduct has generally been considered to be less than 1 percent, but the size of the disbursements and the added reporting requirements (namely, quarterly status reports and updates on job creation) could tempt researchers to cut corners or even fake aspects of applications. Meanwhile at the agencies, the urgency to spend could take precedence over monitoring. "We're not going to know until it happens. It probably is occurring," concedes Patricia Dalton of the Government Accountability Office.

Several agencies have already set advanced oversight procedures in place. The NIH and the NSF say they should have enough staff to handle the flood of new grant requests, and both have introduced formal policies on research misconduct. They also employ personnel with extensive experience in handling science fraud.

Other departments, however, may not be as ready. Having been cited previously for cost overruns, NASA has drawn some congressional scrutiny, as has the Department of Energy, the largest stimulus recipient for science (it will spend $15.9 billion of its $38-billion stimulus package on science and technology). Indeed, DOE inspector general Gregory Friedman told a March hearing of the House Science and Technology Committee that he is concerned about poor monitoring of past contracts by DOE staff. He pointed to the agency's program on technology loan guarantees, which has in the past proved too short-staffed to monitor the loans it makes. Friedman told the committee that the inspector general's office is preparing for an estimated 500 hotline complaints, 200 investigations, and 30 to 35 complaints of retaliation against whistle-blowers arising from stimulus spending every year. The DOE did not respond to requests for comment.

At most agencies, the first line of defense is the program officers who make the funding decision in the first place. Many are undergoing training to minimize the risk of fraud—for example, they are told to make sure expectations under grants and contracts are clearly stated in advance. "We are moving with all speed" to recruit more program officers, says Ellen Herbst, senior official for recovery implementation at the Department of Commerce, which runs the National Institute of Standards and Technology and the National Oceanic and Atmospheric Administration.

KA-CHING! About $31 billion worth of stimulus funds will go to science.

Experts inside and outside government have flagged other ways in which agencies could be doing more. A report on preventing grant fraud, issued in 2006 by the National Procurement Fraud Task Force, recommended that federal agencies share information on people known to be at risk of committing this type of abuse. NASA's chief financial officer Ronald Spoehel says that although there is no federal database on research grants, officials do check a "past performance" database for information about potential contractors. Agencies such as the NIH and the NSF publish the names of those who have been found guilty of research misconduct. Hence, a list of all known cases could be compiled and checked against new grant awardees. "That would be a useful check and balance," remarks C. K. Gunsalus, an attorney at the University of Illinois who has handled research misconduct cases.

Some agency officials, however, express some doubt that a shared database of misconduct cases would be desirable to have. "If someone is reprimanded, would we want to say that person would never be funded again?" asks Peggy Fischer, associate inspector general for investigations at the NSF. "You act with intention to protect integrity but with compassion" toward those who committed minor infractions, she adds. At the same time that the stimulus funding is a boon for science, it will require delicate balancing on the part of government agencies, too.

Eugenie Samuel Reich is author of Plastic Fantastic: How the Biggest Fraud in Physics Shook the Scientific World *(Palgrave Macmillan, 2009), about Jan Hendrik Schön's claimed creation of organic molecular transistors at Bell Laboratories.*

Turning Crowds into Watchdogs

Government officials do not have to be the only ones exercising oversight. Through "crowdsourcing," members of the public could comment on projects online, in such a way that inspectors general would be alerted to problems quickly. "Even for technical projects, if a database is put out there others can police it," says Eileen Norcross of George Mason University, who testified at the science and technology committee's March hearings about Stimuluswatch.org, which monitors the stimulus expenditure. Testimony at a follow-up May hearing suggested that a Web site called recovery.gov could be fully functional by October and enable the public to track expenditures by zip code. But to reap the full benefits of crowdsourcing, the federal agencies need to be more open: Norcross notes that under the recovery act, agencies need provide only some information publicly.

—E.S.R.

JEFFREY COOLIDGE *Getty Images*

BIOLOGY

Deep into the Red

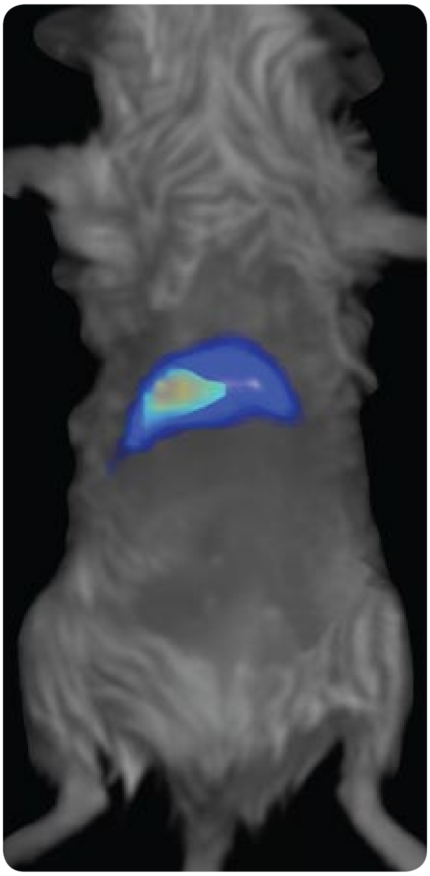
Infrared fluorescent proteins could transform cellular imaging and control BY BIANCA NOGRADY

Mind control has been traditionally the realm of the hypnotist, but research in the field of fluorescent proteins is opening up the possibility of controlling cellular processes, gene activity and even behavior using nothing more than infrared light.

Fluorescent proteins, which are compounds that can absorb and then emit light, have become a powerful instrument in the cell biologist's toolkit—so powerful, in fact, that the discovery and development of green fluorescent proteins from jellyfish earned the 2008 Nobel Prize in Chemistry for Martin Chalfie of Columbia University; Osamu Shimomura of the Marine Biological Laboratory in Woods Hole, Mass.; and Roger Y. Tsien of the University of California, San Diego. But despite their indispensability, these proteins are limited by their wavelengths. They need to be excited with the blue to orange part of the visible spectrum, at wavelengths of 495 to 570 nanometers. These wavelengths of light are too short to penetrate tissue very well, and so green fluorescent proteins are mainly used in test-tube studies to watch cell division or to label certain cell types.

But now Tsien and his U.C.S.D. colleagues have made another grand leap forward. They have developed a new fluorescent protein that after absorbing light from the far-red part of the spectrum, shines in the near-infrared, at wavelengths of around 700 nanometers. These longer wavelengths can penetrate mammalian tissue and even pass through bone, enabling scientists to tag and visualize cellular activity as it happens inside a live animal. "Say you label a tumor with a green fluorescent protein, and if this labeled tumor is buried inside the animal, then you barely can get green fluorescence out," says lead researcher Xiaokun Shu. "But if you label this deeply buried tumor by infrared fluorescent proteins, you will get a stronger signal because infrared penetrates tissue more efficiently."

Tsien's group derived the infrared fluorescent protein from a hardy bacterium called *Deinococcus radiodurans*, famous for its ability to survive extreme environments. Bacteria do not actually use this class of proteins, called bacteriophytochromes, to emit light. "They use these bacteriophytochromes to control gene expression," Shu says. The proteins convert absorbed light into energy to signal certain genes to turn on or off.



VISIBLE MOUSE: A liver tagged with infrared proteins glows visibly via an imaging system that can also photograph the liver's owner. Unlike green fluorescent proteins, which led to a 2008 Nobel Prize, the infrared version can reveal cells inside a living body.

COURTESY OF TODD AGUILERA AND XIAOKUN SHU *University of California, San Diego*

The initial challenge for researchers was to reengineer the protein so that absorbed light would be reemitted rather than being used as a source of power. They accomplished the feat by deleting the part of the protein that converts the absorbed light into chemical energy; this truncated and mutant form instead gave up its absorbed energy as an infrared glow. The scientists incorporated the engineered bacterial protein into mammalian cells—specifically, into the liver of a live mouse, which lit up with infrared light.

This achievement, published in the May 8 *Science*, paves the way for in vivo visualization of a wide range of biochemical processes and deeply buried tissues in animals. (Its use in humans is unlikely, as it would require gene therapy and the ethically dubious transplantation of bacterial genes into humans.)

"This is so important," comments David James, a cell biologist at Australia's Garvan Institute in Sydney, "because a lot of knowledge at the moment is confined to individual cells grown on a glass coverslip," leaving open the question of whether that knowledge "is transferable to an animal." The infrared version could also solve the problem of naturally occurring fluorescence from other biological molecules, which tend to glow at wavelengths similar to conventional fluorescent protein markers and thereby create a lot of "background noise," James says.

But even greater potential lies in harnessing the bacteriophytochromes' original function, namely, powering gene expression. It should be feasible, Tsien thinks, to put back in the signal-controlling properties of the phytochrome. Then it could be possible with animals to "switch on genes and control biochemistry" with light, he says.

For example, you want to explore the effects on mouse behavior of switching on a particular gene that controls some aspect of brain function, but, thankfully for the mouse, you do not want to open up its skull or stick a needle in its brain. "If the infrared fluorescent protein can be made to turn back into an infrared phytochrome, you could have the switch all ready and just waiting for enough infrared light," Tsien speculates. Because infrared light can penetrate the skull, it can reach the phytochrome and remotely switch the gene on, resulting in observable changes in the mouse's behavior.

It is the next evolutionary step for fluorescent proteins, remarks Tsien, who believes that phytochromes represent a class of proteins with enormous potential. If he is correct, then in the coming years, expect more scientists to see the (infrared) light.

Bianca Nogrady is a science and medical writer based near Sydney, Australia.

VIRTUAL REALITY

Avatar Acts

When the Matrix has you, what laws apply to settle conflicts? BY MICHAEL TENNESEN

How much legal weight should actions in the virtual world carry back in the real one? For most people, the answer might be "none," but as online communities conduct actual financial transactions and draw in more participants, some legal experts think that it may be time to extend brick-and-mortar jurisprudence into the virtual realm.

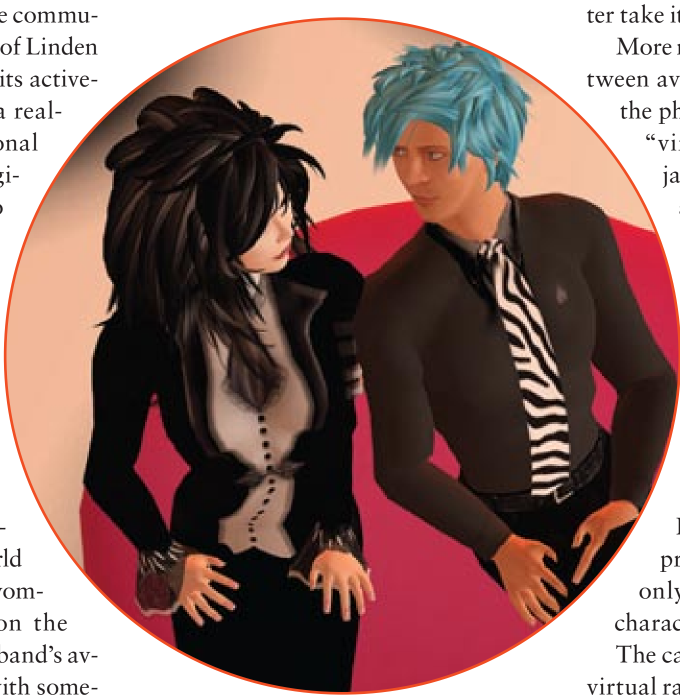
By some estimates, about 100 million users worldwide populate online communities. Second Life, the creation of Linden Lab in San Francisco, provides its active-user base of one million with a real-time experience on their personal computer, in which they use digital characters called avatars to wander around castles, deserted islands and other fantastic 3-D environments. Through their avatars, they can meet and talk to thousands of online participants, even cuddle on couches and have simulated sex with them.

Such immersive experiences have led to several reports of online activities triggering real-world conflicts. Last November one woman filed papers for divorce on the grounds that she caught her husband's avatar being overly affectionate with someone else. (He countered that his wife drove him to virtual infidelity because of her addiction to World of Warcraft.) In fault-based divorce courts, such a claim would be perfectly legitimate, says Greg Lastowka, a professor of law at Rutgers University who is currently writing a book called *Virtual Law*. But he likens it to complaints such as "my husband plays golf all the time and has no time for me"—grievances that are shy of adultery.

But with the average player spending 20 hours a week in these environments, players often put more weight into virtual affairs than lawmakers do. When Chinese gamer Qiu Chengwei acquired a virtual sword in the online game Legend of Mir 3, only to have a friend borrow it and sell it online for $800, Qiu went to the police. Told that there were no laws to protect virtual property, Qiu actually killed the thief. "If somebody is going to die, and somebody else is going to spend the rest of his life in jail for a virtual crime, then we better take it seriously," Lastowka remarks.

More nebulous, though, is behavior between avatars that would be criminal in the physical world. One case involved "virtual rape," according to Benjamin Duranske, a San Francisco attorney and founder of the Second Life Bar Association, which meets once a month in Second Life. In a blog, he recounts a Brussels public prosecutor who had called for an investigation of a rape charge involving a Belgian user of Second Life. The case apparently later died, perhaps because, as Duranske proposes, "most laws prohibiting violence are applied only to real people, not computer characters."

The case echoes an earlier incidence of virtual rape a decade ago, as described by Julian Dibble for the *Village Voice* in 1993. This incident took place in LambdaMOO, a text-based virtual community, and concerned a hacker known as Mr.



COME HERE OFTEN? About 20 hours a week, actually—that is the average time members spend in realms such as Second Life. Conflicts here can open up new legal questions.

COURTESY OF LINDEN LAB

Bungle, who took control of other avatars who were then made to describe violent, explicit acts on the screen. The article spawned a conference at New York University in 1994 where participants discussed the possibility of self-governing on the Internet, which could entail a virtual community limiting or canceling another player's account. (Cancellation is what happened to Mr. Bungle's creator.)

Indeed, members of today's virtual communities must agree to a "terms of service" contract, which enables companies to adjudicate conflicts by, for instance, suspending the offending account. But establishing a new account to create another predatory character is simple enough. And as Lastowka says, "virtual worlds don't want to police their users. They just want to collect their profits." (Linden Lab takes a cut from users conducting business in Second Life.) Online communities, he points out, will always have "griefers" and "goon squads" who wait at game portals to kill new avatars or take sexual advantage of someone who has not figured out how to push the "no" button.

Courts could set precedents as cases arise from the virtual world. South Korean courts, for instance, have done so a number of times in dealing with virtual property; in contrast, U.S. courts have shied away from the issue. The scope of the online realm suggests that legislation may be desirable. Virtual commerce is worth about $1 billion annually and is set to get bigger as the six- to 12-year-olds on Club Penguin and other virtual games grow up. Lastowka and Duranske think society is headed toward a virtual Internet that, Duranske says, "is going to be a major revolution in the way we interact." Whether the law can keep pace with that revolution remains to be seen.

Michael Tennesen maintains his first life as a science writer near Los Angeles.

ENVIRONMENT

A Lower High-Water Mark

The maximum global sea-level rise from the collapse of the rapidly warming West Antarctic ice sheet may be 3.2 meters—not five meters or more as predicted in the past. The revision comes from a new model suggesting that only parts of the ice sheet will collapse—namely, those that are grounded below sea level or sloping downward. Areas of the sheet grounded above sea level or on upward-sloping bedrock would remain in place. The results, in the May 15 *Science,* say nothing about disappearing ice sheets elsewhere, however. Greenland, for instance, holds enough ice to raise sea levels by seven meters.

—David Biello

ENTOMOLOGY

Ants: "I'm Not Dead Yet"

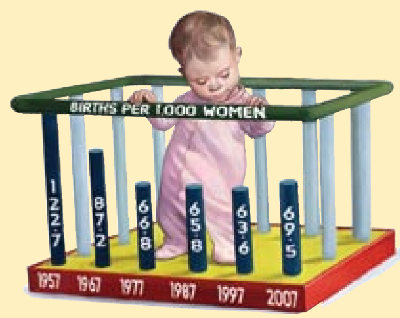
Ants are notoriously efficient undertakers, carrying off dead nestmates before the corpses can infect the colony with their pathogens. Some researchers had hypothesized that ants detected breakdown products in decomposing bodies, but a new study undermines that theory. Entomologists from the University of California, Riverside, found that Argentine ants could detect dead nestmates before decomposition could have taken hold. More telling, the team found that living ants produce two "I'm not dead yet" chemicals, called dolichodial and iridomyrmecin. The compounds curb necrophoresis, the removal of dead colony members by fellow workers. Both chemicals dissipate quickly after death, plummeting to below half strength in just 10 minutes, the researchers write in a paper published in the May 19 *Proceedings of the National Academy of Sciences USA*. *—John Matson*

MATT COLLINS

Data Points

The New Boomers

More Americans were born in 2007 than in any other year in history. According to preliminary data from the National Center for Health Statistics, births topped the previous record of 1957, at the height of the baby boom. Birth rates have been inching up in recent years, for reasons that are not entirely clear. Women living in the U.S. in 2007 will have an average 2.1 children over their lifetimes, a number that demographers consider the bare minimum to sustain population levels without immigration. In addition, U.S. women are having far fewer babies than in the 1950s—before the birth-control pill became available—when the average was nearly four children per woman. But the population is almost twice as large now, which is the main reason behind the record-breaking number of births.



U.S. IN 1957

Population:	171 million
Births:	4,308,000
Births per 1,000 women ages 15 to 44:	122

U.S. IN 2007

Population:	301 million
Births:	4,317,119
Births per 1,000 women ages 15 to 44:	69

Population numbers are U.S. Census Bureau estimates: www.census.gov/popest/estimates.html; NCHS reports are available at www.cdc.gov/nchs/products.htm

SCI AM **Read More . . .** News Scan stories with this icon have extended coverage on **www.ScientificAmerican.com/jul2009**

In Brief

HUMANITY'S GROUND ZERO

A massive new genetic study may have zeroed in on humanity's starting point. By analyzing genetic sequences from 121 populations in Africa, 60 non-African populations and four African-American populations, researchers traced Africans back to 14 ancestral clusters originating at 12.5 degrees east latitude and 17.5 degrees south longitude, near the border of modern-day Angola and Namibia. Besides offering a far more specific understanding of human migrations, the study, in the May 22 *Science,* also promotes a better understanding of health and disease in many of these populations.

—Katherine Harmon

WHAT IS WATSON?

This software program will beat people on the game show *Jeopardy!* At least, that is what IBM hopes will happen with a supercomputer running a powerful semantics-crunching program dubbed Watson, which will have access to a knowledge database but no Internet connection. In following up on its human-beating chess computer Deep Blue, IBM says it has been refining Watson for almost two years and hopes to stage a series of sparring matches before a final showdown in 2010.

—John Matson

ENVIRONMENT

Working on the Railroad

A single railroad crosstie may not impact the environment as much as it helps to keep rails together. But considering that millions are deteriorating around the world, the material chosen as a replacement can affect the amount of carbon dioxide (CO_2) in the air. Wood crossties require harvesting a lot of CO_2-absorbing trees, roughly 89,000 cubic meters of timber per million crossties; concrete versions increase greenhouse gas emissions because of the fuel consumption during their manufacture. Robert H. Crawford of the University of Melbourne in Australia concludes that making enough concrete ties to keep one kilometer of tracks aligned for 100 years generates the equivalent of 656 to 1,312 metric tons of CO_2. That amount is about one-half to one-sixth the amount that timber ties contribute, because concrete versions last longer and timber releases CO_2 as it decays. Track the findings in the June 1 *Environmental Science & Technology.* *—Charles Q. Choi*

CROSSTIES could have a major warming impact depending on the material used.

TIM GRAHAM *Getty Images*

ATMOSPHERIC SCIENCE

Do Rain Forests Make Rain?

Long-standing assumption: rain forests are a consequence of heavy rainfall. New hypothesis: some forested regions may produce conditions that lead to heavy rainfall. This "biotic pump" model contends that a vast forest such as the Amazon draws in large amounts of water vapor. Evaporation and condensation of the acquired water lead to a local atmospheric pressure drop. That decrease causes rain and attracts more water vapor to the forest, in a continuous positive feedback loop. "This theory could explain why continental interiors with huge rain forests remain so moist," says Wildlife Conservation Society researcher Douglas Sheil, who in an April *Bioscience* paper revived the biotic pump model, originally proposed in 2006 by Anastassia Makarieva and Victor Gorshkov, both at the Petersburg Nuclear Physics Institute in Russia. "It could also underline the dangers of widespread deforestation." Though promising, the model needs more data regarding air circulation patterns and vegetation types to support it, Sheil notes. *—Steve Mirsky*

RAIN FORESTS may pull in water vapor, which lowers the local atmospheric pressure, thus attracting even more moisture.

BEHAVIOR

Temptation Zone

An imaging study reveals how the brains of some dieters stay disciplined and others give in to cravings. Researchers at the California Institute of Technology asked volunteers trying to slim down to pick a food toward which they felt neutral in terms of health and taste (many chose yogurt). They next scanned the dieters' brains as they chose between this reference item and either healthy snacks, such as apples, or junk foods, such as candy bars. The team linked a brain region, the ventromedial prefrontal cortex, with the desire for tasty items, regardless of how unhealthy they might be. A separate area, the dorsolateral prefrontal cortex, was associated with self-control; dieters who had strong signals in this region chose the healthier food even if they did not think it tasted better. The findings, in the May 1 *Science,* present new targets that could help treat not only obesity but also addiction, wasteful spending, and other matters dealing with desire and restraint. *—Charles Q. Choi*

D. NORMARK *Getty Images*

Scientific American Perspectives

Act Now on Global Warming

Boost the price on energy from carbon and give the proceeds back to consumers

BY THE EDITORS

This December 7 the United Nations Framework Convention on Climate Change will convene a 12-day meeting in Copenhagen to confront one question: How do we respond to global warming when the five-year period for reducing carbon emissions under the Kyoto Protocol expires in 2012? The U.S. was not a party to Kyoto, but if this country balks once more, Copenhagen may fail to get productive commitments from other nations as well. That's a recipe for climate catastrophe. To show the world leaders soon to gather in Copenhagen that this country is serious about cutting its own carbon emissions, U.S. lawmakers must raise the price on the use of fossil fuels.

Yet how to do so without hurting the little guy? For many economists, a tax imposed on end users of fossil fuels is the most direct approach. A tax high enough to be useful, however, would be dead on arrival in Congress. In his campaign last fall, President Barack Obama called for a "cap and trade" plan that would auction off carbon dioxide (CO_2) emissions allowances to big carbon polluters.

In many ways, though, the continuing debate over taxes versus cap and trade is beside the point. The priority is to put a price on carbon and to do so in a way that avoids the pitfalls of the largely ineffectual European efforts under Kyoto. The cap-and-trade emissions trading system (ETS) set up by the European Union issued so many free emissions allowances that the system had virtually no effect on climate. The excessive supply of allowances led to wild fluctuations in price. Some of Europe's worst polluters collected windfall profits.

President Obama's initial plan for a "100 percent auction" of emissions allowances would correct many of those deficiencies. The allowances would be sold, not distributed for free. The cap would be set, ideally with expert scientific consultation, to make an appropriately deep cut in total CO_2 emissions. The market, working within the cap, would minimize the pain by spreading the costs. Energy providers could buy, sell and trade their allowances—and then pass their additional expenses along to their customers.

Not surprisingly, energy providers and their supporters in Congress are digging in for a fight. Unless the government issues allowances for free, they argue, consumers will face crippling price hikes. Regrettably, the administration has signaled its willingness to cave and reconsider the 100 percent auction.

There is a way, however, to keep strong price signals on fossil fuels without emptying consumers' wallets: send the proceeds of the auction back to citizens as rebates. Energy from fossil fuels would become more expensive, as it must, yet the rebates would help offset the extra costs to consumers. Politically, that could be enough to win passage. Peter Barnes, an entrepreneur who has promoted the mechanism for years, calls it cap and dividend.

Here's how it might work: Next year and in each year thereafter, Congress would set an overall cap on fossil fuels extracted by upstream energy producers, which David A. Weisbach of the University of Chicago Law School identifies as "fewer than 3,000 entities"—petroleum refiners, coal mines and domestic natural gas processors—"plus imports at a few locations." The cap would be divided into allowances that would be offered at auction, though a floor price would be set to ensure that the price signal is sent. Only the 3,000 energy producers would be eligible to purchase them. To keep the legislation simple and pork-free, the proceeds would go directly to U.S. citizens—not to research programs in alternative energy, "concept car" demonstrations, and the like.

To adjust emissions caps in the future, the allowances would expire periodically, perhaps as often as once a year. That would help the system to respond to changes in projections of total atmospheric CO_2 and to offer all parties a chance to learn from the program. It would also limit some—though by no means all—of the possibilities for creating derivative securities based on the emissions allowances.

Global warming is a reality, not an opinion. The U.S. must put the brakes on hard if humanity is to accept the need to slow the emissions of CO_2. We urge Congress to set a cap on fossil-fuel production before Copenhagen, phase in a price on carbon at its source and send the proceeds back to the taxpayer. No measure will be perfect, but if we act today, we buy time to tweak the system tomorrow. Let's not let the best be the enemy of the good. ■

MATT COLLINS

Sustainable Developments

Still Needed: A Climate Plan

Markets and negotiations are no substitute for rational planning and new technology

BY JEFFREY D. SACHS

There is a myth in America that markets, not plans, are the key to success. Markets will supposedly decide our climate future on their own once we institute cap-and-trade legislation to put a market price on carbon emissions. But this is silly: both markets and planning are essential in any successful large-scale undertaking, whether public or private. We need a detailed yet adaptable road map for action that goes far beyond cap and trade.

The Obama administration has declared that U.S. greenhouse gas emissions should be around 15 percent lower by 2020 than they are today and around 80 percent lower by 2050 than they were in 1990. Other regions, notably Europe, are demanding that those U.S. cuts be larger. Such debates are taking place in a near void, however. Because there is no clear plan yet for achieving any particular objective, there are no reliable estimates of the costs, policy instruments and choices that society will have to face. All is, instead, being left to the market.

The administration's climate negotiator has called cap and trade "the centerpiece" of the domestic climate program. A moment's reflection shows why that cannot be right. Cap and trade will have little effect, for example, on whether the U.S. revives its nuclear power industry, as it should to meet climate objectives. A renaissance for nuclear will depend on regulations, public attitudes, liability laws, and both administration leadership and public education much more than on cap and trade, which would play at most a supporting role.

The potentially pivotal carbon capture and sequestration technology for use at coal-fired power plants will depend on proving its safety, soundness and cost-effectiveness. Proof will require several expensive demonstration projects, all of which will need political leadership, clear regulatory standards, public financing and the active engagement of geophysicists to monitor the projects. Cap and trade will be irrelevant until the new technology is tested in a variety of settings. The national emissions-reduction targets may prove to be easy or exceedingly tough, depending on the outcome of these crucial demonstration efforts.

The future of the automobile is similar. Cap and trade or higher gasoline taxes might help nudge consumers toward more fuel-efficient cars, but the advent of a national fleet of plug-in hybrid, fuel-cell-powered or all-electric vehicles will depend much more on a large-scale public-private development effort that links research with investments in a new power grid and in other critical infrastructure.

The administration has started in a "listen and learn" mode in international climate negotiations, which is certainly fair enough after the antiscience bullying and international neglect that characterized the Bush years. It has also left legislative drafting to the Congress, which has so far resulted in an ungainly and nonstrategic 648-page draft bill that has everything possible loaded into it yet little strategic direction other than cap and trade. Global negotiations and legislative horse trading may come to be seen as a real climate policy, but they can never substitute for rational planning and policy making.

A crucial question is whether the U.S. government can produce a detailed and coherent plan. For decades the federal government has distinguished itself with a lack of coordination among competing departments, an allergy to detailed plans and a capacity for narrow interests in Congress to frustrate the most basic logic of thinking ahead. One major plus, though, is that several Obama appointees on the climate change issue are world-class leaders in the field. That expertise will be needed. Climate change is the most complex of all the challenges facing the world: it reaches into the core of the economic system, raises fundamental questions about technology, poses tremendous natural and social uncertainties, requires an outlook of decades, and engages every interest group. These are reasons why we need an adaptable plan and rational framework more than ever, but there are also reasons that help to explain why—nearly 20 years after the 1992 Rio Earth Summit and the agreement on the United Nations Framework Convention on Climate Change—we still lack one. ■

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/jul2009**

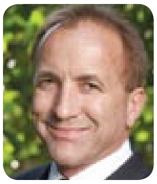
PHOTOGRAPH BY BRUCE GILBERT/EARTH INSTITUTE; ILLUSTRATION BY MATT COLLINS

Skeptic

I Want to Believe

Opus 100: what skepticism reveals about science

BY MICHAEL SHERMER



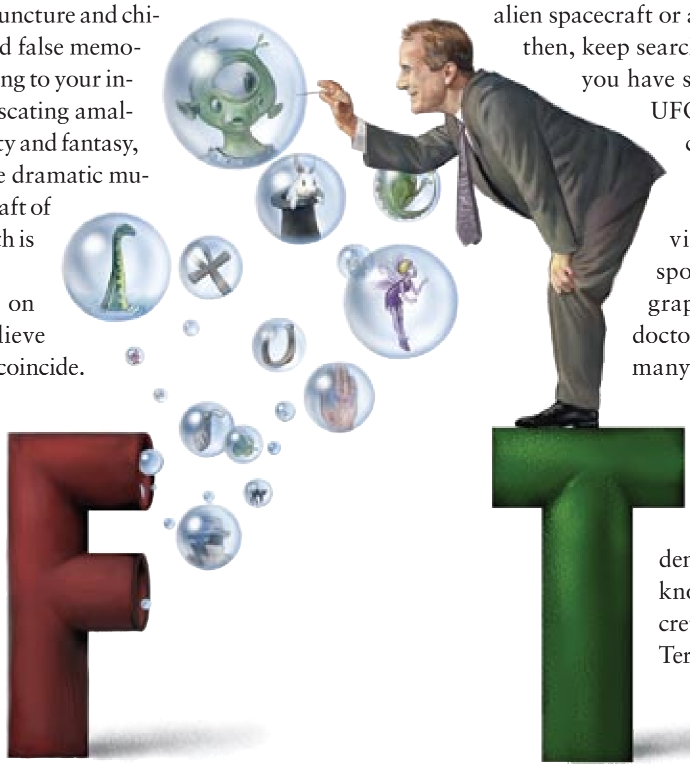
In a 1997 episode of *The Simpsons* entitled "The Springfield Files"—a parody of *X-Files* in which Homer has an alien encounter in the woods (after imbibing 10 bottles of Red Tick Beer)—Leonard Nimoy voices the intro as he once did for his post-Spock run on the television mystery series *In Search of…*: "The following tale of alien encounters is true. And by true, I mean false. It's all lies. But they're entertaining lies, and in the end isn't that the real truth? The answer is no."

No cubed. The postmodernist belief in the relativism of truth, coupled to the clicker culture of mass media where attention spans are measured in New York minutes, leaves us with a bewildering array of truth claims packaged in infotainment units. It must be true—I saw it on television, at the movies, on the Internet. *The Twilight Zone, The Outer Limits, That's Incredible, The Sixth Sense, Poltergeist, Loose Change, Zeitgeist the Movie*. Mysteries, magic, myths and monsters. The occult and the supernatural. Conspiracies and cabals. The face on Mars and aliens on Earth. Bigfoot and Loch Ness. ESP and PSI. UFOs and ETIs. JFK, RFK and MLK—alphabet conspiracies. Altered states and hypnotic regression. Remote viewing and astroprojection. Ouija boards and Tarot cards. Astrology and palm reading. Acupuncture and chiropractic. Repressed memories and false memories. Talking to the dead and listening to your inner child. Such claims are an obfuscating amalgam of theory and conjecture, reality and fantasy, nonfiction and science fiction. Cue dramatic music. Darken the backdrop. Cast a shaft of light across the host's face. The truth is out there. I want to believe.

What I want to believe based on emotions and what I should believe based on evidence does not always coincide. And after 99 monthly columns of exploring such topics (this is Opus 100), I conclude that I'm a skeptic not because I do not want to believe but because I want to *know*. I believe that the truth is out there. But how can we tell the difference between what we would like to be true and what is actually true? The answer is science.

Science begins with the null hypothesis, which assumes that the claim under investigation is not true until demonstrated otherwise. The statistical standards of evidence needed to reject the null hypothesis are substantial. Ideally, in a controlled experiment, we would like to be 95 to 99 percent confident that the results were not caused by chance before we offer our provisional assent that the effect may be real. Failure to reject the null hypothesis does not make the claim false, and, conversely, rejecting the null hypothesis is not a warranty on truth. Nevertheless, the scientific method is the best tool ever devised to discriminate between true and false patterns, to distinguish between reality and fantasy, and to detect baloney.

The null hypothesis means that the burden of proof is on the person asserting a positive claim, not on the skeptics to disprove it. I once appeared on *Larry King Live* to discuss UFOs (a perennial favorite of his), along with a table full of UFOlogists. King's questions for other skeptics and me typically miss this central tenet of science. It is not up to the skeptics to disprove UFOs. Although we cannot run a controlled experiment that would yield a statistical probability of rejecting (or not) the null hypothesis that aliens are not visiting Earth, proof would be simple: show us an alien spacecraft or an extraterrestrial body. Until then, keep searching and get back to us when you have something. Unfortunately for UFOlogists, scientists cannot accept as definitive proof of alien visitation such evidence as blurry photographs, grainy videos and anecdotes about spooky lights in the sky. Photographs and videos can be easily doctored, and lights in the sky have many prosaic explanations (aerial flares, lighted balloons, experimental aircraft, even Venus). Nor do government documents with redacted paragraphs count as evidence for ET contact, because we know that governments keep secrets for national security reasons. Terrestrial secrets do not equate to extraterrestrial cover-ups.



PHOTOGRAPH BY BRAD SWONETZ; ILLUSTRATION BY MATT COLLINS

So many claims of this nature are based on negative evidence. That is, if science cannot explain X, then your explanation for X is necessarily true. Not so. In science, lots of mysteries are left unexplained until further evidence arises, and problems are often left unsolved until another day. I recall a mystery in cosmology in the early 1990s whereby it appeared that there were stars older than the universe itself—the daughter was older than the mother! Thinking that I might have a hot story to write about that would reveal something deeply wrong with current cosmological models, I first queried California Institute of Technology cosmologist Kip S. Thorne, who assured me that the discrepancy was merely a problem in the current estimates of the age of the universe and that it would resolve itself in time with more data and better dating techniques. It did, as so many problems in science eventually do. In the meantime, it is okay to say, "I don't know," "I'm not sure" and "Let's wait and see."

To be fair, not all claims are subject to laboratory experiments and statistical tests. Many historical and inferential sciences require nuanced analyses of data and a convergence of evidence from multiple lines of inquiry that point to an unmistakable conclusion. Just as detectives employ the convergence of evidence technique to deduce who most likely committed a crime, scientists employ the method to determine the likeliest explanation for a particular phenomenon. Cosmologists reconstruct the history of the universe by integrating data from cosmology, astronomy, astrophysics, spectroscopy, general relativity and quantum mechanics. Geologists reconstruct the history of Earth through a convergence of evidence from geology, geophysics and geochemistry. Archaeologists piece together the history of a civilization from pollen grains, kitchen middens, potshards, tools, works of art, written sources and other site-specific artifacts. Climate scientists prove anthropogenic global warming from the environmental sciences, planetary geology, geophysics, glaciology, meteorology, chemistry, biology, ecology, among other disciplines. Evolutionary biologists uncover the history of life on Earth from geology, paleontology, botany, zoology, biogeography, comparative anatomy and physiology, genetics, and so on.

Once an inferential or historical science is well established through the accumulation of positive evidence, however, it is just as sound as a laboratory or experimental science. For creationists to disprove evolution, for example, they need to unravel all these independent lines of evidence as well as construct a rival theory that can explain them better than the theory of evolution. They have not, instead employing only negative evidence in the form of "if evolutionary biologists cannot present a natural explanation of X, then a supernatural explanation of X must be true."

The principle of positive evidence applies to all claims. Skep-

tics are from Missouri, the Show-Me state. Show me a Sasquatch body. Show me the archaeological artifacts from Atlantis. Show me a Ouija board that spells words with securely blindfolded participants. Show me a Nostradamus quatrain that predicted World War II or 9/11 before (not after) the fact (postdictions don't count in science). Show me the evidence that alternative medicines work better than placebos. Show me an ET or take me to the Mothership. Show me the Intelligent Designer. Show me God. Show me, and I'll believe.

Most people (scientists included) treat the God question separate from all these other claims. They are right to do so as long as the particular claim in question cannot—even in principle—be examined by science. But what might that include? Most religious claims are testable, such as prayer positively influencing healing. In this case, controlled experiments to date show no difference between prayed-for and not-prayed-for patients. And beyond such controlled research, why does God only seem to heal illnesses that often go away on their own? What would compel me to believe would be something unequivocal, such as if an amputee grew a new limb. Amphibians can do it. Surely an omnipotent deity could do it. Many Iraqi War vets eagerly await divine action.

There is one mystery I will concede that science may not be able to answer, and that is the question of what existed before our universe began. One answer is the multiverse. According to the theory, multiple universes each had their own genesis, and some of these universes gave birth (perhaps through collapsing black holes) to baby universes, one of which was ours. There is no positive evidence for this conjecture, but neither is there positive evidence for the traditional answer to the question—God. And in both cases, we are left with the *reductio ad absurdum* question of what came before the multiverse or God. If God is defined as that which does not need to be created, then why can't the universe (or multiverse) be defined as that which does not need to be created?

In both cases, we have only negative evidence along the lines of "I can't think of any other explanation," which is no evidence at all. If there is one thing that the history of science has taught us, it is that it is arrogant to think we now know enough to know that we cannot know. So for the time being, it comes down to cognitive or emotional preference: an answer with only negative evidence or no answer at all. God, multiverse or Unknown. Which one you choose depends on your tolerance for ambiguity and how much you want to believe. For me, I remain in sublime awe of the great Unknown. ■

Michael Shermer is publisher of Skeptic *(www.skeptic.com) and author of* How We Believe.

MATT COLLINS

From the Moon

The only scientist and field geologist ever to visit the moon offers some pointers to those who will one day visit Mars

KEY CONCEPTS

- The Apollo lunar exploration that began 40 years ago was not done primarily for science, but science nonetheless benefited hugely. The astronauts collected samples and took measurements that narrowed hypotheses of the moon's origin and provided a point of comparison for observations of other planets.
- On the final moon shot, *Apollo 17* in December 1972, the author became the only scientist ever to visit the moon. As he describes here, lunar exploration proved to be similar to geologic fieldwork on Earth. He learned to mentally disentangle the effects of meteor impacts to see the underlying rock types. But it was tricky to judge distance in the alien landscape, and stiff spacesuit gloves limited how fast he could work.
- Similar issues will arise on Mars missions.

—The Editors

USING A SPECIALLY DESIGNED **metal scoop, the author took soil samples from the floor of Camelot Crater on December 12, 1972. Human geologists may one day do the same on Mars; in the meantime, they rely on robot proxies such as Mars Pathfinder, which explored Ares Vallis in 1997 (*right*).**

to Mars

By Harrison H. Schmitt

Forty years ago this month the lunar surface reverberated with life for the first time. Forty years from now will Mars, too, come alive? President Barack Obama has affirmed the broad goals for human spaceflight that his predecessor put forward in 2004: retire the shuttle in 2010, develop a replacement line of rockets (named Ares), return to the moon by 2020, and go to Mars, perhaps in the mid-2030s [see "To the Moon and Beyond," by Charles Dingell, William A. Johns and Julie Kramer White; Scientific American, October 2007]. The program is known as Constellation.

For now, policy makers are worried less about Mars than about the downtime between the last shuttle launch and first Ares flight, during which the U.S. will depend on Russia or private companies to launch its astronauts into orbit. What was originally supposed to be a two-year gap has widened to six, and in May the Obama administration announced that former aerospace executive Norman Augustine will lead a review of the program to see how it might get back on track.

Although Mars is still far off, at least NASA is designing spacecraft with an eye toward an eventual interplanetary flight. Planners are guided by the experiences that Harrison H. Schmitt relates in the following article. *—The Editors*

PANORAMA of *Apollo 17* landing site demonstrates some of the visual effects that complicated lunar exploration. Backscattered light created a halo around the shadow of photographer Eugene Cernan, and the lack of air and familiar landmarks made objects appear closer than they actually were. The lunar module was about 150 meters away, and the hill behind it, named South Massif, was about eight kilometers. The astronaut shown is the author. As he deployed the surface electrical properties experiment, he had to lean to his right because his suit was too stiff for him to bend over.

Mountains higher than the walls of the Grand Canyon of the Colorado towered above the long, narrow valley of Taurus-Littrow. A brilliant sun, brighter than any sun experienced on Earth, illuminated the cratered valley floor and steep mountain slopes, starkly contrasted against a blacker-than-black sky. My crewmate Gene Cernan and I explored this nearly four-billion-year-old valley, as well as the slightly younger volcanic lava rocks and ash partially filling it, for three days in 1972—concluding the Apollo program. It was the first and, so far, only time a geologist has ever done hands-on study of another world. Now the U.S., the European Union, Russia and other international partners are contemplating sending astronauts to Mars to do fieldwork there, probably beginning within the first third of this century. What will be new and what will be familiar to the first geologist to step before a red Martian sunrise?

Most accounts of the Apollo missions focus on their historic firsts and their high-tech achievements, but those of us who participated also remember the low-tech, human side: hiking over the terrain, chipping away with a geology hammer, hauling rocks and getting our bearings under the alien conditions. Any geologist would recognize the principles and techniques of field exploration that we applied. The fundamentals did not change. The goal was still to document and graphically represent the structure, relative age, and alteration of natural features so as to infer their origins and the resources they might provide to civilization one day. Nor did leaving Earth change the principles related to expedition planning and execution, such as how to collect and document samples; if anything, those principles become more important as revisits to the same place become less likely. Particularly unchanged was the need for human touch, experience and imagination in fully realizing the scientific and humanistic value of exploration.

For each new body that people explore, we must build on our experience exploring the last place we have been—as geologists have done on Earth for more than two centuries. We must continually ask what may be similar and what may be different. How will Martian geology, accessibility, exploration strategy and optimal crew composition compare with the experience of Apollo?

[THE AUTHOR]

Harrison H. "Jack" Schmitt was the lunar module pilot for the *Apollo 17* mission, the longest and last of the Apollo moon landings. He served as U.S. senator of New Mexico from 1977 to 1983. Schmitt attended college at the California Institute of Technology, obtained his doctorate in geology from Harvard University, and worked with renowned planetary geologist Eugene Shoemaker at the U.S. Geological Survey before being selected for the astronaut program. Since 1994 he has taught at the University of Wisconsin–Madison, and he served as chairman of the NASA Advisory Council from 2005 to 2008.

In the Lunar Field

Extremely complex influences affect geologic features on Earth. The crust, magma, water and atmosphere interact; oceanic plates and continents break and collide; objects from space impact; and the biosphere, including humans, alters the landscape. On the moon, the influences in the past four billion years largely have been external, confined to the effects of impacts and of energetic particles that constitute the solar wind [see "The New Moon," by Paul D. Spudis; Scientific American, December 2003, and "The Carbon Chemistry of the Moon," by Geoffrey Eglinton, James R. Maxwell and Colin T. Pillinger; Scientific American, October 1972].

The absence of an atmosphere exposes surface materials to the extraordinarily hard vacuum of space. Meteors and comets, some as small as dust grains and traveling at tens of kilometers per second, strike and modify the rocks, rock fragments, glass and dust. This process has produced what passes for "soil" on the moon: a covering of fragmented and partially glassy debris,

PRECEDING PAGES: PHOTOILLUSTRATION BY SCIENTIFIC AMERICAN; COURTESY OF NASA (*moon* and *Mars*); THIS PAGE: COURTESY OF NASA (*moon*); COURTESY OF HARRISON H. SCHMITT (*Schmitt*)

called the lunar regolith, that blankets most older volcanic flows and older impact-generated formations to a depth of several meters. Therefore, field exploration on the moon requires that a geologist have x-ray vision of a sort. To identify the interfaces, or contacts, between major rock units, I had to visualize how the gradual formation and spreading of regolith by impacts had broadened and subdued the original contrasts in the rocks' minerals, color and texture.

For example, in the valley of Taurus-Littrow, I explored the contact between dark, fine-grained basalt flows and older, gray, fragmented rocks, known as impact breccias. When this contact formed, it must have been sharp—an abrupt juncture between the rock types. But 3.8 billon years of exposure to space had smeared it out over a few hundred meters. Elsewhere, a contact between a dust avalanche deposit and the dark regolith had spread only a few tens of meters in the 100 million years since the avalanche occurred. By understanding the processes actively modifying these contacts, I could determine their original positions. Similarly, a geologist on Earth must determine how terrestrial erosion obscures or covers underlying rock contacts and structures.

Field identification of different rock types in exposed boulders on the lunar surface required understanding the effects of continuous micrometeorite bombardment. When extremely high velocity particles hit the surface, they create a localized, high-temperature plasma and melt rock at the point of impact. The ejected plasma and molten rock redeposit on nearby surfaces, producing a thin, brownish, glassy patina—containing extremely small iron particles—over the entire boulder. Just as a geologist on Earth must look through the desert varnish on exposed rocks in Earth's dry regions, I had to quickly scan and interpret what lay underneath this patina until I could chip or break the boulder with a hammer.

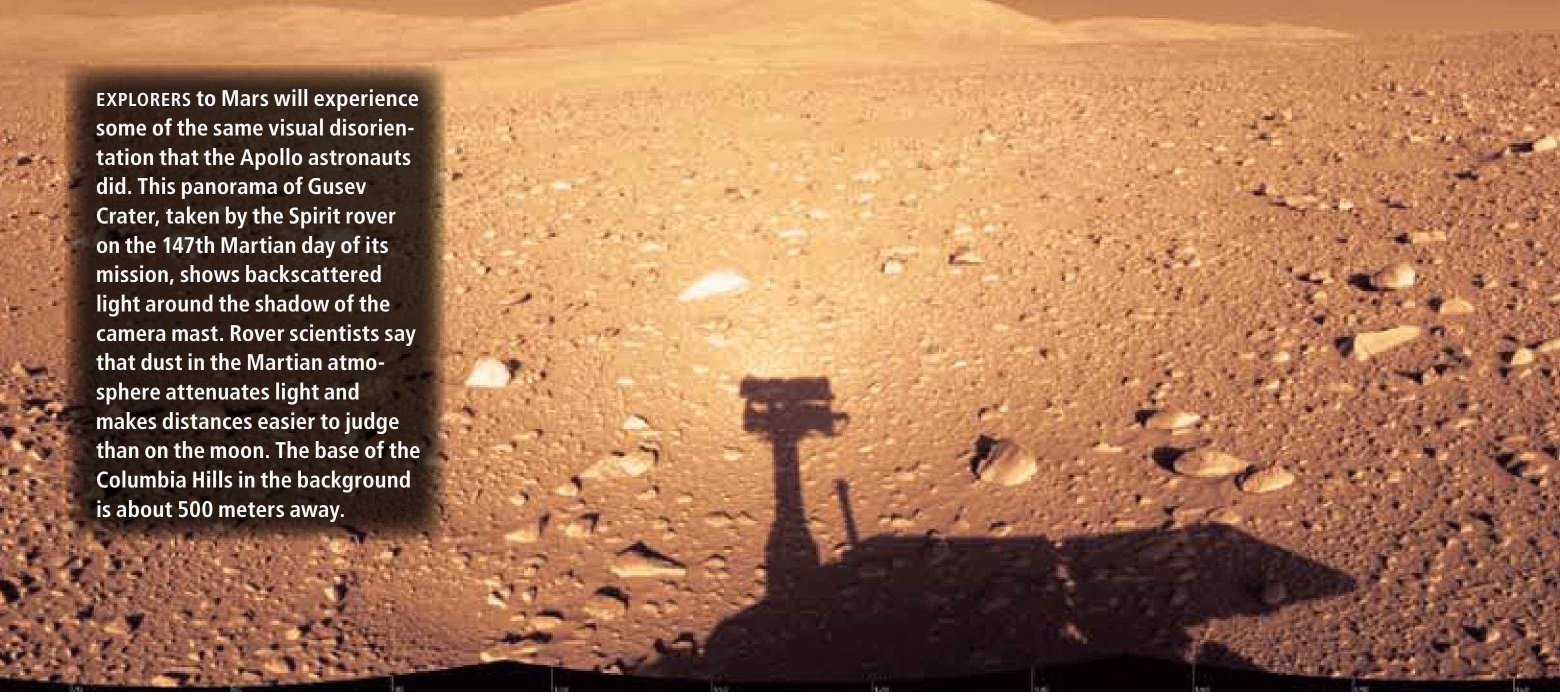
Small impact pits that interrupt the lunar patina contain glass of varying colors, reflecting variations in the chemical composition of impacted minerals. Where the pit formed on a white mineral (such as plagioclase feldspar, a major component of volcanic rocks), the results are a light-gray glass and a distinctive white spot, caused by very fine spider cracks in the mineral grain. Where an iron- or magnesium-rich mineral has been hit, the result is a green glass. Knowledge of this process allowed me to determine a rock's composition just by looking.

What Will Explorers Find on Mars?

On Mars, scientists expect influences that combine those affecting Earth and the moon, because the Red Planet is intermediate in size. Indeed, our growing geologic knowledge about Mars already confirms this blend of processes. Since the first photographs provided by orbital cameras and the Viking landers, we have known that

GLASSY MATERIAL appears in this close-up view of lunar dust collected by *Apollo 11*. It is probably soil that melted during a meteor impact, splashed out and then refroze. Many lunar rocks are covered in a glassy patina that makes them look different from their terrestrial counterparts.

COURTESY OF NASA (*lunar dust*)



EXPLORERS to Mars will experience some of the same visual disorientation that the Apollo astronauts did. This panorama of Gusev Crater, taken by the Spirit rover on the 147th Martian day of its mission, shows backscattered light around the shadow of the camera mast. Rover scientists say that dust in the Martian atmosphere attenuates light and makes distances easier to judge than on the moon. The base of the Columbia Hills in the background is about 500 meters away.

geologic features on Mars resulted from combinations of internal and external influences.

Unlike the moon, Mars has a thin atmosphere, with a ground-level pressure of about 1 percent the pressure at sea level on Earth. The existence of this atmosphere changes the geologic overprint that explorers will have to evaluate and look through to identify, analyze and understand the underlying rock units. The atmosphere filters out small meteors and comets—those capable of forming craters smaller than about 30 meters in diameter. Consequently, the surface is not covered in impact-generated spray, as on the moon. Instead the dominant migrating material is windblown dust. The dust comes from a variety of sources, such as rocks eroded by wind, landslides, impacts and chemical reactions. It forms soft dunes that explorers may need to avoid, much like deep, wind-formed snowdrifts in the plains and mountain passes of Earth. Indeed, the Spirit and Opportunity rovers have gotten stuck on occasion.

In spite of the filtering effect of the atmosphere, impact-related geology still dominates the surface and near-surface fabric of most exposed Martian formations. The first geologists must decipher the ejecta, fractures and shock modification of rocks. Not all the rocks are impact-related, however. In many rift valleys as well as throughout other regions, layered rocks resembling sedimentary or volcanic strata dominate. The impact-generated regolith is not continuous, and many outcrops of underlying Martian bedrock formations are accessible for normal geologic examination and sampling.

Whereas the moon is dry, liquid water sculpted landforms and created new minerals on Mars. Laboratory inspection of lunar samples identified no water-bearing minerals in them, but orbital sensors and robotic analyses of Martian minerals have detected a variety of water-containing clays as well as sulfate salts that probably precipitated from water. Further, unlike the moon, whose rocks contain nonoxidized iron metal, Mars has extensive deposits of oxidized iron (hematite, Fe_2O_3), another sign of processing by liquid water [see "The Red Planet's Watery Past," by Jim Bell; Scientific American, December 2006, and "The Many Faces of Mars," by Philip R. Christensen; Scientific American, July 2005]. The Martian geologist must be prepared to interpret a much larger spectrum of minerals than we encountered on the moon. Water also transports material. It carved valleys, and some impacts appear to have melted subsurface ice to generate mudflows.

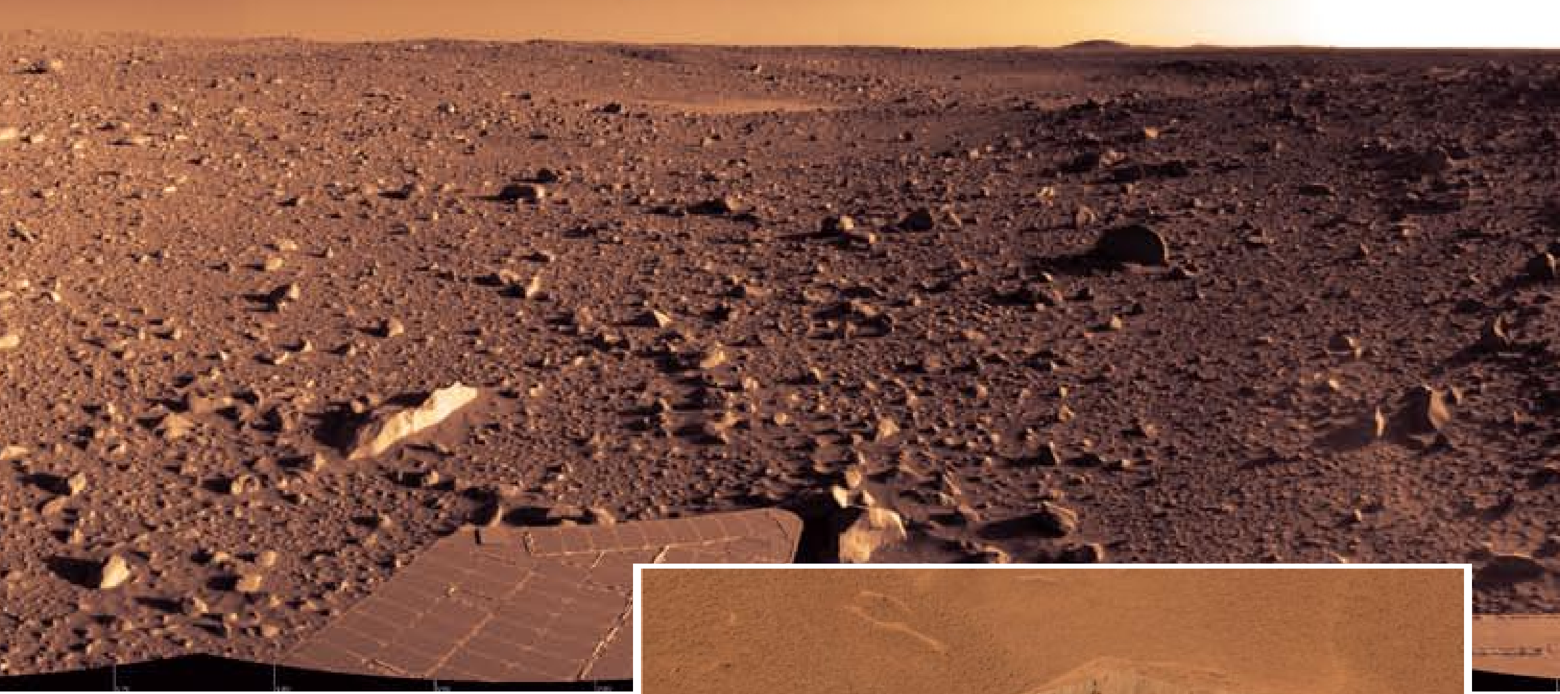
In sum, the Martian regolith generally consists of impact ejecta and debris from mudflows or floods, interstratified with windblown dust. In polar regions, it also contains water and carbon dioxide ices and frosts, as the Phoenix lander recently confirmed. The lunar regolith was not nearly as complex.

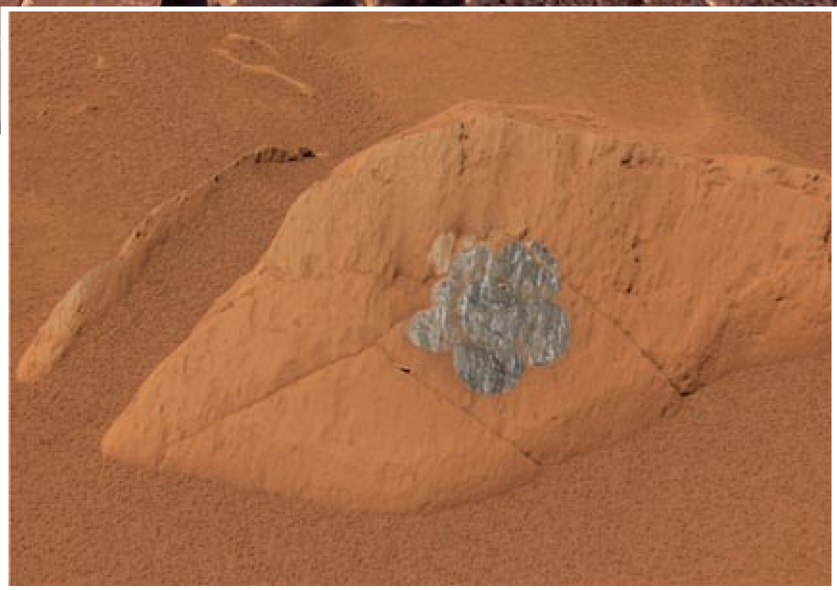
As a consequence of these differences from the moon, new challenges will face the Martian field geologist. The explorer will still need x-ray vision; however, it will be more like that required on Earth, where one must take into account the effect of wind, gravity or water-transported materials. In other ways, exploration may be easier than on the moon. Images from Mars show that although fine, windblown dust forms a very thin, patinalike coating on many rocks, the wind frequently cleans surfaces, so that dust coatings will not be a significant impediment to visual rock and mineral identification.

THE LOST DECADES

Author Harrison H. Schmitt has long argued that the cancellation of the Apollo program in 1972 was a costly mistake, and NASA administrator Michael Griffin made the same point in a March 2007 paper. If NASA had stuck with Apollo technology rather than opting to develop a whole new system—the space shuttle—even the tight budgets of the time would have been enough to fly four times a year to Earth orbit, expand the Skylab space station and go to the moon twice a year. With incremental improvement, the system could have gone to Mars. "If we had done all this," Griffin wrote, "we would be on Mars today, not writing about it as a subject for 'the next 50 years.' "

COURTESY OF NASA/JPL (*Mars panorama* and *Mars rock*)





MARTIAN ROCKS, like lunar ones, have coatings that geologists must look through to identify the rock type. Fortunately, the wind keeps the coating from becoming overly thick. On the 99th Martian day of its mission, the Spirit rover used its rock abrasion tool (RAT) to scrape away the dust and weathered minerals from this rock, known as Route 66.

One similarity to lunar exploration may be visual distortion. In a vacuum or a thin atmosphere, our brain tends to underestimate distances. People experience the same problem in the clear air of Earth's deserts and mountains; the absence of familiar objects such as houses, trees, bushes, power poles and the like worsens matters. Neil Armstrong first noticed this problem after landing *Apollo 11*. I learned to compensate by comparing the known length of my shadow to what it seemed to be and then scaling up my distance estimates by about 50 percent.

Surface dust also plays tricks on the eyes. On the moon, it caused an intense backscatter of light whenever we looked directly away from the sun. This so-called opposition effect—which looks like a bright, diffuse spot—is the same phenomenon that one sees looking toward one's shadow on snow or a plane's shadow when flying over a leafy forest or cropland. Mars astronauts will see it, too. Backscattering provides some light into shadows, whereas shadows seen looking in the direction of the sun are lit only by the small amount of light scattered from other surface features. We had to adjust the f-stop of our cameras relative to the sun line for every photograph we took. Future exploration cameras and video systems should be able to adjust to lighting conditions automatically.

The Difficulty of Access

I personally felt very at ease while on the moon. I attribute this comfort level to being highly motivated and highly trained, as well as having great confidence in the support team on Earth. But the moon was only three and a half days away. Mars, using conventional chemical rockets, is eight to nine months away at best. Even with fusion or electric propulsion, which speeds the journey by continuously accelerating and decelerating the ship, the trip will take months [see "How to Go to Mars," by George Musser and Mark Alpert; Scientific American, March 2000]. Because of its isolation, a Mars crew will have to be much more self-reliant than the lunar crews were.

That said, I suspect that psychological issues will not be much of a problem. A minimum of several months to return home versus a few days might affect some individuals in adverse ways, but explorers of Earth have surmounted this and worse challenges. Historically, adventurers have been subjected to separations from home comparable to those of early Mars crews—and without any means of telecommunication. Mars astronauts' motivation, training, team confidence and survival instincts will be much the same as they were for Apollo. Everyone will be extraordinarily busy with spacecraft operation and maintenance, scientific tasks, physical exercise, simulation training for future tasks, updating of the plans for exploration, and many other duties. In fact, if the history of spaceflight to date is any indication, finding personal time to relax may be the main psychological challenge facing the crew. Planners on the ground will need to bear that in mind.

The primary constraint on exploration efficiency on Mars, as it was on the moon, will be the need to wear a pressurized space suit. The Apollo 7LB suit we used during the exploration of Taurus-Littrow allowed us to do a remarkable amount of fieldwork in a very hostile environment. The suit was pressurized to 3.7 pounds per square inch, about a quarter of atmospheric pressure at sea level on Earth. I could have run in it at about six miles per hour at a steady pace for several miles if need be, using a cross-country skiing gait. With the tools we had and working as a team, we could take samples, document them photographically and bag them at a reasonable rate. In about 18 hours of exploration we collected 250 pounds of rocks and regolith. I would have liked much better leg, waist and arm mobility, but what we had with the A7LB worked.

What almost did not work, or at least created significant fatigue and hand trauma, were the suit gloves. Something must be done about the technology of the gloves when we return to the moon and go on to Mars. Finger flexibility was limited, and my forearms became tired after about 30 minutes. It was like squeezing a tennis ball continuously. After an eight-hour rest period, I felt no residual muscle soreness—one advantage of more efficient cardiovascular circulation in one-sixth gravity. But after three eight- to nine-hour pressurized excursions, I am not sure how many more would have been possible with the hand abrasions and fingernail damage that the gloves caused.

Something must be done about the gloves. My forearms became tired after about 30 minutes. It was like squeezing a tennis ball continuously.

GLOVES WORN by the author on the lunar surface.

Space-suit technology may evolve so that the suit glove or its equivalent will approach the dexterity of the human hand and that the suit itself will become as mobile as cross-country ski clothing [see "A Spaceship for One," by Glenn Zorpette; Scientific American, June 2000]. Conceivably, robotic field assistants may help with preplanning traverses. In addition, based on the experience of astronauts constructing the International Space Station, we now know of physical training techniques that provide superior conditioning of arm muscles for continuous hand exertion. Other new procedures and equipment could further enhance exploration efficiency.

Forming a Crew

The political urgency and test-flight nature of early Apollo planning and development left few options for selecting experienced field geologists as regular members of lunar mission crews. NASA chose mostly professional test and military pilots with only one pilot-trained field geologist (me). All crewmembers needed to be accomplished, experienced and confident in the use of the machines and methods necessary for flight. There was no room for field geologist "passengers."

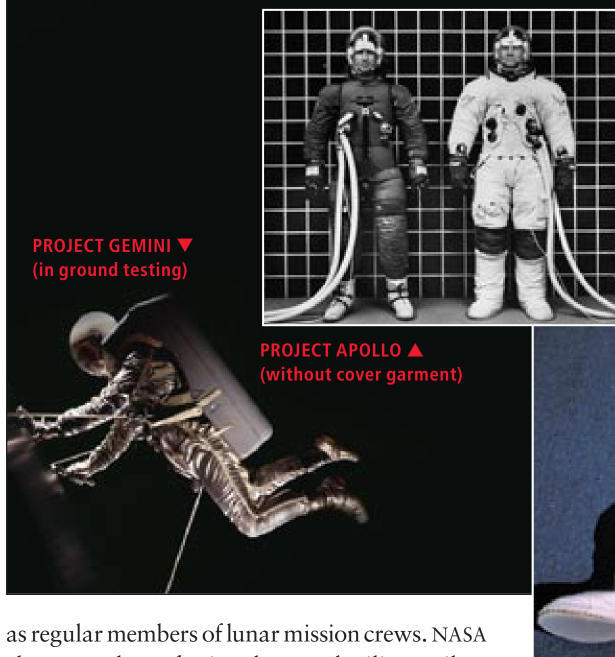
That should change beginning with the return to the moon by the Constellation program a decade or so from now. Professional field explorers should be part of every crew sent to the moon, establishing the precedent for Mars exploration. As with the last several Apollo missions, all crewmembers and their operational support teams should receive as much terrestrial field training on real geologic problems as possible. The optimum crew size for early exploration appears to be four: two professional pilots cross-trained as field explorers and systems engineers, as was done for Apollo lunar crews; one professional field geologist cross-trained as a pilot, systems engineer and field biologist; and one professional field biologist cross-trained as a physician and field geologist.

With this cross training, mission success depends not on any one individual but on teamwork. In addition to being fully prepared to contribute specialized skills to an integrated team, each member of a Martian crew must be completely and unhesitatingly comfortable and com-

[SPACE SUITS]

A SPACE SUIT FOR ALL

Space suits look sexy in science fiction but are hard to work in. They must be pressurized for the astronaut to breathe, but pressure makes the suit rigid, restricting mobility. The Apollo



COURTESY OF NASA (*Schmitt's gloves*); RALPH MORSE *Getty Images* (*Gemini* and *Apollo*); ROGER RESSMEYER *Corbis* (*space shuttle* and *AX-5*); COURTESY OF NASA (*Constellation program*)

OCCASIONS

astronauts required extensive practice to get used to working in their suits. Future suits might provide more flexibility.

SPACE SHUTTLE ▼

AX-5 HARD-SHELL SUIT ▲

CONSTELLATION PROGRAM ▲

patible with a hierarchical command structure. Historically, small, isolated teams of explorers have achieved greatest success when they worked under a clear, experienced leader.

In many ways, Martian exploration will differ from lunar exploration. First, because the trip will be measured in months rather than days, the crew will need to continue practicing landing and other flight procedures throughout their trip. For the Apollo missions, we rehearsed landing in a simulator on the ground, and our last dry run was a few days before launch, when we had less than a week before we would begin our powered descent to the moon. The gap between launch and landing would be on the order of nine months for Mars trips—clearly too long without regular training activity onboard.

Second, ground control on Earth will not be able to perform the traditional mission-control functions because of the long delays in communications (as long as 22 minutes, one-way). Earth will instead handle activities that do not require live interaction with the crew, such as data analysis and synthesis, weekly planning, systems and consumables monitoring and analysis, maintenance planning, and scenario development. The actual live mission-control functions will need to be performed by the astronauts themselves. For instance, the mission might consist of two crews, one of which lands while the other remains in orbit to act as an orbiting mission-control center. When the first returns to orbit, the second descends and explores a different site.

This degree of autonomy is not unprecedented. Even during Apollo, although we planned the lunar exploration activities before launch using available photographs, NASA left significant latitude to the crews to pursue unanticipated targets of opportunity. For instance, late in the second exploration period of *Apollo 17,* I discovered orange volcanic glass in the rim of Shorty Crater with only 30 minutes left to work at that site. Without waiting for suggestions from mission control, Gene and I began to describe, photograph and sample the deposit. We did not have the time to discuss this plan with controllers, but we knew immediately what needed to be done. Exactly this approach will be required of the crews on Mars, all the time, with mission control on Earth finding out everything tens of minutes after the fact.

A third difference from Apollo is that, in light of the expense and historical importance of each Mars exploration mission, the mission philosophy must be totally success-oriented. If something goes wrong, the astronauts should still be able to continue their mission and achieve all its major goals. For example, the ship should ideally carry two landers in case one cannot be used. Further, if systems or software anomalies occur during the entry, descent and landing sequence, the astronauts should be able to abort to land rather than abort to orbit, as was the plan during Apollo. The problems can be resolved over time, in consultation with Earth, once the crew lands safely on Mars.

Young people now alive will have the privilege and adventure of exploring Mars, if their parents and grandparents provide them the opportunity. It will not be easy. As with anything worthwhile, risks exist. Not only are the rewards from new knowledge great, but the costs of ceasing our exploration also would be great. Postponing the exploration of Mars beyond what is already planned would leave Americans to follow in the footsteps of other explorers and nations. Moreover, without a gradual effort to learn how to explore and eventually settle on other worlds, the very existence of humankind will remain vulnerable to the impact of asteroidal and cometary travelers of the solar system. Curiosity, the lessons of history and our self-preservation instinct all demand that we continue to move outward. ■

➥ MORE TO EXPLORE

Exploring Taurus-Littrow (What Is It Like to Walk on Another World?). Harrison H. Schmitt in *National Geographic,* Vol. 144, No. 3, pages 290–307; September 1973.

A Trip to the Moon. Harrison H. Schmitt in *Where Next, Columbus?: The Future of Space Exploration.* Edited by Valerie Neal. Oxford University Press, 1994.

Apollo 17 and the Moon. Harrison H. Schmitt in *Encyclopedia of Space Science and Technology.* Edited by Hans Mark. Wiley, 2003.

Return to the Moon. Harrison H. Schmitt. Springer-Praxis, 2006.

Decoding the Mineral History of Mars. Vivien Gornitz in *Mineral News,* Vol. 24, No. 2, pages 12–13; February 2008.

Paper Astronaut: The Paper Spacecraft Mission Manual. Juliette Cezzar. Introduction by Buzz Aldrin. Universe, 2009.

New Ways to Squash Superbugs

Scientists are using new tools and tactics in the race to discover novel antibiotics

By Christopher T. Walsh and Michael A. Fischbach

KEY CONCEPTS

- Dangerous bacteria are developing resistance to existing antibiotics faster than humans can invent or discover new drugs.
- Searching exotic environments and microbial genomes are among the innovative strategies being applied to the problem.
- New approaches that narrowly target single organisms or stop short of killing them may help break the vicious cycle of resistance.

—The Editors

"Superbug Strikes in City" sounds like a horror movie title, but instead it is a headline printed in the October 26, 2007, edition of the *New York Post*. Twelve days earlier a 12-year-old Brooklyn boy, Omar Rivera, died after a wound he received on the basketball court became infected with methicillin-resistant *Staphylococcus aureus* (MRSA), a bacterium that has become resistant to one of the most potent drug classes in the current antibiotic arsenal.

The prospect of healthy people contracting an untreatable bacterial infection may have seemed remote a decade ago, but it has now become a reality. In 2007 a research team led by Monina Klevens at the Centers for Disease Control and Prevention reported that MRSA causes 19,000 deaths every year in the U.S., which is more than HIV/AIDS causes. The number is especially alarming because almost 20 percent of people who contract MRSA die from it, and an increasing number of its victims are young, healthy people who were infected going about everyday activities. The problem was once limited to hospitals or nursing homes, where many people were already vulnerable because of impaired immunity. Even for those who survive, the price of MRSA is high: a patient who contracts it while hospitalized stays an average 10 days longer and costs an additional $30,000.

The total annual expenditure on treating MRSA infections in U.S. hospitals is an astounding $3 billion to $4 billion, and staph is just one of the pathogens that are becoming more and more difficult to subdue. Modern medicine is losing the war against disease-causing bacteria that were once considered vanquished, and new approaches to discovering and creating antibiotics are needed to turn the tide.

Recurring Resistance

The story of MRSA illustrates how quickly drug resistance can arise. Indeed, the natural mechanisms that cause resistance in staph and other bacteria make the problem almost inevitable, creating a constant need for new antibiotics.

Methicillin, a derivative of the better-known penicillin, was introduced in 1959 to treat infections caused by strains of bacterial species—such as *S. aureus* and *Streptococcus pneumoniae*—that had become resistant to penicillin. European hospitals, however, observed methicillin-resistant strains of *S. aureus* just two years later, and by the 1980s MRSA was becoming widespread in health care facilities throughout the world. By the mid-1990s a new class of MRSA infections had emerged: those that were contracted in the "community," rather than a health care setting.

MRSA is challenging to treat, in part because it can spread quickly if it gains access to the bloodstream. But the most pernicious quality of MRSA is its ability to resist a major class of antibiotics known as beta-lactams (which includes cephalosporins and all variations of penicillin) by producing an enzyme that cleaves and destroys the drugs. Resistance to beta-lactams limits the physician's arsenal of anti-MRSA weapons to a small set of antibiotics, each of which has serious side effects. And some strains of MRSA have already become resistant to the most effective of these, namely, vancomycin.

The advent of vancomycin resistance among bacteria already resistant to methicillin exemplifies a daunting problem for doctors and drug developers alike: from the moment an antibiotic is introduced in the clinic, its useful lifetime begins to tick down. The culprit is natural selection: the mere presence of an antibiotic creates an environment in which a bacterial strain that happens to be resistant will suddenly have a growth advantage over its competitors. Vancomycin was approved by the U.S. Food and Drug Administration in 1958, and once MRSA arose, it became the mainstay of therapy for MRSA infections. But in 2002 strains of MRSA that were also resistant to vancomycin began to emerge in hospitals. These strains, known as vancomycin-resistant *S. aureus* (VRSA), were progeny of MRSA that had acquired a set of five genes that travel together as a "cassette" and confer vancomycin resistance. The enzymes encoded by these genes allow VRSA to replace vancomycin's target on the bacterial cell wall with a variant structure that vancomycin is no longer able to bind. As a result, vancomycin—a drug once known as the "antibiotic of last resort"—no longer inhibits the growth of VRSA.

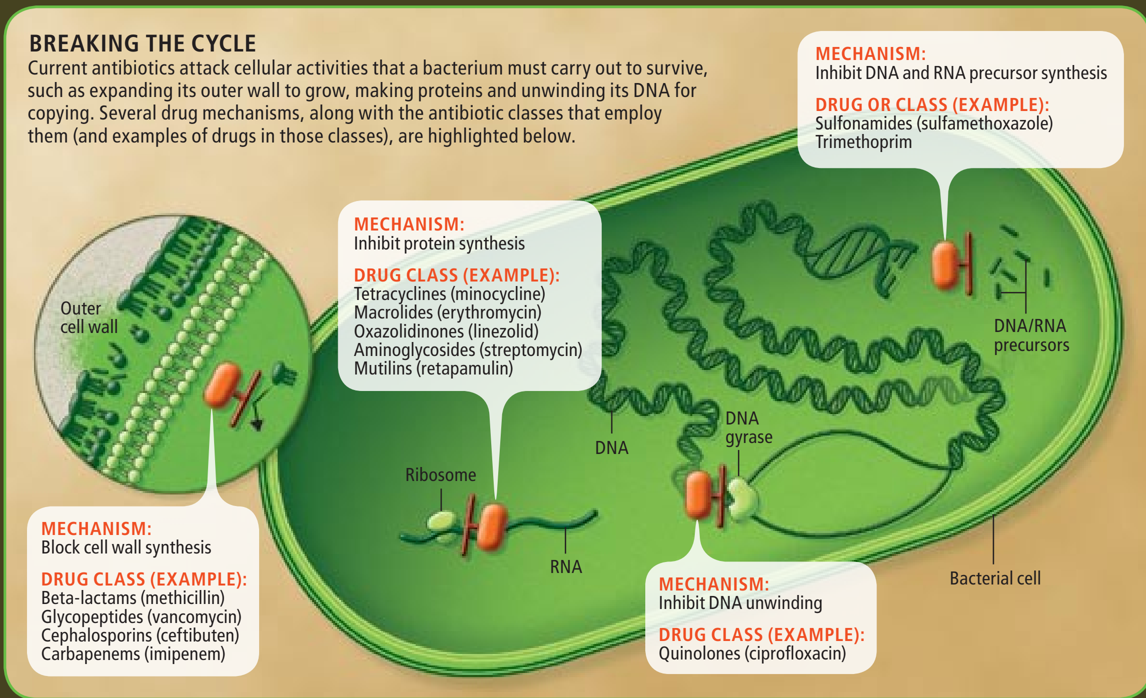
Replacing an antibiotic's target is just one of three major strategies bacteria use to evade death. As a second strategy, many antibiotic-

PETER AND MARIA HOEY

[BASICS]

CURRENT ANTIBIOTIC MECHANISMS …

Typical antibiotics in doctors' arsenal today aim to kill bacteria by interfering with some aspect of their essential life functions. In turn, bacteria have several ways of destroying or evading the drugs.



resistance genes, such as the one that makes MRSA resistant to beta-lactams, encode an enzyme that destroys or chemically modifies the antibiotic, rendering it ineffective. Still other resistance genes carry instructions for a pump that gets mounted in the cell membrane and excretes antibiotic molecules that enter the bacterial cell, keeping its internal concentration of the antibiotic low enough to avoid death.

Where do these resistance genes originate? Some arise through random mutations in the bacterial cell's own genes, such as the variant gene that replaces the enzyme target of ciprofloxacin and other fluoroquinolone antibiotics with a resistant form of the same enzyme. Other resistance genes are picked up from nearby bacteria; for instance, the five-gene cassette that confers vancomycin resistance originally came from a bacterium that *produces* the antibiotic. It needed the genes to protect itself from its own chemical weapon, but other bacteria probably acquired the same defense through the ongoing genetic swap meet that bacteria engage in, known as horizontal gene transfer.

Such transfers are often carried out by circular pieces of DNA called plasmids, which behave like stripped-down viruses: they transfer themselves from one bacterium to a new host cell, where they are recognized as a native piece of DNA and copied using the bacterial host's own replication machinery. To aid their spread, plasmids also bear genes that promote the survival of their host, including antibiotic-resistance genes. One plasmid isolated from bacteria in a sewage treatment plant was found to encode nine different antibiotic-resistance genes.

The process of horizontal gene transfer was also witnessed in action when MRSA, VRSA and a third bacterium, *Enterococcus faecalis*, were isolated from the same dialysis patient in a Michigan hospital in 2002. Genetic analysis of these strains showed that a plasmid containing the vancomycin-resistance gene cassette (along with resistance genes for three other antibiotics and one class of disinfectants) had been transferred from *E. faecalis* to MRSA, creating a novel strain of VRSA.

That one chronically ill patient became coinfected by two different bacterial pathogens that gave rise to a third is, sadly, not surprising. Because hospital intensive care units and nursing homes are often populated with immunocompromised patients undergoing intensive antibiotic treatment, they are the best-known breeding grounds for new antibiotic-resistant bacteria. Nurses and doctors can unwittingly facilitate bacterial transfer by shuttling from patient to patient to change intravenous lines and

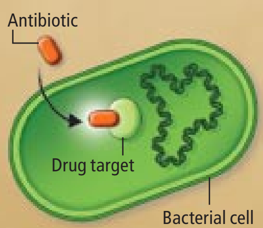
[THE AUTHORS]

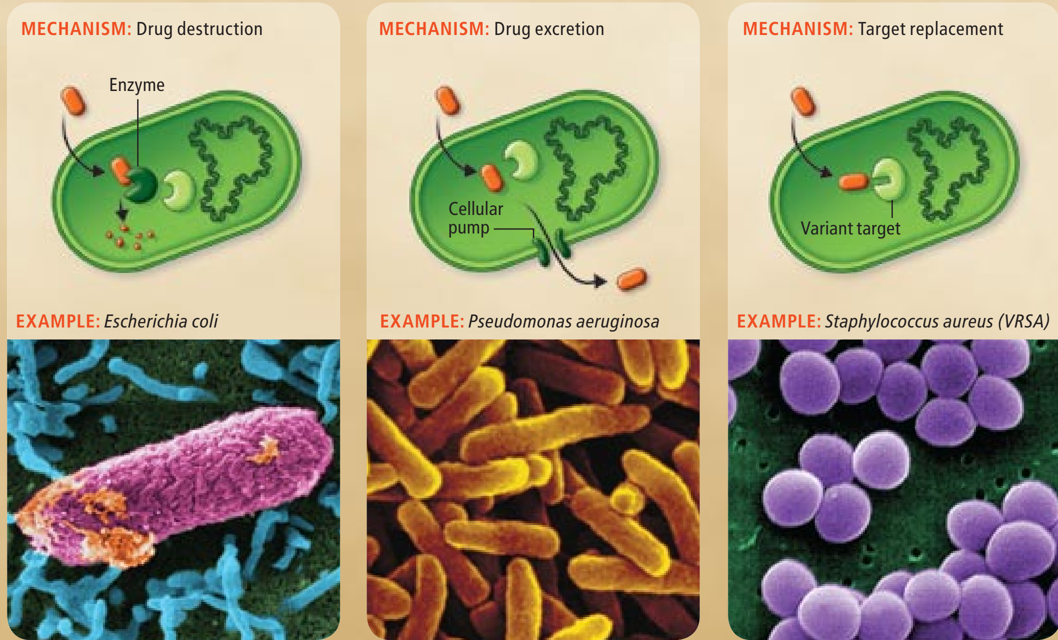

Christopher T. Walsh is Hamilton Kuhn Professor of Biological Chemistry and Molecular Pharmacology at Harvard Medical School and serves as an adviser or board member for several biotechnology and pharmaceutical companies. His research focuses on studying the mechanisms microorganisms use to synthesize antibiotics and other molecules with potential therapeutic value. Until recently, Michael A. Fischbach was a junior fellow in the department of molecular biology at Massachusetts General Hospital, where he began collaborating with Walsh to search microbial genomes for antibiotic-producing genes. He has just begun an assistant professorship in the department of bioengineering and therapeutic sciences at the University of California, San Francisco.

COURTESY OF WALSH LAB (*Walsh*); COURTESY OF PAUL STRAIGHT (*Fischbach*); TAMI TOLPA (*illustrations*) (*this page and opposite page*)

… AND HOW BUGS FIGHT BACK

RESISTANCE TACTICS
Through a lucky gene mutation or acquisition of a gene from another organism, bacteria find ways to resist current antibiotics. The three most common forms of resistance are deployment of an enzyme that destroys or disables the antibiotic drug; use of a pump in the cell wall that excretes the drug before it can work; and replacement of the drug's target protein with a variant version the drug cannot recognize. Pathogens known to use each of these methods are shown below each mechanism.





catheters, which is why programs that encourage hospital staff to sanitize their hands between each patient encounter inevitably lead to a reduction in the number of infections.

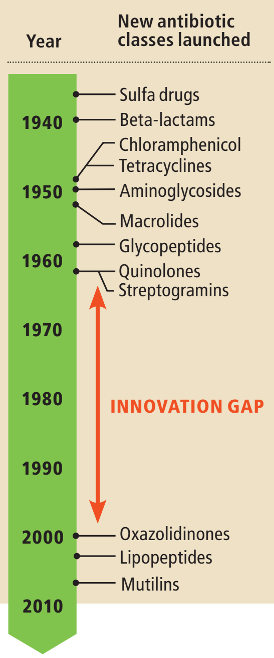
VRSA, which has not yet spread widely, is sensitive to very few antibiotics in clinical use and has a high death rate. Another class of emerging pathogens, the pan-drug-resistant gram-negative bacteria, has an even scarier profile of resistance. Gram-negative bacteria have, in effect, two cell membranes, and the additional outer membrane prevents many antibiotics from getting inside gram-negative cells. Gram-negative pathogens that are resistant to almost all clinically used antibiotics include strains of the food-poisoning pathogen *Escherichia coli,* its relative *Klebsiella pneumoniae,* and two opportunistic bugs—*Pseudomonas aeruginosa* and *Acinetobacter baumannii*—that can cause pneumonia, meningitis and bacteremia in immunocompromised hospital patients.

Clearly, health care providers must do everything possible to help prevent the spread of resistant bacteria—and, therefore, resistance genes—in clinical settings and in communities. But new antibiotics are also needed to complement those efforts and to combat already resistant bugs.

The period from the late 1930s to the early 1960s was a Golden Age for antibiotic discovery in which almost all the major classes of currently used antibiotics were introduced. Unfortunately, the four decades between the launch of the quinolones in 1962 and the approval of the oxazolidinones in 2000 represent an innovation gap in which no new antibiotic classes made it to the clinic. One reason is a slew of economic disincentives for pharmaceutical companies to invest in antibiotic research—in part because it is so challenging, with small profit margins when compared with so-called lifestyle drugs that must be taken long-term for a condition such as high blood pressure or arthritis. Another reason is that the current antibiotics were discovered by techniques that are now dated, and finding new ones will require novel discovery strategies.

ANTIBIOTIC INNOVATION

In 1962 traditional drug discovery methods yielded the last new antibiotic classes for the next 40 years. The classes introduced in recent years were also discovered decades earlier but not pursued at the time.



Seek and Synthesize

Most antibiotics sold today are produced by bacteria and fungi or are chemically modified derivatives of these natural antibiotics. Microbes wield their antibiotics against one another as "chemical warfare" and perhaps also secrete them in lower concentrations as signaling molecules. Investigators have traditionally searched for such natural antibiotics by isolating microbes, often from soil samples, growing them in the laboratory, then extracting their secretions from the culture medium. By testing those chemicals

GARY GAUGLER *Photo Researchers, Inc.* (E. coli); STEM JEMS *Photo Researchers, Inc.* (P. aeruginosa); COURTESY OF JANICE HANEY CARR *Centers for Disease Control and Prevention* (S. aureus)

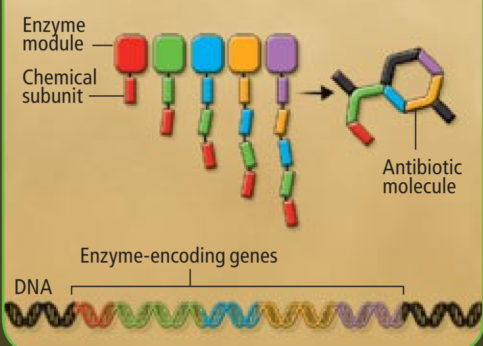
[TECHNIQUES]

MINING GENES FOR DRUGS

Most of the antibiotics in use today are manufactured by bacteria themselves. In nature, they serve as a form of chemical warfare against rivals. More of these natural weapons can be found or modified to be more useful by applying techniques for scanning genomes and manipulating genes.

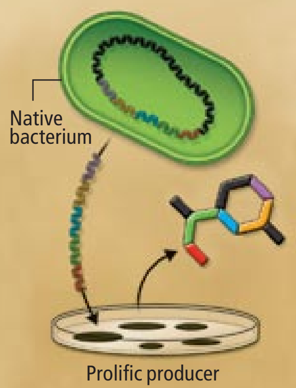
HUNTING GENES

Bacteria manufacture certain natural antibiotics by setting up assembly lines of enzymes grouped into modules, each adding successive components. Those enzymes are encoded by suites of genes. Scientists can scan whole genomes of many different bacteria for gene sets that might give rise to novel antibiotics. Not all such gene clusters are active within the cells, so hunting within the genome is the only way to identify these "cryptic" antibiotics.



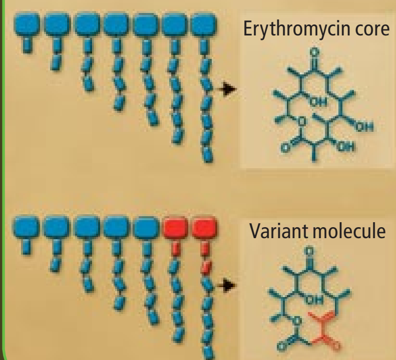
MOVING GENES

When a newly discovered antibiotic compound is dormant in its native bacterium or is made in amounts too small for the bacterium to serve as a drug "factory," scientists can transfer the entire gene suite encoding the necessary enzymes into a more cooperative organism.



MODIFYING GENES

A drug can be modified to overcome bacterial resistance by genetically engineering the organism that manufactures it so that the microbe uses novel enzyme modules. In one set of experiments, scientists mixed and matched genes to produce 50 variants of the erythromycin molecule core, which could give rise to new versions of erythromycin.



against disease-causing bacteria, drugmakers look for individual molecules that might have therapeutic potential. Pharmaceutical companies have tested millions of bacterial extracts in this way, yet only about 10 classes of natural antibiotics are on the market. Others have been discovered, but for various reasons—including weak antibacterial activity and unmanageable toxicity—none are widely prescribed.

These approaches worked well during the Golden Age of antibiotic discovery, but all the low-hanging fruit has now been picked. Despite the continued efforts of pharmaceutical companies over the past five decades, the rate of antibiotic discovery actually declined. One frustrating reason is rediscovery: because most antibiotic-producing microbes form spores that travel the globe—and the genes responsible for antibiotic production can be transferred horizontally, just like antibiotic-resistance genes—many different microbes make the same antibiotics. According to a recent estimate, for example, about one in 250 strains of the most commonly mined order of antibiotic-producing bacteria, the actinomycetes, makes tetracycline. Although the high rate of rediscovery has caused some research groups to conclude that the antibiotic "mother lode" has been mined out, genetic analyses of bacteria have recently cast doubt on this conclusion and instead suggest that new tactics are necessary.

Technological advances often lead to the rebirth of an old discipline, however, and antibiotic discovery seems to be on the verge of such a renaissance. Current strategies for developing new antibiotics fall into two categories: modifying existing ones and discovering entirely novel ones. Chemically modifying microbially produced antibiotics yields "semisynthetic" antibiotics in which the warhead is intact and the periphery has been altered. A recent example of this approach started with antibiotics in the tetracycline class, which inhibit the bacterial cell's protein-making factory, the ribosome. Resistance to the tetracyclines is often caused by a pump in the bacterial cell membrane that excretes them before they can do their work—which has become a serious problem among pan-drug-resistant gram-negative bacteria.

Scientists at Wyeth synthesized a chemically modified tetracycline, called tigecycline, that can no longer be pumped out of target cells. Approved by the FDA in 2005, tigecycline is now used against a variety of tetracycline-resistant pathogens, although its use is restricted to health care settings because it requires intravenous administration. Ominously, resistance to tigecy-

FIGHTING FLU

Antibiotics have no effect on viruses such as the novel influenza A (H1N1) strain shown below, but in the event of a pandemic caused by this new flu virus, most of the fatalities would likely be caused by secondary bacterial infections that lead to pneumonia. Flu weakens its victims' defenses, leaving them vulnerable to opportunistic bacteria. When MRSA or other resistant bacteria cause pneumonia, an already bad situation becomes harder to treat and more lethal.

TAMI TOLPA *(illustration)*; C. S. GOLDSMITH AND A. BALISH *Centers for Disease Control and Prevention (H1N1)* cline has already been observed among strains of *A. baumannii;* time will tell how quickly tigecycline resistance spreads.

Instead of chemically tweaking microbially produced antibiotics such as penicillin, vancomycin and erythromycin, scientists can also modify drugs by genetically altering the organisms that produce them. Most organisms synthesize natural antibiotics using enormous assembly lines of enzyme teams, or "modules," each of which inserts a building block into the growing antibiotic molecule. By making genetic changes that alter particular enzyme modules, investigators can induce the organisms that serve as antibiotic factories to produce drugs that differ by a single building block at a specified position. Kosan, a biotechnology company recently purchased by Bristol-Myers Squibb, applied this form of programmed genetic engineering to generate dozens of derivatives of the antibiotic erythromycin that would otherwise have been difficult to make using standard synthetic chemistry.

Even though modifying existing antibiotics has been a fruitful strategy, discovering brand-new antibiotic classes would be even more desirable because they are less likely to suffer from the rapid rise of resistance that plagues successive generations of existing antibiotics.

Mining Genomes

Research efforts in recent years have focused on identifying enzymes that bacteria require for survival, in the hope that molecules that inhibit these essential enzymes could be found in chemical libraries and turned into drugs. Before embarking on that search, however, the first step is to establish what effect losing the enzyme would have on the bacterium. Once researchers have deciphered a bacterium's genome—its full sequence of DNA code—they can then disable genes encoding certain enzymes to see whether the bacterium can survive without them.

Although efforts to identify new enzyme targets this way have disappointingly not yet yielded new antibiotics, they may bear fruit in the coming years. One major challenge is the formidable barrier to entry presented by the bacterial cell wall: even when a small molecule that potently inhibits an important bacterial enzyme is discovered, it is useless if it cannot reach its target inside the cell. Instead of seeking weak spots in pathogens, another way of discovering new antibiotics is to study antibiotic-producing microbes. Genomics can be useful here, too.

The first genome sequences of antibiotic-producing bacteria, in 2002, raised an intriguing mystery: these microbes, in the actinomycete class, had 25 to 30 gene sets that, according to their sequences, looked as if they were blueprints for enzyme modules that produced antibioticlike molecules, but the bacteria did not appear to use most of those genes. When cultured in the laboratory, they synthesized just one or two of the molecules.

To see if such apparently dormant genes encode machinery for making novel antibiotics, we, along with several of our co-workers at Harvard Medical School and the Broad Institute, are sequencing the genomes of 20 additional actinomycete strains and applying sophisticated computer algorithms to pick out any genes that might contain instructions for antibiotic-producing

Organisms in exotic settings are more likely to make antibiotics that have not been discovered already.

[NEW SOURCES]

EXPANDING THE SEARCH

Bacteria that live in soil proved to be such a rich source of antibiotic compounds during the early era of antibiotic discovery that scientists have traditionally not looked much further afield. Searching for novel compounds in new environments and overlooked organisms is yielding antibiotic molecules whose mechanisms are different enough from current drug classes to avoid meeting resistance.

MARINE ORGANISMS

Extreme environments are a good place to look for unusual chemicals because the organisms that produce them are responding to exotic conditions and threats. A powerful new antibiotic called abyssomicin, for example, is made by *Verrucosispora* (*in culture, left, and as spore, right*), a bacterium that lives in the Sea of Japan at a depth of nearly 300 meters.

MUTUALIST MICROBES

Cooperation leads to specialization, and participants in mutualist relationships produce highly targeted molecules. A fungus that lives on the southern pine beetle helps it to digest wood pulp. In return, the beetle plays host to a bacterium that produces a powerful antifungal agent, which kills competing fungi but not the beetle's mutualist.

UNCOOPERATIVE PRODUCERS

Certain bacteria are prolific generators of novel antibiotics but are unable or unwilling to grow in laboratory and industrial conditions. *Stigmatella aurantiaca* (*left*) makes an antibioticlike molecule called myxochromide, but like its fellows in the group of myxobacteria, it is difficult to culture. With new tools for moving the relevant genes into more willing producers, families of bacteria that have been ignored until now can be explored for useful molecules.

COURTESY OF RODERICH SÜSSMUTH AND HANS-PETER FIEDLER (*Verrucosispora*); COURTESY OF USDA FOREST SERVICE (*beetle*); DAVID WHITE, COLORIZED BY YVES BRUN, COVER OF *JOURNAL OF BACTERIOLOGY,* VOL. 185, NO. 4; FEBRUARY 2003 (*S. aurantiaca*) enzyme modules. Studying the genome sequences around these modules should also help reveal the regulatory mechanisms that cells use to determine when an antibiotic gets made. With both sets of information, we can engineer the cells to switch on the desired genes so we can test the cryptic molecules for antibiotic activity.

Instead of trying to coax bacteria into making their antibiotics on demand, however, a research group at Saarland University in Germany has chosen to move antibiotic-producing genes from their recalcitrant producers to different bacteria that seem better suited for antibiotic manufacture. Rolf Müller and his colleagues work with

Scientists can modify drugs by genetically engineering the organisms that produce them.

myxobacteria, an order of bacteria that, like actinomycetes, are prolific producers of antibiotics. Because myxobacteria can be more difficult to culture in the laboratory than actinomycetes, far fewer efforts have been made to screen them for novel antibiotic production.

Müller circumvented this problem by splicing the genes involved in producing myxochromide, an antibioticlike molecule, from the myxobacterium *Stigmatella aurantiaca* into *Pseudomonas putida*, a bacterial strain that is easier to grow. Indeed, *P. putida* is commonly used for commercial production of industrially useful enzymes. In meeting two key challenges—finding a genetically manipulable bacterial host that has the metabolic infrastructure required for antibiotic production and developing techniques to move large DNA fragments from one microbe to another—Müller's work opens the door to discovering and producing a treasure trove of new antibiotics from myxobacteria and suggests that a large-scale myxobacterial genome-sequencing effort would be well worth undertaking.

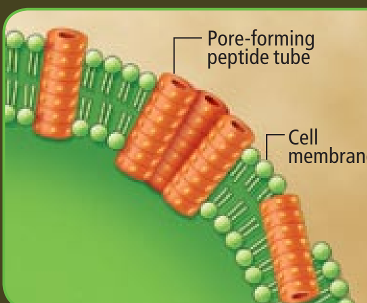
In addition to exploring underexploited soil microbes, researchers can turn their attention to as yet unexplored ecological settings that might be fruitful because organisms in exotic settings are more likely to make antibiotics that have not been discovered already. Roderich Süssmuth and his colleagues at the University of Tübingen in Germany made just such a discovery: a new antibiotic called abyssomicin from an actinomycete isolated from a sediment sample taken at a depth of 289 meters in the Sea of Japan. Another group studying marine bacteria—Bradley Moore, William Fenical and their colleagues at the Scripps Institution of Oceanography in La Jolla, Calif.—sequenced the genomes of two formerly unknown marine actinomycete strains. These genomes displayed a diverse array of genes for antibiotics and related molecules, providing further evidence for the potential of marine bacteria to yield new classes of antibiotics.

A different approach to mining new ecological settings for useful drugs is to study microbes that take part in mutualisms—interspecies interactions in which both parties benefit. For instance, the southern pine beetle is known to carry around a mutualistic fungus that digests the insides of pine trees the beetle invades. How the beetle protects its fungal mutualist from a second, antagonistic strain of fungus that competes with the first strain for food was a mystery, however, until Cameron Currie, Jon Clardy and their research groups at the University of Wis-

[NEW STRATEGIES]

NOVEL WAYS TO BEAT BUGS

Beyond improving existing antibiotics and seeking new molecules with antibioticlike effects, researchers are also pursuing novel approaches to killing or disabling pathogenic bacteria. Many of these have the added advantage of avoiding mechanisms that usually lead to resistance.

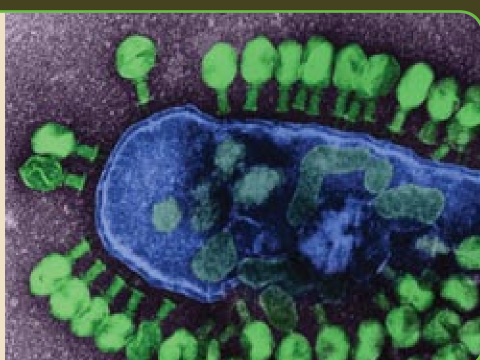


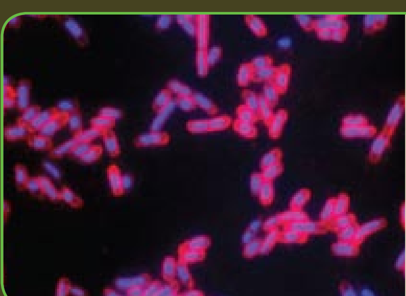
POKING HOLES

Rather than attacking bacterial enzymes or life processes, pore-forming tubes kill by simply puncturing a bacterial cell's membrane. Small, naturally occurring proteins called definsins perform a similar function in vertebrates to defend against microbes. Several research groups are developing synthetic protein fragments called peptides that would self-assemble into tubes within bacterial membranes.

NARROW TARGETING

Bacteriophages (*green*) are viruses that infect a bacterium (*blue*), typically preferring only one host. Phages have long been studied for possible use against pathogenic bacteria, but they also exemplify the principle underlying new "narrow spectrum" drugs, which target only a single pathogen, leaving human cells and friendly bacteria unharmed.



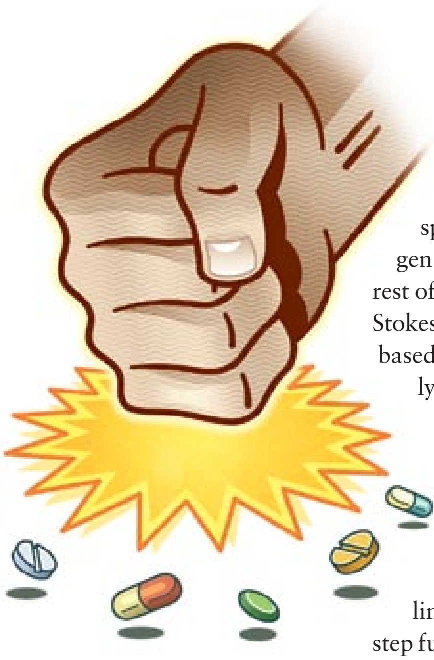


SUBDUE WITHOUT KILLING

Sparing the pathogen itself but taking away its ability to cause illness is one way to treat disease without promoting antibiotic resistance. An example of this approach is genetically engineered *E. coli* (*red*) designed to imitate cells in the human gut. When the harmless *E. coli* are consumed, they soak up deadly Shiga toxin (*blue*) produced by another microbe.

LEE D. SIMON *Photo Researchers, Inc.* (*bacteriophage*); SOURCE: "DESIGNER PROBIOTICS FOR PREVENTION OF ENTERIC INFECTION," BY ADRIENNE W. PATON, RENATO MORONA AND JAMES C. PATON, IN *NATURE REVIEWS MICROBIOLOGY*, 2006, REPRINTED BY PERMISSION FROM MACMILLAN PUBLISHERS LTD (*modified E. coli*); TAMI TOLPA (*peptide tubes*) consin–Madison and at Harvard Medical School recently showed that the beetle totes a second mutualistic microbe—an actinomycete—that produces a powerful and previously unknown antifungal agent. This molecule, called mycangimycin, kills the antagonistic fungus but not the mutualistic one.

Jörn Piel of the University of Bonn in Germany has shown that a different kind of beetle and a marine sponge both harbor bacterial symbionts that produce related antibioticlike molecules. Also in Germany, Christian Hertweck of the Hans-Knöll Institute in Jena has discovered a fungus that carries its own bacterial symbiont that produces an antibioticlike drug called rhizoxin. Indeed, podophyllotoxin and camptothecin, two widely used anticancer drugs long thought to be made by plants, are actually produced by fungi living inside the plants. Although symbiotic microbes have only begun to be explored, they are among the most promising sources of naturally occurring antibiotics, perhaps including compounds that define new antibiotic classes or have novel mechanisms of action. In addition, explorations of the role of symbiont microbes within our own bodies are yielding new approaches to antibiotic treatment.



Preserving Allies

Humans, like insects and sponges, harbor a rich variety of bacterial symbionts that perform an array of useful functions, from helping us digest food to promoting the proper development of our immune systems. Unfortunately, all the antibiotics sold today are blunt instruments; they not only kill the pathogens that cause infections, they also kill the helpful bacterial mutualists that inhabit our gut. In some cases, this eradication of a patient's gut microflora clears the way for a different harmful strain of bacteria, such as *Clostridium difficile,* to multiply and cause a new, "secondary" infection that can sometimes be more dangerous than the first.

Using friendly microbes or substances that foster the mutualists' growth, so that they can outcompete pathogens, is one approach to preventing bacterial infections. Although such "probiotic" treatments can be helpful in avoiding the kind of widespread antibiotic use that promotes resistance, probiotics have never been demonstrated to be effective at treating an existing infection.

Nevertheless, growing recognition that our natural gut microflora can help stave off infection has led to a new strategy for antibacterial discovery: developing narrow-spectrum drugs designed to kill the pathogen causing the infection, while leaving the rest of our bacterial mutualists untouched. Neil Stokes and his colleagues at Prolysis, a company based in Oxford, England, for example, recently developed a new potential antibiotic that kills *S. aureus* and its relatives by preventing them from undergoing cell division, while leaving other bacteria intact. Victor Nizet and Andrew Wang, both at the University of California, San Diego, with Eric Oldfield of the University of Illinois, led a team that took this concept one step further. They discovered a drug that blocks synthesis of a pigment molecule that contributes to *S. aureus* virulence, thereby inhibiting *S. aureus*'s ability to make someone ill without actually killing the bacterium.

Experimental approaches to inhibiting bacterial virulence have the added benefit of possibly avoiding mechanisms that generate resistance. If a therapy does not kill a pathogen, then natural selection cannot favor the "survivors," and resistant strains are less likely to evolve. Similarly, the narrow-spectrum approach relies on finding a target that is unique or essential to the pathogenic bacterium but does not occur in others. Thus, even if the target microbe eventually develops resistance to the drug, it is at least a form of resistance that is unlikely to spread and be useful to other pathogens.

Whether such therapies, on their own or as part of a combination of treatments, will prove practical in the real world remains to be seen. For one, these drugs would require rapid diagnostic tests that could pinpoint the pathogen responsible for a patient's infection; such tests have been developed, but they are not yet in widespread use. Narrow-spectrum antibiotics, with their limited applications, might also be economically unattractive to drug companies.

The idea of one-size-fits-all antibiotics is no longer viable, however. During the 1960s and 1970s infectious disease was widely believed to be on the verge of being conquered. More recently, reports in the popular press have proclaimed that multidrug-resistant bacteria have brought about the "end of antibiotics." We now know that neither is true: humans may never definitively win this race against time, but for the past century new therapies have kept us a step ahead of the pathogens. Every effort must be made to retain our lead. ■

MORE TO EXPLORE

Antibiotics: Actions, Origins, Resistance. Christopher Walsh, ASM Press, 2003.

Antibiotics at the Crossroads. Carl Nathan in *Nature,* Vol. 431, pages 899–902; October 21, 2004.

New Antibiotics from Bacterial Natural Products. Jon Clardy, Michael A. Fischbach and Christopher T. Walsh in *Nature Biotechnology,* Vol. 24, No. 12, pages 1541–1550; December 2006.

Superbugs. Jerome Groopman in *New Yorker;* August 11, 2008.

PETER AND MARIA HOEY

GRASSOLINE at the Pump

Scientists are turning agricultural leftovers, wood and fast-growing grasses into a huge variety of biofuels—even jet fuel. But before these next-generation biofuels go mainstream, they have to compete with oil at $60 a barrel

By George W. Huber and Bruce E. Dale

KEY CONCEPTS

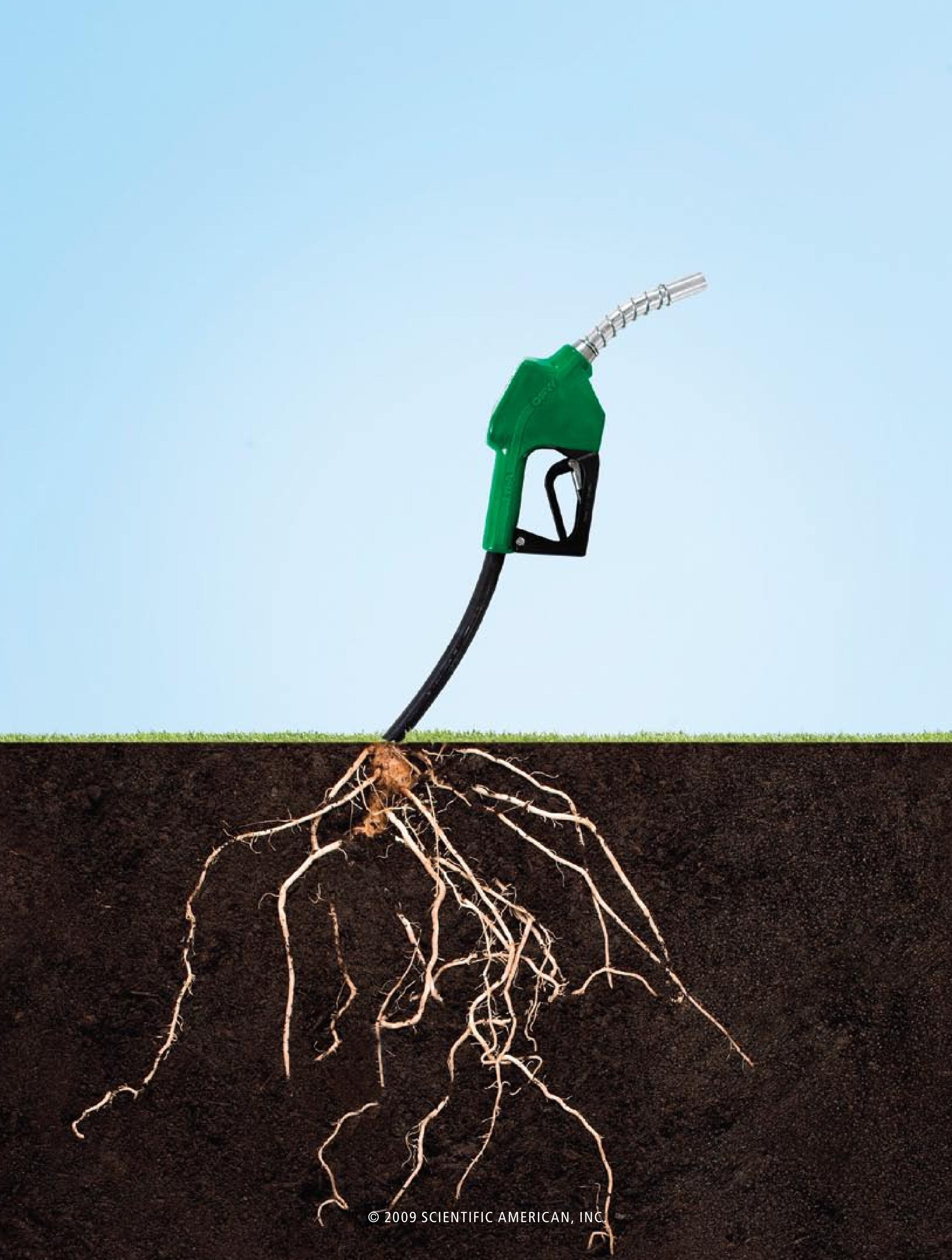
- Second-generation biofuels made from the inedible parts of plants are the most environmentally friendly and technologically promising near-term alternatives to oil.
- Most of this "grassoline" will come from agricultural residues such as cornstalks, weedlike energy crops and wood waste.
- The U.S. can grow enough of these feedstocks to replace about half the country's total consumption of oil without affecting food supplies. *—The Editors*

By now it ought to be clear that the U.S. must get off oil. We can no longer afford the dangers that our dependence on petroleum poses for our national security, our economic security or our environmental security. Yet civilization is not about to stop moving, and so we must invent a new way to power the world's transportation fleet. Cellulosic biofuels—liquid fuels made from inedible parts of plants—offer the most environmentally attractive and technologically feasible near-term alternative to oil.

Biofuels can be made from anything that is, or ever was, a plant. First-generation biofuels derive from edible biomass, primarily corn and soybeans (in the U.S.) and sugarcane (in Brazil). They are the low-hanging fruits in a forest of possible biofuels, given that the technology to convert these feedstocks into fuels already exists (180 refineries currently process corn into ethanol in the U.S.). Yet first-generation biofuels are not a long-term solution. There is simply not enough available farmland to provide more than about 10 percent of developed countries' liquid-fuel needs with first-generation biofuels. The additional crop demand raises the price of animal feed and thus makes some food items more expensive—though not nearly as much as the media hysteria last year would indicate. And once the total emissions of growing, harvesting and processing corn are factored into the ledger, it becomes clear that first-generation biofuels are not as environmentally friendly as we would like them to be.

Second-generation biofuels made from cellu-

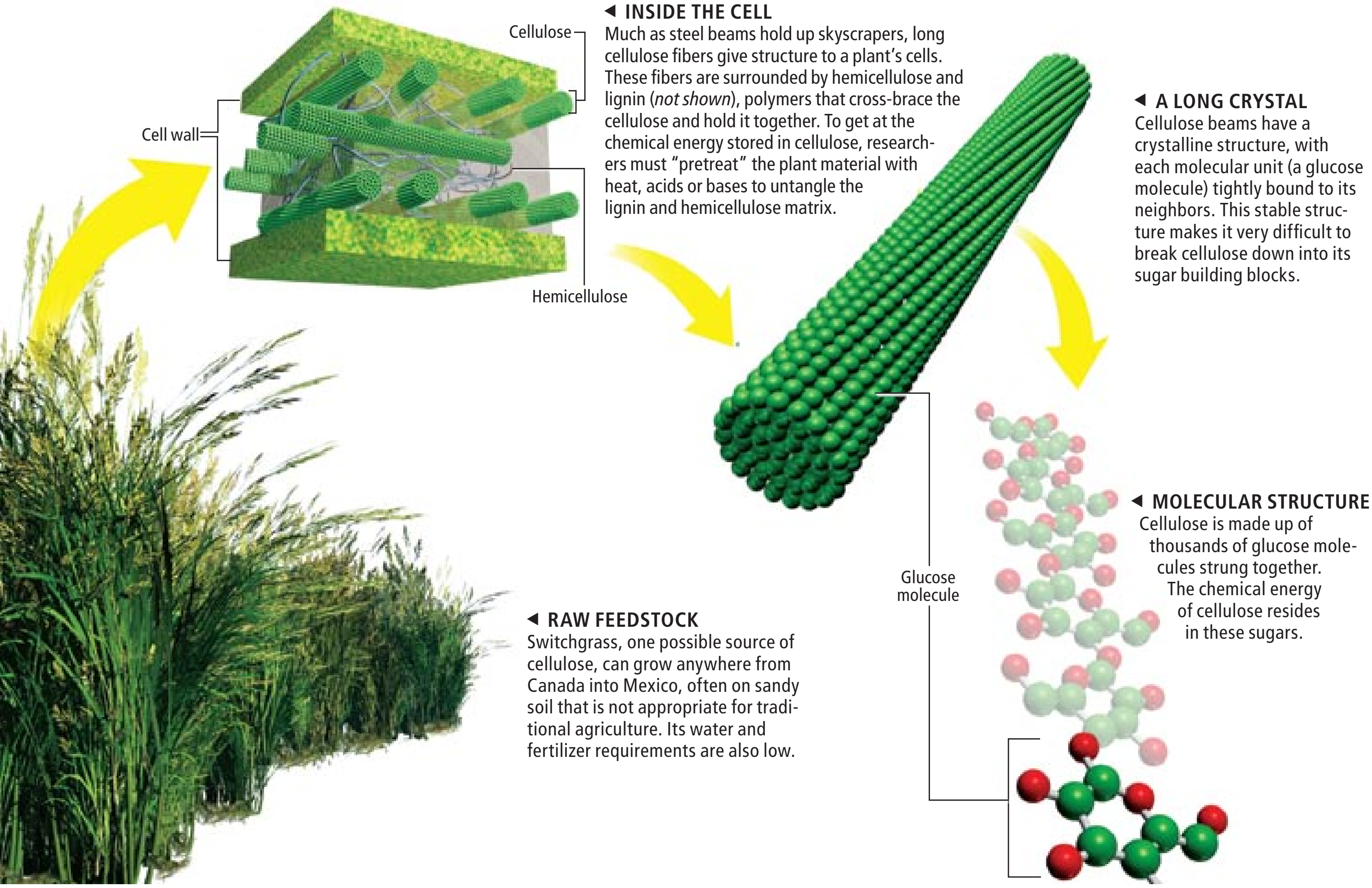
GETTY IMAGES



[BASICS]

Cellulose Scaffolding

In nature, cellulose supports a plant's vertical growth. It has a crystalline molecular structure that is both rigid and highly resistant to decomposition. Those features lend the plant stiffness but pose difficulties for those who would convert it into useful fuel.



losic material—colloquially, "grassoline"—can avoid these pitfalls. Grassoline can be made from dozens, if not hundreds, of sources: from wood residues such as sawdust and construction debris, to agricultural residues such as cornstalks and wheat straw, to "energy crops"—fast-growing grasses and woody materials that are grown expressly to serve as feedstocks for grassoline [*see box on page 45*]. The feedstocks are cheap (about $10 to $40 per barrel of oil energy equivalent), abundant and do not interfere with food production. Most energy crops can grow on marginal lands that would not otherwise be used as farmland. Some, such as the short-rotation willow coppice, will decontaminate soil that has been polluted with wastewater or heavy metals as it grows.

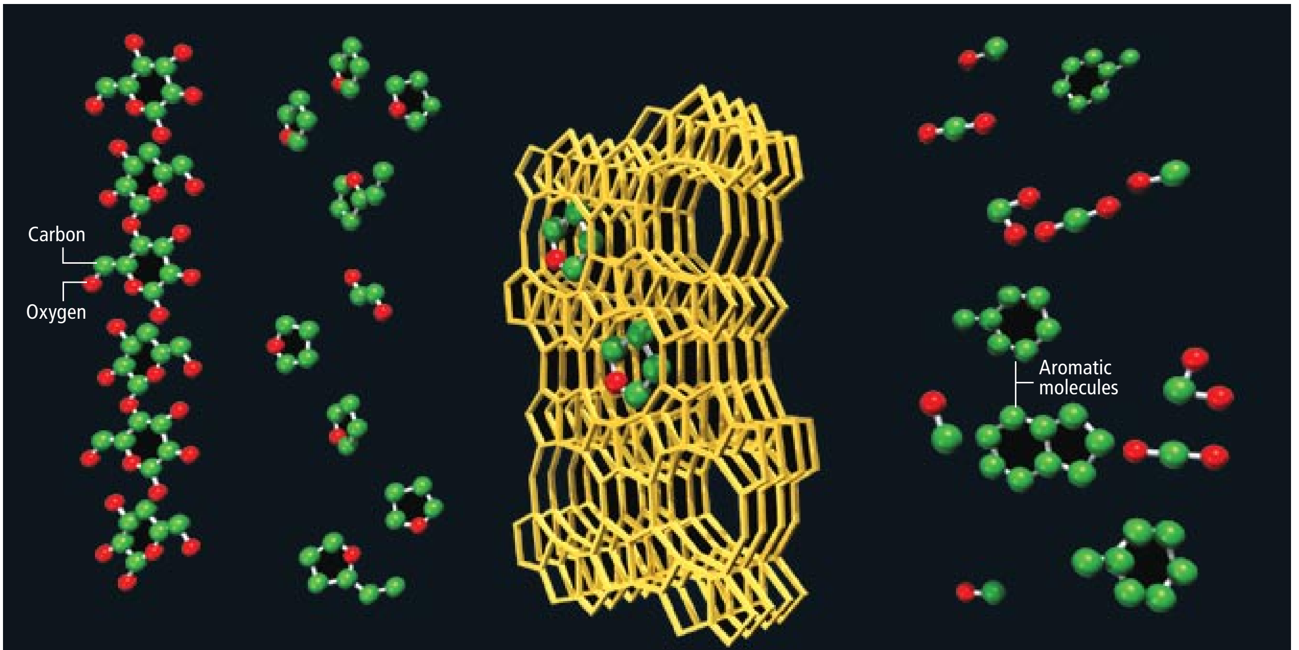
Huge amounts of cellulosic biomass can be sustainably harvested to produce fuel. According to a study by the U.S. Department of Agriculture and the Department of Energy, the U.S. can produce at least 1.3 billion dry tons of cellulosic biomass every year without decreasing the amount of biomass available for our food, animal feed or exports. This much biomass could produce more than 100 billion gallons of grassoline a year—about half the current annual consumption of gasoline and diesel in the U.S. [*see bottom left graph on page 45*]. Similar projections estimate that the global supply of cellulosic biomass has an energy content equivalent to between 34 billion to 160 billion barrels of oil a year, numbers that exceed the world's current annual consumption of 30 billion barrels of oil. Cellulosic biomass can also be converted to any type of fuel—ethanol, ordinary gasoline, diesel, even jet fuel.

Scientists are still much better at fermenting corn kernels than they are at breaking down

[HOW-TO #1]

TURNING CELLULOSE DIRECTLY INTO FUEL

Cellulose consists of carbon, oxygen and hydrogen atoms (*hydrogen not shown*). Gasoline is made of carbon and hydrogen. Thus, turning cellulose into grassoline is a matter of removing the oxygen from the cellulose to make high-energy-density molecules that contain only carbon and hydrogen. In the catalytic fast pyrolosis approach shown, the cellulose decomposes and is converted to gasoline in a single step.



FIRST BREAK
Cellulose entering the chamber is heated to 500 degrees Celsius in less than a second, breaking it apart into smaller, oxygen-rich molecules.

THE CATALYST
These broken fragments then fit into an intricate three-dimensional catalyst. This catalyst encourages chemical reactions that remove the oxygen from the cellulose fragments and create carbon rings. The detailed chemical process is not yet well understood.

FINAL PRODUCTS
After the reaction—which takes only a few seconds—the cellulose has been transformed into aromatic components of gasoline. By-products of the reaction include water (*not shown*), carbon dioxide and carbon monoxide.

tough stalks of cellulose, but they have recently enjoyed an explosion of progress. Powerful tools such as quantum-chemical computational models allow chemical engineers to build structures that can control reactions at the atomic level. Research is done with an eye toward quickly scaling conversion technologies up to refinery scales. And although the field is still young, a number of demonstration plants are already online, and the first commercial refineries are scheduled for completion in 2011. The age of grassoline may soon be at hand.

The Energy Lock

Blame evolution. Nature designed cellulose to give structure to a plant. The material is made out of rigid scaffolds of interlocking molecules that provide support for vertical growth [*see box on opposite page*] and stubbornly resist biological breakdown. To release the energy inside it, scientists must first untangle the molecular knot that evolution has created.

In general, this process involves first deconstructing the solid biomass into smaller molecules, then refining these products into fuels. Engineers generally classify deconstruction methods by temperature. The low-temperature method (50 to 200 degrees Celsius) produces sugars that can be fermented into ethanol and other fuels in much the same way that corn or sugar crops are now processed. Deconstruction at higher temperatures (300 to 600 degrees C) produces a biocrude, or bio-oil, that can be refined into gasoline or diesel. Extremely high temperature deconstruction (above 700 degrees C) produces gas that can be converted into liquid fuel.

So far no one knows which approach will convert the maximum amount of the stored energy into liquid biofuels at the lowest costs. Perhaps different pathways will be needed for different cellulosic biomass materials. High-temperature processing might be best for wood, say, whereas low temperatures might work better for grasses.

DON FOLEY

INSECT POWER: **Termites are model biofuel factories. Microbes living inside the gut of a termite break cellulose down into sugars. Biological engineers are attempting to replicate this process on an industrial scale.**

Hot Fuel

The high-temperature syngas approach is the most technically developed way to generate biofuels. Syngas—a mixture of carbon monoxide and hydrogen—can be made from any carbon-containing material. It is typically transformed into diesel fuel, gasoline or ethanol through a process called Fischer-Tropsch synthesis (FTS), developed by German scientists in the 1920s. During World War II the Third Reich used FTS to create liquid fuel out of Germany's coal reserves. Most of the major oil companies still have a syngas conversion technology that they may introduce if gasoline becomes prohibitively expensive.

The first step in creating a syngas is called gasification. Biomass is fed into a reactor and heated to temperatures above 700 degrees C. It is then mixed with steam or oxygen to produce a gas containing carbon monoxide, hydrogen gas and tars. The tars must be cleaned out and the gas compressed to 20 to 70 atmospheres of pressure. The compressed syngas then flows over a specially designed catalyst—a solid material that holds the individual reactant molecules and preferentially encourages particular chemical reactions. Syngas conversion catalysts have been developed by the petroleum chemistry primarily for converting natural gas and coal-derived syngas into fuels, but they work just as well for biomass.

Although the technology is well understood, the reactors are expensive. An FTS plant built in Qatar in 2006 to convert natural gas into 34,000 barrels a day of liquid fuels cost $1.6 billion. If a biomass plant were to cost this much, it would have to consume around 5,000 tons of biomass a day, every day, for a period of 15 to 30 years to produce enough fuel to repay the investment. Because significant logistic and economic challenges exist with getting this amount of biomass to a single location, research in syngas technology focuses on ways to reduce the capital costs.

Bio-Oil

Eons of subterranean pressure and heat transformed Cambrian zooplankton and algae into present-day petroleum fields. A similar trick—on a much reduced timescale—could convert cellulosic biomass into a biocrude. In this scenario, a refinery heats up biomass to anywhere from 300 to 600 degrees C in an oxygen-free environment. The heat breaks the biomass down into a charcoal-like solid and the bio-oil, giving off some gas in the process. The bio-oil that is produced by this method is the cheapest liquid biofuel on the market today, perhaps $0.50 per gallon of gasoline energy equivalent (in addition to the cost of the raw biomass).

The process can also be carried out in relatively small factories that are close to where biomass is harvested, thus limiting the expense of biomass transport. Unfortunately, this crude is highly acidic, is insoluble with petroleum-based fuels and contains only half the energy content of gasoline. Although you can burn biocrude directly in a diesel engine, you should attempt it only if you no longer have a need for the engine.

Oil refineries could convert this biocrude into a usable fuel, however, and many companies are studying how they could adapt their existing hardware to the task. Some are already producing a different form of green diesel fuel, suggesting that refineries could handle cellulosic biocrude as well. At the moment, the facilities co-feed vegetable oils and animal fats with petroleum oil directly into their refinery. ConocoPhillips recently demonstrated this approach at a refinery in Borger, Tex., creating more than 12,000 gallons of biodiesel a day out of beef fat shipped from a nearby Tyson Foods slaughterhouse [*see box on page 47*].

Researchers are also figuring out ways to carry out the two-stage process using the chemical engineering equivalent of one-pot cooking—

[THE AUTHORS]

George W. Huber is a professor of chemical engineering at the University of Massachusetts Amherst. In 2003 *Scientific American* cited his work on hydrogen production from biomass feedstocks as one of the top 50 breakthroughs of the year. He is the founder of Anellotech, a biofuel startup, and serves as an occasional consultant for various oil and biofuel companies. **Bruce E. Dale** is a professor and former chair of the chemical engineering department at Michigan State University and one of the leaders of the Great Lakes Bioenergy Research Center (greatlakesbioenergy.org). He also occasionally serves as a biofuel industry consultant.

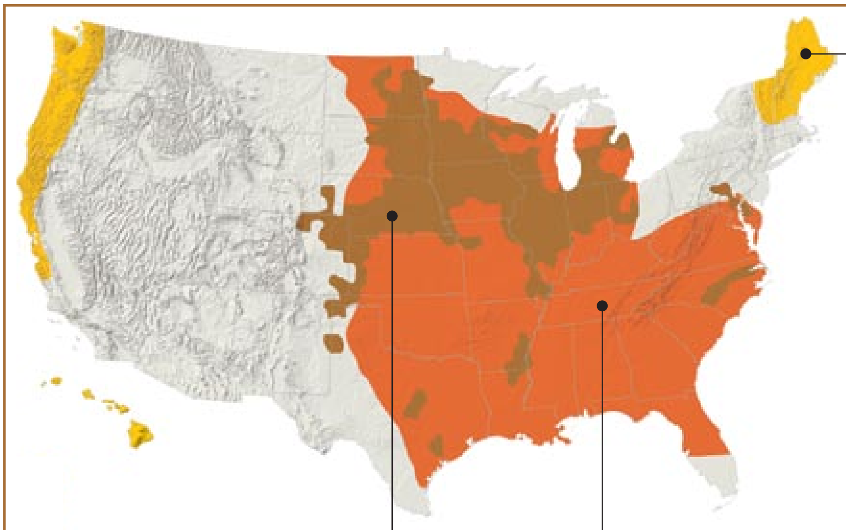
KURT STEPNITZ *Michigan State University (Dale)*; COURTESY OF GEORGE W. HUBER *(Huber)*; PHOTO RESEARCHERS, INC. *(termites)*

[PROSPECTS]

Cellulosic Feedstock Options across the U.S.

Once scientists are able to efficiently turn cellulosic material into fuel, they will find no shortage of available feedstocks to supply the necessary plant material. A study by the U.S. Department of Agriculture and the Department of Energy earlier this decade concluded that the U.S. could produce more than 1.3 billion tons of cellulosic feedstocks annually without affecting exports or the food supply (an updated version of the "Billion-Ton Vision" study will be released this fall). In addition to energy crops that could be grown over much of the U.S.—especially on land that is not fertile enough to support traditional food crops—the Northeast and Northwest could contribute waste material from logging, and leftover residues from the corn and soy harvest—including cornstalks and cobs—could power much of the Midwest.

FERTILE LAND FOR BIOFUELS



FOREST PRODUCTS

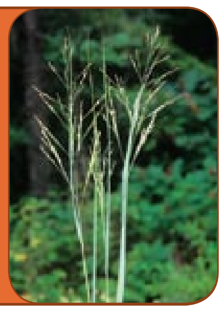
The wood supply would come from two main sources: residues that are currently left over from industries, such as logging and paper, and excess small-diameter trees that the U.S. Forest Service has identified as needing to be removed to improve forest health.

AGRICULTURAL RESIDUES

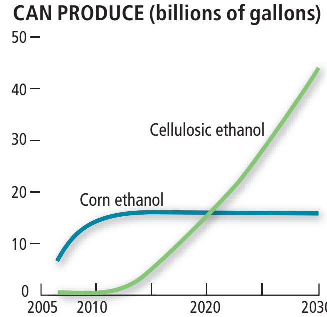
Leftover stalks, leaves and cobs from corn farming make up about half of the total crop yield. Some of these residues must be left on the field to replenish the soil, but most currently go to waste.

ENERGY CROPS

These plants can grow quickly with minimal fertilizer and water needs. Common examples include switchgrass, sorghum, miscanthus and energycane. Some, such as the short-rotation willow coppice, will not only grow on soil contaminated with wastewater or heavy metals, they will clean it up as they do so.

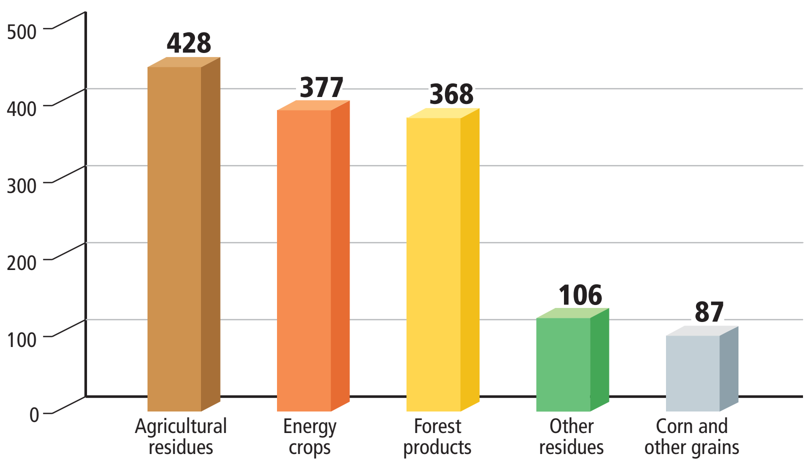


AMOUNT OF ETHANOL THE U.S. CAN PRODUCE (billions of gallons)



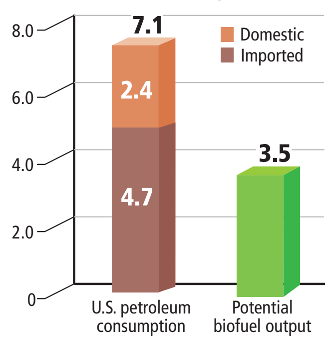
The U.S. has nearly capped its ability to produce ethanol from corn, according to a study published this year by Sandia National Laboratories. Yet the amount of ethanol the U.S. can derive from cellulose can increase for decades.

AMOUNT OF BIOFUEL FEEDSTOCK THE U.S. CAN SUSTAINABLY PRODUCE (millions of tons)



LAURIE GRACE; PETER ESSICK *Getty Images (forest)*; VAST PHOTOGRAPHY *Getty Images (cornstalks)*; WALLY EBERHART *Getty Images (switchgrass)*

CURRENT OIL CONSUMPTION AND POTENTIAL BIOFUEL PRODUCTION (billion barrels of oil equivalent)

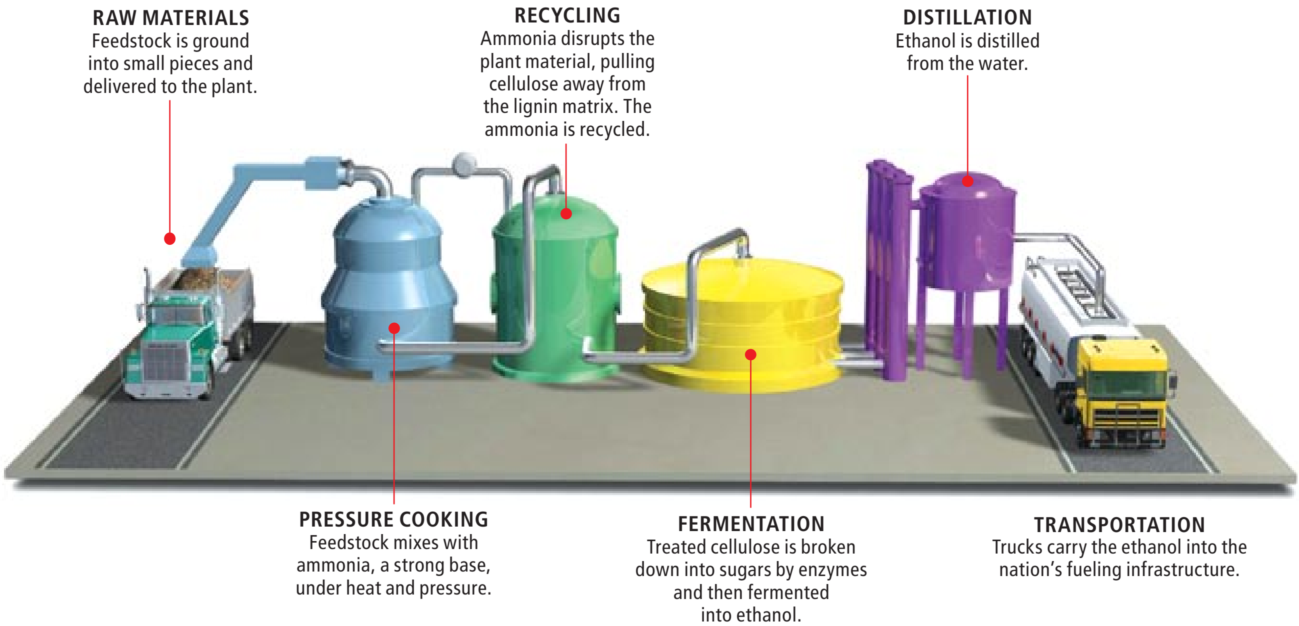


The potential biofuel output equals the peak U.S. oil production, which the country hit in 1970.

[HOW-TO #2]

BREAKING DOWN CELLULOSE WITH AMMONIA

Although there are many possible ways to pretreat plant fibers to get at the cellulose—acids and heat are most commonly mentioned—the ammonia fiber expansion (AFEX) process offers a unique combination of low energy requirements, low costs and high efficiency.



DON FOLEY

converting the solid biomass to oil and then the oil into fuel inside a single reactor. One of us (Huber) and his colleagues are developing an approach called catalytic fast pyrolysis. The "fast" in the name comes from the initial heating—once biomass enters the reactor, it is cooked to 500 degrees C in a second, which breaks down the large molecules into smaller ones. Like eggs in an egg carton, these small molecules are now the perfect size and shape to fit into the surface of a catalyst.

Once ensconced inside the catalyst's pores, the molecules go through a series of reactions that change them into gasoline—specifically, the high-value aromatic components of gasoline that increase the octane [*see box on page 43*]. (High-octane fuels allow engines to run at higher internal pressures, which increases efficiency.) The entire process takes just two to 10 seconds. Already the start-up company Anellotech is attempting to scale up this process from the laboratory to the commercial level. It expects to have a commercial facility in operation by 2014.

Sugar Solution

The route that has attracted most of the public and private investment thus far relies on a more traditional mechanism—unlock the sugars in plants, then ferment these sugars into ethanol or other biofuels. Scientists have studied literally dozens of possible ways to break down the digestion-resistant cellulose and hemicellulose—the fibers that bind cellulose together inside the cells [*see box on page 42*]—to their constituent sugars. You can heat the biomass, irradiate it with gamma rays, grind it into a fine slurry, or subject it to high-temperature steam. You can douse it with concentrated acids or bases or bathe it in solvents. You can even genetically engineer microbes that will eat and degrade the cellulose.

Unfortunately, many techniques that work in the lab have no chance of succeeding in commercial practice. To be commercially viable, the pretreatments must generate easily fermentable sugars at high yields and concentrations and be implemented with modest capital costs. They should not use toxic materials or require too much energy input to work. They must also be able to produce grassoline at a price that can compete with gasoline.

The most promising approaches involve subjecting the biomass to extremes of pH and temperature. We are developing a strategy that uses ammonia—a strong base—in one of our laboratories (Dale's). In this ammonia fiber expansion (AFEX) process, cellulosic biomass is cooked at

100 degrees C with concentrated ammonia under pressure. When the pressure is released, the ammonia evaporates and is recycled. Subsequently, enzymes convert 90 percent or more of the treated cellulose and hemicellulose to sugars. The yield is so high in part because the approach minimizes the sugar degradation that often occurs in acidic or high-temperature environments. The AFEX process is "dry to dry": biomass starts as a mostly dry solid and is left dry after treatment, undiluted with water. It thus can provide large amounts of highly concentrated, high-proof ethanol.

AFEX also has the potential to be very inexpensive: a recent economic analysis showed that, assuming biomass can be delivered to the plant for around $50 a ton, AFEX pretreatment, combined with an advanced fermentation process called consolidated bioprocessing, can produce cellulosic ethanol for approximately $1 per gallon of equivalent gasoline energy content, probably selling for less than $2 at the pump.

[ALTERNATIVE SOURCES]

The Fat of the Matter

There is a new drive to make fuel off the fat of the land. In April, High Plains Bioenergy opened a biorefinery next to a pork-processing plant in Guymon, Okla. The refinery takes pork fat—an abundant, low-value by-product of the industrial butchering process—and converts it, along with vegetable oil, into biodiesel. The plant is expected to turn 30 million pounds of lard into 30 million gallons of biodiesel a year. In 2010 the High Plains facility will be joined by a plant in Geismar, La., that will be run by Dynamic Fuels, a joint venture between Tyson Foods and energy company Syntroleum. That plant will use the fat from Tyson's beef, chicken and pork operations to create 75 million gallons of biodiesel and jet fuel annually.

PETER CADE *Getty Images*

Yet the biodiesel industry has been battered recently, with many plants sitting idle for lack of demand. Low oil prices have made petroleum-based diesel fuel less expensive than biodiesel, which in the U.S. is typically made from soy and vegetable oils. A $1 per gallon federal tax credit for biodiesel has helped soften the blow, but that credit is set to expire at the end of the year. Some manufacturers worry that if the credit disappears, so will their business. Tyson had earlier partnered with ConocoPhillips to produce biodiesel at an existing ConocoPhillips refinery in Borger, Tex. But insecurity about the status of the tax break has put the project on hold. —***The Editors***

The Cost of Change

Cost, of course, will be the primary determinant of how fast the use of grassoline will grow. Its main competitor is petroleum, and the petroleum industry has been reaping the technological benefits of dedicated research programs for more than a century. Moreover, most petroleum refineries now in use have already paid off their initial capital costs; grassoline refineries will require investments of hundreds of millions of dollars, a cost that will have to be integrated into the price of the fuel it produces through the years.

Grassoline, on the other hand, enjoys several major advantages over fuels from petroleum and other petroleum alternatives such as oil sands and liquefied coal. First, the raw feedstocks are far less expensive than raw crude, which should help keep costs down once the industry gets up and running. Grassoline will be domestically produced, with the national security benefits that confers. And it is far better for the environment than any fossil fuel–based alternative.

In addition, new analytical tools and computer-modeling techniques will let researchers build better, more efficient biorefinery operations at a rate that would have been unattainable to petroleum engineers just a decade ago. We are gaining a deeper understanding of the properties of our raw feedstocks and the processes we can use to convert them into fuel at an ever increasing pace. The U.S. government's support for research into alternative forms of energy should help this process to accelerate even further. The stimulus bill signed into law by President Barack Obama earlier this year contained $800 million in funding for the Department of Energy's Biomass Program, which will accelerate advanced biofuels research and development and provide funding for commercial-scale biorefinery projects. In addition, the bill contained $6 billion in loan guarantees for "leading edge biofuel projects" that will commence construction by October 2011.

Indeed, if the U.S. maintains its current commitment to biofuels, the logistical and conversion challenges the industry now faces should be readily overcome. Over the next five to 15 years, biomass conversion technologies will move from the laboratory to the market, and the number of vehicles powered by cellulosic biofuels will grow dramatically. This move toward grassoline can fundamentally change the world. It is a move that is now long overdue. ■

➥ MORE TO EXPLORE

Breaking the Chemical and Engineering Barriers to Lignocellulosic Biofuels. A research road map from the Biomass to Biofuels Workshop: **www.ecs.umass.edu/biofuels**

Development of Cellulosic Biofuels. Video lecture given by Chris Somerville, director of the Energy Biosciences Institute at the University of California, Berkeley: **http://tinyurl.com/grassoline**

U.S. Department of Energy Biomass Program Web site: **http://eere.energy.gov/biomass**

IN THE HUMAN BRAIN the left hemisphere controls language, the dexterity of the right hand, the ability to classify, and routine behavior in general. The right hemisphere specializes in reacting to emergencies, organizing items spatially, recognizing faces and processing emotions.

ORIGINS OF THE Left & Right Brain

The division of labor by the two cerebral hemispheres—once thought to be uniquely human—predates us by half a billion years. Speech, right-handedness, facial recognition and the processing of spatial relations can be traced to brain asymmetries in early vertebrates

By Peter F. MacNeilage, Lesley J. Rogers and Giorgio Vallortigara

KEY CONCEPTS

- The authors have proposed that the specialization of the brain's two hemispheres was already in place when vertebrates arose 500 million years ago.
- The left hemisphere originally seems to have focused in general on controlling well-established patterns of behavior; the right specialized in detecting and responding to unexpected stimuli.
- Both speech and right-handedness may have evolved from a specialization for the control of routine behavior.
- Face recognition and the processing of spatial relations may trace their heritage to a need to sense predators quickly.

—The Editors

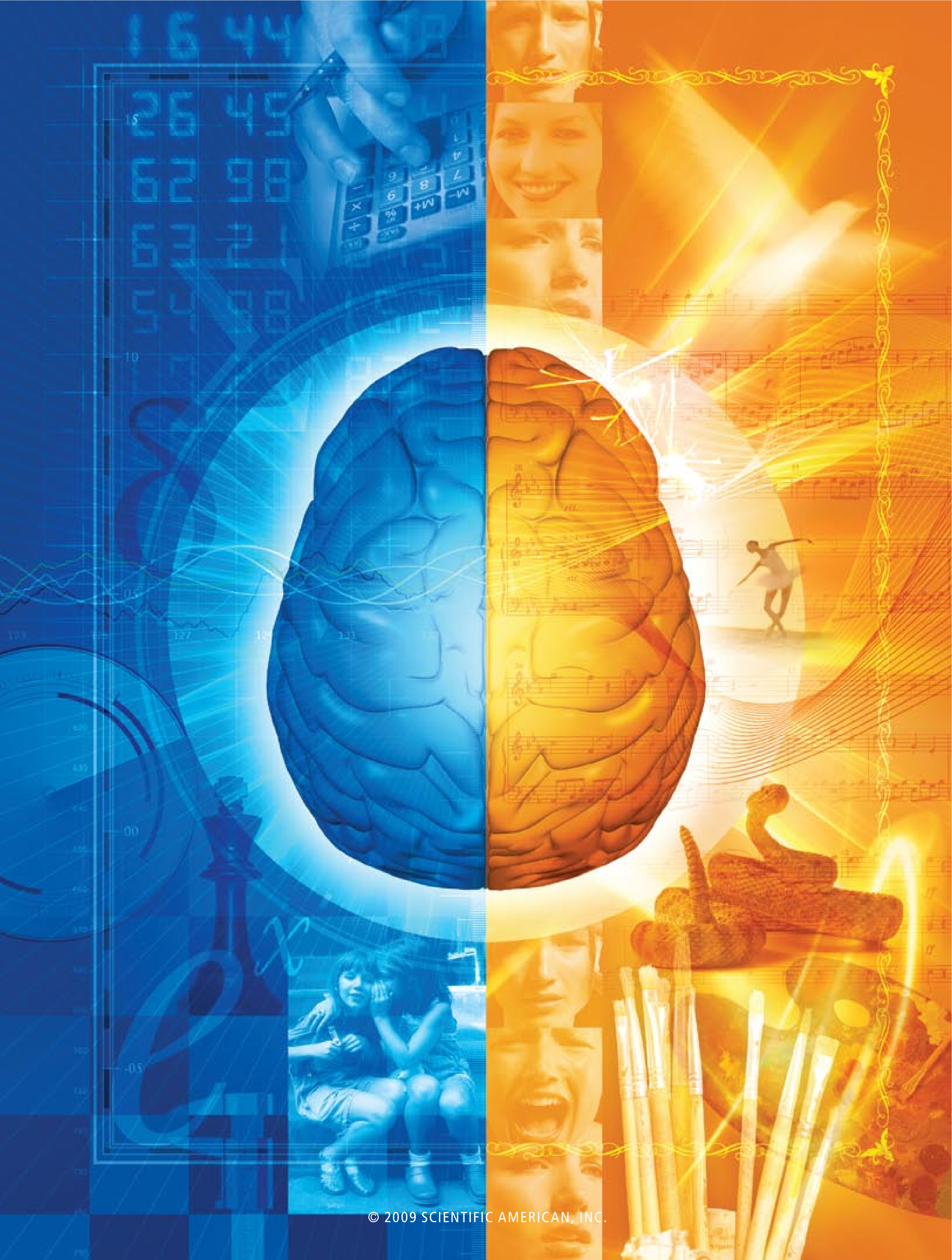
The left hemisphere of the human brain controls language, arguably our greatest mental attribute. It also controls the remarkable dexterity of the human right hand. The right hemisphere is dominant in the control of, among other things, our sense of how objects interrelate in space. Forty years ago the broad scientific consensus held that, in addition to language, right-handedness and the specialization of just one side of the brain for processing spatial relations occur in humans alone. Other animals, it was thought, have no hemispheric specializations of any kind.

Those beliefs fit well with the view that people have a special evolutionary status. Biologists and behavioral scientists generally agreed that right-handedness evolved in our hominid ancestors as they learned to build and use tools, about 2.5 million years ago. Right-handedness was also thought to underlie speech. Perhaps, as the story went, the left hemisphere simply added sign language to its repertoire of skilled manual actions and then converted it to speech. Or perhaps the left brain's capacity for controlling manual action extended to controlling the vocal apparatus for speech. In either case, speech and language evolved from a relatively recent manual talent for toolmaking. The right hemisphere, meanwhile, was thought to have evolved by default into a center for processing spatial relations, after the left hemisphere became specialized for handedness.

In the past few decades, however, studies of many other animals have shown that their two brain hemispheres also have distinctive roles. Despite those findings, prevailing wisdom continues to hold that people are different. Many investigators still think the recently discovered specializations of the two brain hemispheres in nonhumans are unrelated to the human ones; the hemispheric specializations of humans began with humans.

Here we present evidence for a radically different hypothesis that is gaining support, particularly among biologists. The specialization of each hemisphere in the human brain, we argue, was already present in its basic form when vertebrates emerged about 500 million years ago. We suggest that the more recent specializations of the brain hemispheres, including those of humans, evolved from the original ones by the Darwinian process of descent with modification. (In that process, capabilities relevant to ancient traits are changed or co-opted in the service of other developing traits.) Our hypothesis holds that the left hemisphere of the vertebrate brain was originally specialized for the control of well-established patterns of behavior under ordinary and familiar circumstances. In contrast, the right hemisphere, the primary seat of emotional arousal,

PHOTOILLUSTRATION BY TWIST CREATIVE; MEDICALRF.COM *Corbis* (*brain*); MEDIOIMAGES *Getty Images* (*calculator*); JOERG STEFFENS *Corbis* (*faces*); WESTEND61 *Corbis* (*woman smiling*); DOUGAL WATERS *Getty Images* (*ballerina*); MIKE KEMP *Getty Images* (*rattlesnake*); C SQUARED STUDIOS *Getty Images* (*palette*); VLADIMIR GODNIK *Getty Images* (*paintbrushes*); CARRIE BORETZ *Corbis* (*girls whispering*); ROBERT LLEWELLYN *Corbis* (*calipers*)



was at first specialized for detecting and responding to unexpected stimuli in the environment.

In early vertebrates such a division of labor probably got its start when one or the other hemisphere developed a tendency to take control in particular circumstances. From that simple beginning, we propose, the right hemisphere took primary control in potentially dangerous circumstances that called for a rapid reaction from the animal—detecting a predator nearby, for instance. Otherwise, control passed to the left hemisphere. In other words, the left hemisphere became the seat of self-motivated behavior, sometimes called top-down control. (We stress that self-motivated behavior need not be innate; in fact, it is often learned.) The right hemisphere became the seat of environmentally motivated behavior, or bottom-up control. The processing that directs more specialized behaviors—language, toolmaking, spatial interrelations, facial recognition, and the like—evolved from those two basic controls.

The Left Hemisphere

Most of the evidence that supports our hypothesis does not come from direct observation of the brain but rather from observations of behavior that favors one or the other side of the body. In the vertebrate nervous system the connections cross between body and brain—to a large degree, nerves to and from one side of the body are linked to the opposite-side hemisphere of the brain.

Evidence for the first part of our hypothesis—that the vertebrate left hemisphere specializes in controlling routine, internally directed behaviors—has been building for some time. One routine behavior with a rightward bias across many vertebrates is feeding. Fishes, reptiles and toads, for instance, tend to strike at prey on their right side under the guidance of their right eye and left hemisphere [*see box on page 52*]. In a variety of bird species—chickens, pigeons, quails and stilts—the right eye is the primary guide for various kinds of food pecking and prey capture. In one instance, such a lateralized feeding preference has apparently led to a lateralized bias in the animal's external anatomy. The beak of the New Zealand wry-billed plover slopes to the right; that way, the plover's right eye can guide the beak as the bird seeks food under small river stones.

As for mammals, the feeding behavior of humpback whales is a spectacular example of a lateral feeding preference. Phillip J. Clapham, now at the Alaska Fisheries Science Center in Seattle, and his colleagues discovered that 60 out of 75 whales had abrasions only on the right jaw; the other 15 whales had abrasions only on the left jaw. The findings were clear evidence that whales favor one side of the jaw for food gathering and that "right-jawedness" is by far the norm.

In feeding, animals from all five vertebrate classes retain an ancestral bias for the right side.

In short, in all vertebrate classes—fishes, reptiles, amphibians, birds and mammals—animals tend to retain what was probably an ancestral bias toward the use of the right side in the routine activity of feeding.

Origins of Right-Handedness

What do these findings say about the alleged uniqueness of human right-handedness? Evidence for a right-side bias in birds and whales is intriguing, but it hardly makes a convincing argument against the old belief that right-handedness in humans had no evolutionary precursors. Yet more than a dozen recent studies have now demonstrated a right-handed bias among other primates, our closest evolutionary relatives—clearly suggesting that human right-handedness descended from that of earlier primates. The right-hand preference shows itself in monkeys (baboons, *Cebus* monkeys and rhesus macaques) as well as in apes, particularly in chimpanzees.

Many of the studies of apes have been done by William D. Hopkins of the Yerkes National Primate Research Center in Atlanta and his colleagues. Hopkins's group observed right-hand preferences particularly in tasks that involved either coordinating both hands or reaching for food too high to grab without standing upright. For example, experimenters placed honey (a favorite food) inside a short length of plastic pipe and gave the pipe to one of the apes. To get the honey, the ape had to pick up the pipe in one hand and scrape out the honey with one finger of the opposite hand. By a ratio of 2 to 1, the apes preferred to scrape honey out with a finger of the right hand. Similarly, in the reaching experiments, the apes usually grabbed the food they wanted with the right hand.

The Yerkes findings also suggest to us that as early primates evolved to undertake harder and more elaborate tasks for finding food, their handedness preferences became stronger, too. The reason, we suspect, is that performing ever more complex tasks made it increasingly neces-

◄ IN PEOPLE and other vertebrates, nerves to and from one side of the body are linked to the opposite-side hemisphere of the brain. As a result, each hemisphere generally controls the opposite side of the body.

ANDREW SWIFT

sary for the control signals from the brain to pass as directly as possible to the more skilled hand. Since the most direct route from the left hemisphere—the hemisphere specialized for routine tasks—to the body follows the body-crossing pathways of the peripheral nerves, the right hand increasingly became the preferred hand among nonhuman primates for performing elaborate, albeit routine, tasks.

Communication and the Left Brain

The evolutionary descent of human right-handed dexterity via the modification of ancient feeding behavior in ancestral higher primates now seems very likely. But could feeding behavior also have given rise to the left-brain specialization for language? Actually we do not mean to suggest that this development was direct. Rather we argue that the "language brain" emerged from an intermediate and somewhat less primitive specialization of the left hemisphere—namely, its specialization for routine communication, both vocal and nonvocal. But contrary to long-held beliefs among students of human prehistory, neither of those communicative capabilities first arose with humans; they, too, are descended from hemispheric specializations that first appeared in animals that lived long before our species emerged.

In birds, for instance, studies have shown that the left hemisphere controls singing. In sea lions, dogs and monkeys, the left hemisphere controls the perception of calls by other members of the same species. One of us (Rogers), in collaboration with Michelle A. Hook-Costigan, now at Texas A&M University, observed that common marmosets open the right side of their mouths wider than the left side when making friendly calls to other marmosets. People also generally open the right side of their mouths to a greater extent than the left when they speak—the result of greater activation of the right side of the face by the left hemisphere.

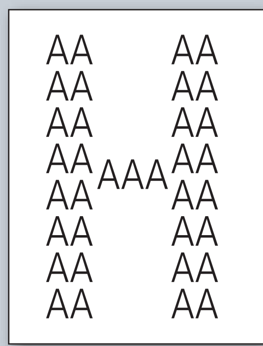
Little is universal in nature, though, and in some animals a vocal response to highly emotional circumstances has also been linked to the left brain, not—as one might expect—to the right. When a male frog is clasped from behind and held by a rival male, for instance, the left hemisphere seems to control the vocal responses of the first frog. The left hemisphere in mice controls the reception of distress calls from infant mice, and in gerbils it controls the production of calls during copulation. But those animals may be exceptions. In humans and monkeys—and perhaps in most other animals—the right brain takes control in highly emotional vocalizing; the left brain sticks to the routine.

Nonvocal communication in humans has evolutionary antecedents as well. Not only do chimpanzees tend to be right-handed when they manipulate objects, but they also favor the right hand for communicative gestures. Gorillas, too, tend to incorporate the right hand into complex communications that also involve the head and the mouth. Adrien Meguerditchian and Jacques Vauclair, both at the University of Provence in France, have even observed a right-handed bias for one manual communication (patting the ground) in baboons.

The evolutionary significance of all this becomes clear as soon as one notes that humans also tend to make communicative gestures with the right hand. The lateralized behavior we share with baboons suggests that right-handed communications arose with the first appearance of the monkeylike ancestor we share with baboons. That creature emerged perhaps 40 million years ago—well before hominids began to evolve.

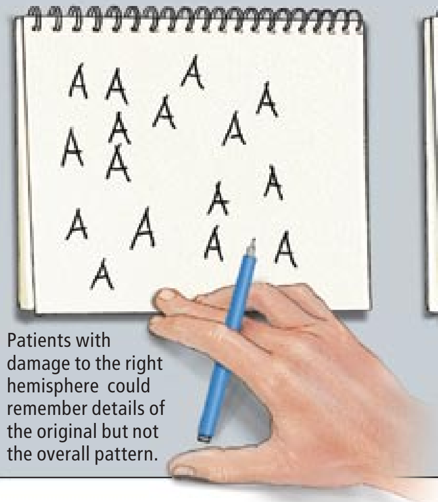
[THE HUMAN BRAIN]

Division of Labor in the Hemispheres

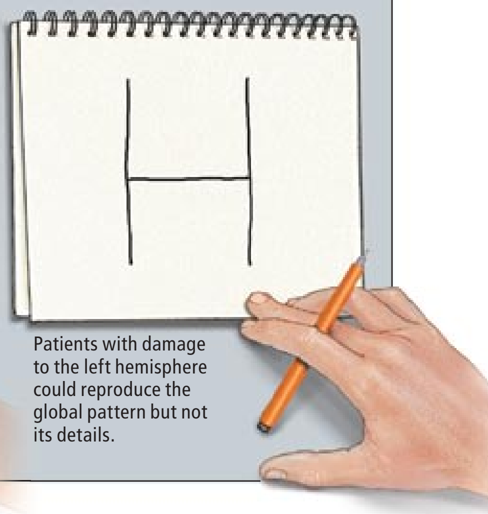


▲ Original picture

In a classic experiment, Dean C. Delis of the University of California, San Diego, and his colleagues asked brain-damaged patients to study a picture of a large capital **H** made up of little **A**'s (*left*) and then redraw it from memory. The patients with damage to the right hemisphere (thus dependent solely on the left hemisphere) often simply scattered **A**'s over the page (*below left*). Patients with damage to the left hemisphere often just drew a large capital **H** with no **A**'s (*below right*). Thus, the human left brain characterizes stimuli according to one or a few details, whereas the right brain specializes in synthesizing global patterns.



Patients with damage to the right hemisphere could remember details of the original but not the overall pattern.



Patients with damage to the left hemisphere could reproduce the global pattern but not its details.

ANDREW SWIFT; SOURCE: "HEMISPHERIC SPECIALIZATION OF MEMORY FOR VISUAL HIERARCHICAL STIMULI," BY D. C. DELIS ET AL., IN *NEUROPSYCHOLOGIA*, VOL. 24, NO. 2; 1986

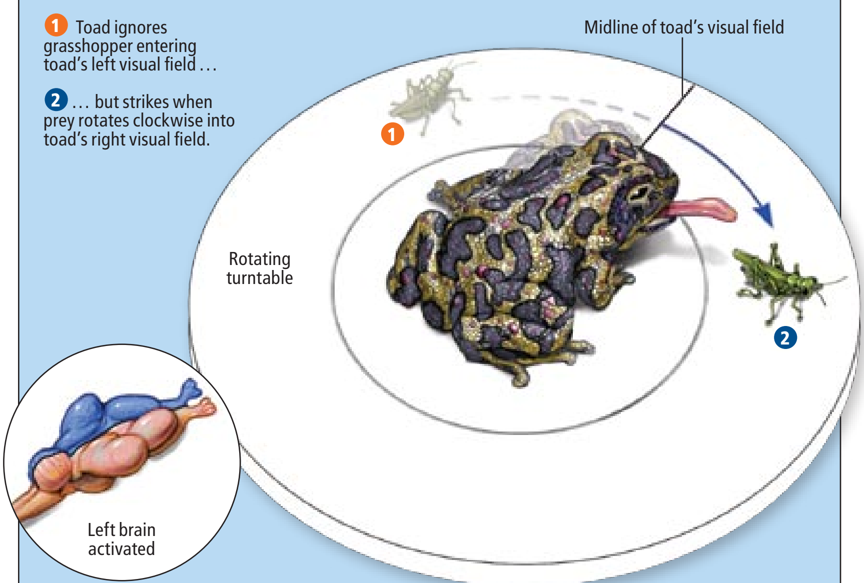
[THE AUTHORS]

Peter F. MacNeilage is a professor of psychology at the University of Texas at Austin. He has written more than 120 articles on the evolution of complex action systems; his book *The Origin of Speech* was published by Oxford University Press last year. **Lesley J. Rogers** is an emerita professor of neuroscience and animal behavior at the University of New England in Australia. She discovered lateralization in the chick forebrain when lateralization was still thought to be a unique feature of the human brain. **Giorgio Vallortigara** is a professor of cognitive neuroscience at the Center for Mind/Brain Sciences and in the department of cognitive sciences at the University of Trento in Italy. With Rogers, he discovered the first evidence of functional brain asymmetry in fishes and amphibians.

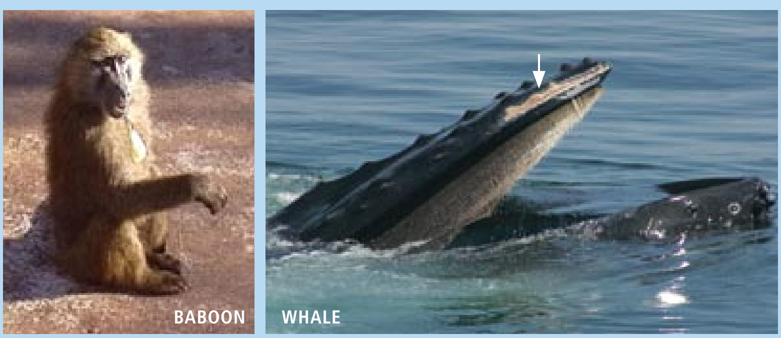
[LEFT BRAIN]

ROUTINE BEHAVIOR CONTROL

A right-side—hence left-brain—bias for controlling behavior patterns under ordinary circumstances has been found in nearly every class of vertebrate animal tested so far. Catching prey is a typical routine behavior. In the experiment diagrammed below, a simulated grasshopper was glued to a turntable and rotated into one or the other visual field of a toad. When the grasshopper was placed to the toad's left and rotated clockwise, the toad struck at the insect only when it crossed the midline into the toad's right visual field. When the prey was rotated counterclockwise, the toad struck at it less often overall and with about the same frequency in each visual field (*not shown*).



▼ Among the many other animals that also display a preference for the right side in certain behaviors are baboons and whales, indicating control by the left side of the brain. Adrien Meguerditchian and Jacques Vauclair, both at the University of Provence in France, have reported that baboons seem to communicate by patting the right hand on the ground. Phillip J. Clapham, now at the Alaska Fisheries Science Center in Seattle, found that whales suffered abrasions primarily on the right side of the jaw (*arrow*), indicating that they strongly favored that side in gathering food.



Evolution of Speech

A fundamental question remains: Just how could any of the behaviors already controlled by the left brain—feeding, vocalizing, communicating with the right hand—have been modified to become speech—one of the most momentous steps in the history of life on earth?

One of us (MacNeilage) has hypothesized that it required the evolution of the syllable, the basic organizational unit underlying a stream of speech in time. The typical syllable is a rhythmic alternation between consonants and vowels. (Consonants are the sounds created when the vocal tract is momentarily closed or almost closed; vowels are the sounds created by resonance with the shape of the vocal tract as air flows relatively freely out through the open mouth.) The syllable may have evolved as a by-product of the alternate raising (consonant) and lowering (vowel) of the mandible, a behavior already well established for chewing, sucking and licking. A series of these mouth cycles, produced as lip smacks, may have begun to serve among early humans as communication signals, just as they do to this day among many other primates.

Somewhat later the vocalizing capabilities of the larynx could have paired with the communicative lip smacks to form spoken syllables. Syllables were perhaps first used to symbolize individual concepts, thus forming words. Subsequently, the ability to form sentences (language) presumably evolved when early humans combined the two kinds of words that carry the main meaning of sentences: those for objects (nouns) and those for actions (verbs).

The Right Hemisphere

What about the second half of our hypothesis? How strong is the evidence that, early in vertebrate evolution, the right hemisphere specialized in detecting and responding to unexpected stimuli? In what ways has that underlying specialization evolved and been transformed?

One set of findings that lend strong support to our hypothesis comes from studies of the reactions to predators by various animals. After all, few events in ancient vertebrate environments could have been more unexpected and emotion-laden than the surprise appearance of a deadly predator. Sure enough, fishes, amphibians, birds and mammals all react with greater avoidance to predators seen in the left side of their visual field (right side of the brain) than in their right visual field [*see box on page 54*].

Evidence that the same hemispheric specialization for reactions holds for humans comes from brain-imaging studies. In a summary of those studies, Michael D. Fox and his colleagues at Washington University in St. Louis conclude that humans possess an "attentional system" in the right hemisphere that is particularly sensitive to unexpected and "behaviorally relevant stimuli"—or in other words, the kind of stimuli that say, in effect, Danger ahead! The existence of such an

ANDREW SWIFT; SOURCES: "COMPLEMENTARY RIGHT AND LEFT HEMIFIELD USE FOR PREDATORY AND AGONISTIC BEHAVIOR," BY G. VALLORTIGARA ET AL., IN *NEUROREPORT*, VOL. 9, NO. 14; 1998, AND "LATERALIZED PREY CATCHING RESPONSES IN THE CANE TOAD, *BUFO MARINUS*: ANALYSIS OF COMPLEX VISUAL STIMULI," BY A. ROBINS AND L. J. ROGERS, IN *ANIMAL BEHAVIOUR*, VOL. 68, NO. 4; 2004; ADRIEN MEGUERDITCHIAN AND JACQUES VAUCLAIR *University of Provence* (*baboon*); SOURCE: "BABOONS COMMUNICATE WITH THEIR RIGHT HAND," BY A. MEGUERDITCHIAN AND J. VAUCLAIR, IN *BEHAVIOURAL BRAIN RESEARCH*, VOL. 171, NO.1; 2006; PROVINCETOWN CENTER FOR COASTAL STUDIES (*whale*) attentional system helps to make sense of an otherwise inexplicable human propensity: in the laboratory, even right-handed people respond more quickly to unexpected stimuli with their left hand (right hemisphere) than with their right hand.

Even in nonthreatening circumstances, many vertebrates keep a watchful left eye on any visible predators. This early right-hemisphere specialization for wariness in the presence of predators also extends in many animals to aggressive behavior. Toads, chameleons, chicks and baboons are more likely to attack members of their own species to their left than to their right.

In humans the relatively primitive avoidance and wariness behaviors that manifest right-hemisphere attentiveness in nonhuman animals have morphed into a variety of negative emotions. Nineteenth-century physicians noticed that patients complained more often of hysterical limb paralyses on the left side than on the right. There is some evidence for right-hemisphere control of emotional cries and shouts in humans—in striking contrast with the emotionally neutral vocalizations controlled by the left hemisphere. People are more likely to become depressed after damage to the left hemisphere than to the right. And in states of chronic depression the right hemisphere is more active than the left.

Recognizing Others

Along with the sudden appearance of a predator, the most salient environmental changes to which early vertebrates had to react quickly were encounters with others of their own species. In fishes and birds the right hemisphere recognizes social companions and monitors social behavior that might require an immediate reaction. Hence, the role of the right hemisphere in face perception must have descended from abilities of relatively early vertebrates to recognize the visual appearance of other individuals of their species.

For example, only some species of fishes—among the earliest evolving vertebrates—may be able to recognize individual fish, but birds in general do show a right-hemisphere capacity to recognize individual birds. Keith M. Kendrick of the Babraham Institute in Cambridge, England, has shown that sheep can recognize the faces of other sheep (and of people) from memory and that the right hemisphere is preferentially involved. Charles R. Hamilton and Betty A. Vermeire, both at Texas A&M, have observed similar behavior in monkeys.

In humans neuroscientists have recently recognized that the right hemisphere specializes in face recognition. Prosopagnosia, a neurological disorder that impairs that ability, is more often a result of damage to the right hemisphere than to the left. Extending face recognition to what seems another level, both monkeys and humans interpret emotional facial expressions more accurately with the right hemisphere than with the left. We think that this ability is part of an ancient evolutionary capacity of the right hemisphere for determining identity or familiarity—for judging whether a present stimulus, for instance, has been seen or encountered before.

Global and Local

We have argued for a basic distinction between the role of the left hemisphere in normal action and the role of the right hemisphere in unusual circumstances. But investigators have highlighted additional dichotomies of hemispheric function as well. In humans the right hemisphere "takes in the whole scene," attending to the global aspects of its environment rather than focusing on a limited number of features. That capacity gives it substantial advantages in analyzing spatial relations. Memories stored by the right hemisphere tend to be organized and recalled as

PHOTOGENIC LEFT

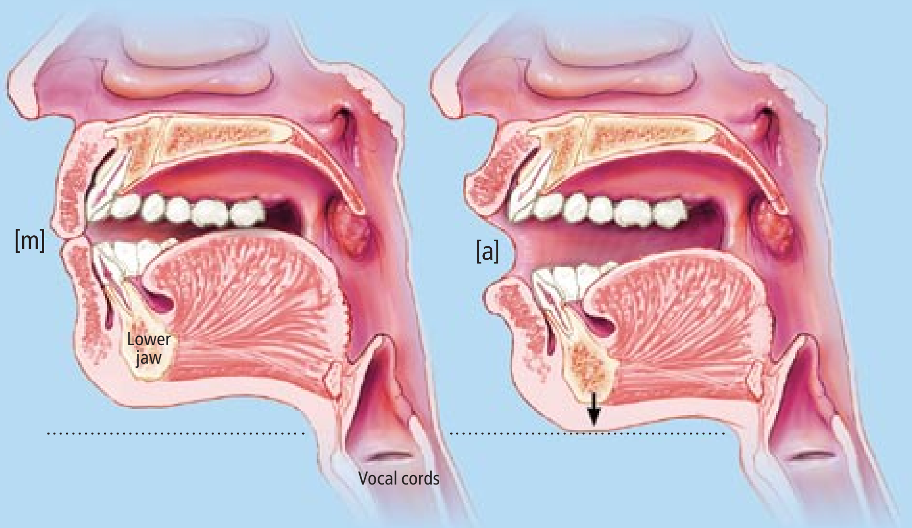
A 1999 study of the pictures in London's National Portrait Gallery analyzed the directions that the portrait sitters turned their heads.

- Overall, the sitters turned their heads slightly to the right, showing the left side of the face. The investigators argued that sitters wanted to show their left side because it is controlled by the emotive, right hemisphere of the brain.
- Portraits of males, however, show a reduced leftward bias, perhaps out of a desire to conceal emotion.
- Portraits of scientists from the Royal Society show no leftward bias.

[SPEECH AND THE LEFT BRAIN]

Did the Syllable Evolve from Chewing?

According to one of the authors (MacNeilage), the origin of human speech may be traceable to the evolution of the syllable—typically an alternation between consonant and vowel. In the word "mama," for instance, each syllable begins with the consonant sound [m] and ends with the vowel sound [a]. As the cutaway diagrams show, the [m] sound is made by temporarily raising the jaw, or lower mandible, and stopping the flow of air from the lungs by closing the lips (*below left*). To make the following vowel sound [a], the jaw drops and air flows freely through the vocal tract (*below right*). MacNeilage has thus proposed that the making of syllabic utterances is an evolutionary modification of routine chewing behavior, which first evolved in mammals 200 million years ago.



ANDREW SWIFT; SOURCE: SUSANNA DOUGLAS *University of Texas at Austin* overall patterns rather than as a series of single items. In contrast, the left hemisphere tends to focus on local aspects of its environment.

Striking evidence for the global-local dichotomy in humans has been brought to light by a task invented by David Navon of the University of Haifa in Israel. Brain-damaged patients are asked to copy a picture in which 20 or so small copies of the uppercase letter A have all been arranged to form the shape of a large capital H [*see box on page 51*]. Patients with damage to the left hemisphere often make a simple line drawing of the H with no small A letters included; patients with damage to the right hemisphere scatter small A letters unsystematically all over the page.

A similar dichotomy has been detected in chickens, suggesting its relatively early evolution. Richard J. Andrew of the University of Sussex in England and one of us (Vallortigara) have discovered that, as in humans, the domestic chick pays special attention to broad spatial relations with its right hemisphere. Moreover, chicks with the right eye covered, hence receiving input only to the right hemisphere, show interest in a wide range of stimuli, suggesting they are attending to their global environment. Chicks that can attend only with the left hemisphere (left eye covered) focus only on specific, local landmark features.

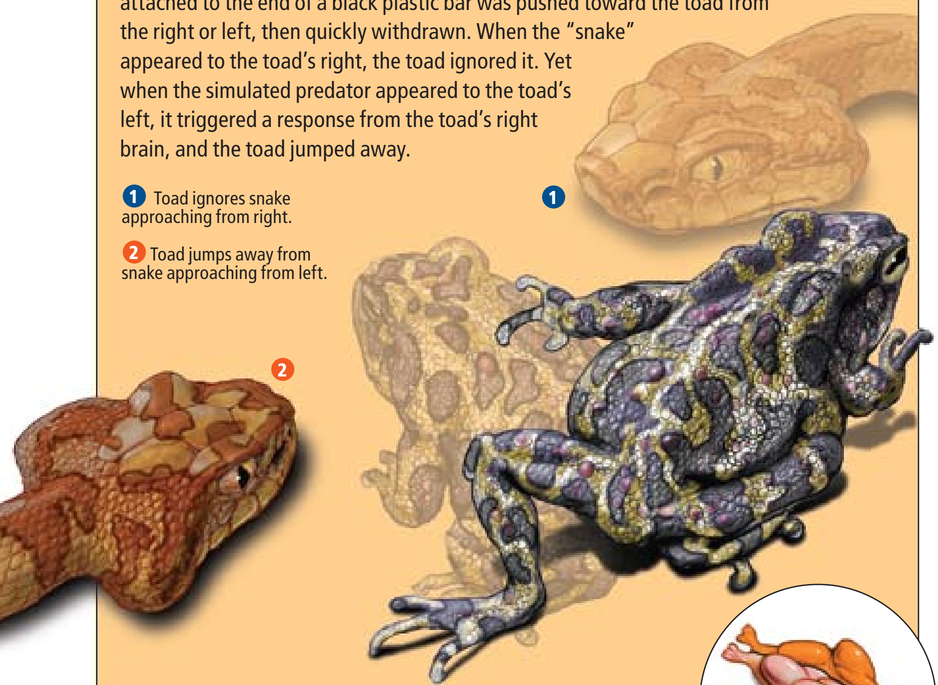
[RIGHT BRAIN]

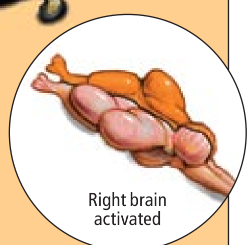
RESPONDING TO SURPRISE

The sudden appearance of a predator—or of another member of one's own species—calls for instant, appropriate action, and the right brain has evolved to handle such events. In another experiment with toads, the rubber head of a model snake attached to the end of a black plastic bar was pushed toward the toad from the right or left, then quickly withdrawn. When the "snake" appeared to the toad's right, the toad ignored it. Yet when the simulated predator appeared to the toad's left, it triggered a response from the toad's right brain, and the toad jumped away.

1 Toad ignores snake approaching from right.

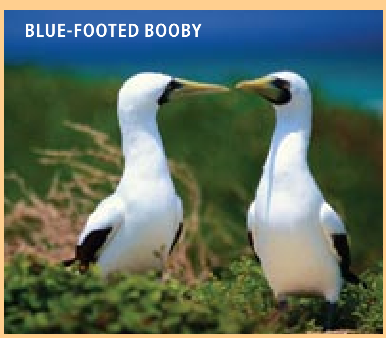
2 Toad jumps away from snake approaching from left.





Right brain activated

▼ Many vertebrates recognize individuals of their own species. Keith M. Kendrick of the Babraham Institute in Cambridge, England, has shown that sheep can recognize other individual sheep from memory, primarily with the right hemisphere. The right hemisphere in birds such as the blue-footed booby also enables them to recognize one another.



Why Do Hemispheres Specialize?

Why have vertebrates favored the segregation of certain functions in one or the other half of the brain? To assess an incoming stimulus, an organism must carry out two kinds of analyses simultaneously. It must estimate the overall novelty of the stimulus and take decisive emergency action if needed (right hemisphere). And it must determine whether the stimulus fits some familiar category, so as to make whatever well-established response, if any, is called for (left hemisphere).

To detect novelty, the organism must attend to features that mark an experience as unique. Spatial perception calls for virtually that same kind of "nose for novelty," because almost any standpoint an animal adopts results in a new configuration of stimuli. That is the function of the right hemisphere. In contrast, to categorize an experience, the organism must recognize which of its features are recurring, while ignoring or discarding its unique or idiosyncratic ones. The result is selective attention, one of the brain's most important capabilities. That is the function of the left hemisphere.

Perhaps, then, those hemispheric specializations initially evolved because collectively they do a more efficient job of processing both kinds of information at the same time than a brain without such specialized systems. To test this idea, we had to compare the abilities of animals having lateralized brains with animals of the same species having nonlateralized brains. If our idea was correct, those with lateralized brains would be able to perform parallel functions of the left and right hemisphere more efficiently than those with nonlateralized brains.

Fortunately, one of us (Rogers) had already

ANDREW SWIFT; SOURCE: "LATERALISATION OF PREDATOR AVOIDANCE RESPONSES IN THREE SPECIES OF TOADS," BY G. LIPPOLIS ET AL., IN *LATERALITY*, VOL. 7, NO. 2; 2002; JOHN GIUSTINA *Getty Images* (*sheep*); KEVIN MORRIS *Getty Images* (*blue-footed booby*) shown that by exposing the embryo of a domestic chick to light or to dark before hatching, she could manipulate the development of hemispheric specialization for certain functions. Just before hatching, the chick embryo's head is naturally turned so that the left eye is covered by the body and only the right eye can be stimulated by light passing through the egg shell. The light triggers some of the hemispheric specializations for visual processing to develop. By incubating eggs in the dark, Rogers could prevent the specializations from developing. In particular, she found, the dark treatment prevents the left hemisphere from developing its normal superior ability to sort food grains from small pebbles, and it also prevents the right hemisphere from being more responsive than the left to predators.

Rogers and Vallortigara, in collaboration with Paolo Zucca of the University of Teramo in Italy, tested both kinds of chicks on a dual task: the chicks had to find food grains scattered among pebbles while they monitored for the appearance of a model predator overhead. The chicks incubated in light could perform both tasks simultaneously; those incubated in the dark could not—thereby confirming that a lateralized brain is a more efficient processor.

Social "Symmetry Breaking"

Enabling separate and parallel processing to take place in the two hemispheres may increase brain efficiency, but it does not explain why, within a species, one or the other specialization tends to predominate. Why, in most animals, is the left eye (and the right hemisphere) better suited than the right eye (and the left hemisphere) for vigilance against predation? What makes the predominance of one kind of handedness more likely than a symmetric, 50–50 mixture of both?

From an evolutionary standpoint a "broken" symmetry, in which populations are made up mainly of left types or mainly of right types, could be disadvantageous because the behavior of individuals would be more predictable to predators. Predators could learn to approach on the prey's less vigilant side, thereby reducing the chance of being detected. The uneven proportion of left- and right-type individuals in many populations thus indicates that the imbalance must be so valuable that it persists despite the increased vulnerability to predators. Rogers and Vallortigara have suggested that, among social animals, the advantage of conformity may lie in knowing what to expect from others of one's own species.

Together with Stefano Ghirlanda of the Universities of Stockholm in Sweden and of Bologna in Italy, Vallortigara recently showed mathematically that populations dominated by left-type or by right-type individuals can indeed arise spontaneously if such a population has frequency-dependent costs and benefits. The mathematical theory of games often shows that the best course of action for an individual may depend on what most other members of its own group decide to do. Applying game theory, Ghirlanda and Vallortigara demonstrated that left- or right-type behavior can evolve in a population under social selection pressures—that is, when asymmetrical individuals must coordinate with others of their species. For example, one would expect schooling fish to have evolved mostly uniform turning preferences, the better to remain together as a school. Solitary fish, in contrast, would probably vary randomly in their turning preferences, because they have little need to swim together. This is in fact the case.

With the realization that the asymmetrical brain is not specific to humans, new questions about a number of higher human functions arise: What are the relative roles of the left and right hemispheres in having self-awareness, consciousness, empathy or the capacity to have flashes of insight? Little is known about those issues. But the findings we have detailed suggest that these functions—like the other human phenomena discussed here—will be best understood in terms of the descent with modification of prehuman capabilities. ■

[THE TWO-SIDED ADVANTAGE]

A Lateralized Brain Is More Efficient

One of the authors (Rogers) discovered that if she exposed chick embryos to light or to dark before they hatched, she could control whether the two halves of the chick brains developed their specializations for visual processing—that is, whether the chicks hatched with weakly or strongly lateralized brains. Rogers and another one of the authors (Vallortigara), with Paolo Zucca of the University of Teramo in Italy, then compared normal, strongly lateralized chicks with weakly lateralized chicks on two tasks. One task was to sort food grains from small pebbles (usually a job for the left hemisphere); the other task was to respond to a model of a predator (a cutout in the shape of a hawk) that was passed over the chicks (usually a task for the right hemisphere). The weakly lateralized chicks had no trouble learning to tell grains from pebbles when no model hawk was present. But when the hawk "flew" overhead, they frequently failed to detect it, and they were much slower than normal chicks in learning to peck at grains instead of pebbles. In short, without the lateral specializations of their brain, the chicks could not attend to two tasks simultaneously.

STOCKBYTE *Getty Images* (chick)

➥ MORE TO EXPLORE

Comparative Vertebrate Lateralization. Edited by Lesley J. Rogers and Richard J. Andrew. Cambridge University Press, 2002.

Advantages of Having a Lateralized Brain. Lesley J. Rogers, Paolo Zucca and Giorgio Vallortigara in *Proceedings of the Royal Society B*, Vol. 271, Suppl. 6, pages S420–S422; December 7, 2004.

Survival with an Asymmetrical Brain: Advantages and Disadvantages of Cerebral Lateralization. Giorgio Vallortigara and Lesley J. Rogers in *Behavioral and Brain Sciences*, Vol. 28, No. 4, pages 575–633; August 2005.

The Origin of Speech. Peter F. MacNeilage. Oxford University Press, 2008.

Mechanisms and Functions of Brain and Behavioural Asymmetries. Luca Tommasi in *Philosophical Transactions of the Royal Society B*, Vol. 364, pages 855–859; April 12, 2009.

DEAD ZONE: This elephant was killed inside Chad's Zakouma National Park last October when poachers trained automatic weapons on a grazing herd. It is one of the estimated 38,000 annual victims of the illegal ivory trade.

JEFF HUTCHENS *Reportage by Getty Images*

In 1983 while exploring a small forest called Malundwe on the edge of the Selous Game Reserve in Tanzania, one of us (Wasser) came across two elephant skulls lying side by side. One, from a female, was big, and the other was small—it had molars just a quarter the size of the female's and they had not yet been used enough to show any signs of wear. The poachers had first shot the young elephant, a ranger explained, so that they could draw its grieving mother close enough to kill her for her enormous tusks. This exploitation of familial ties in the sophisticated social system of elephants has been repeated thousands of times in Africa.

The Selous Game Reserve is the largest protected area in Africa but was nonetheless among the most heavily poached during the well-publicized slaughters that occurred between 1979 and 1989. At least 700,000 elephants were killed during this period—70,000 in the Selous alone. Then, in 1989, Tanzania's new director of wildlife launched a major antipoaching initiative called Operation Uhai. The combined effort of wildlife rangers, police officers and the military rapidly brought an end to most poaching in the country.

Tanzania then joined six other countries in successfully petitioning for the agreement administered by the United Nations known as CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) to list the African elephant as an Appendix I species. This ruling effectively banned all international trade in elephants and their products. Publicity surrounding the issue turned public sentiment so far against the ivory trade that it nearly eliminated the demand for ivory worldwide; most poaching stopped abruptly in response. Western nations helped to maintain the calm by pouring large sums of aid into antipoaching efforts throughout Africa. Collectively, this was probably the most effective act of international wildlife legislation in history, and public pressure was instrumental to its success.

But the lull was short-lived. Some African countries opposed a continent-wide ban from the outset and never stopped advocating for its

The Ivory Trail

The illegal slaughter of African elephants for ivory is now worse than it was at its peak in the 1980s. New forensic tools based on DNA analysis can help stop the cartels behind this bloody trade

By Samuel K. Wasser, Bill Clark and Cathy Laurie

reversal. Aid from Western countries dried up, leaving poor African nations with plenty of antipoaching equipment but no money for upkeep. Ivory also became an important status symbol among the new middle class in the industrial countries of the Far East such as China and Japan. Demand from these and other wealthy nations, including the U.S., drove the wholesale price for high-quality ivory from $200 per kilogram in 2004 to $850 per kilogram by 2007. The price doubled again by 2009. Chinese authorities estimated the retail value of 790 kilograms of ivory seized in southern China in March 2008 at $6,500 per kilogram.

Under pressure from African countries that wanted to sell their ivory as well as the Eastern nations that wanted to import it, CITES eventually decided to permit two one-time legal sales of ivory stocks. In each case, the ivory had to be obtained by natural deaths or legitimate culling of problem animals only. Individual countries had to apply to participate in the sale and demonstrate progress in curbing their country's illegal ivory trade. A monitoring program was also established to determine whether the legal sales would promote increased poaching (although its data were never deemed sufficient to answer this question).

By 2006 poaching had become arguably worse than it was before the ban. That year between 25,000 and 29,000 kilograms of ivory were seized en route from Africa. Major crime syndicates had become involved in the trade, eager to capitalize on this growing demand, particularly because prosecution risk remained low and the liberalization of global trade made it easy to move large volumes of contraband. Based on the 2006 seizures, we estimate that more than 8 percent of the African elephant population is being wiped out annually [*see box on page 60*]. This mortality rate exceeds the elephants' 6 percent annual reproductive rate under optimal conditions and even exceeds the 7.4 percent annual poaching mortality rate that instigated the ban.

To stop this slaughter, law-enforcement agents need to target their operations at the locations where the elephants are being poached.

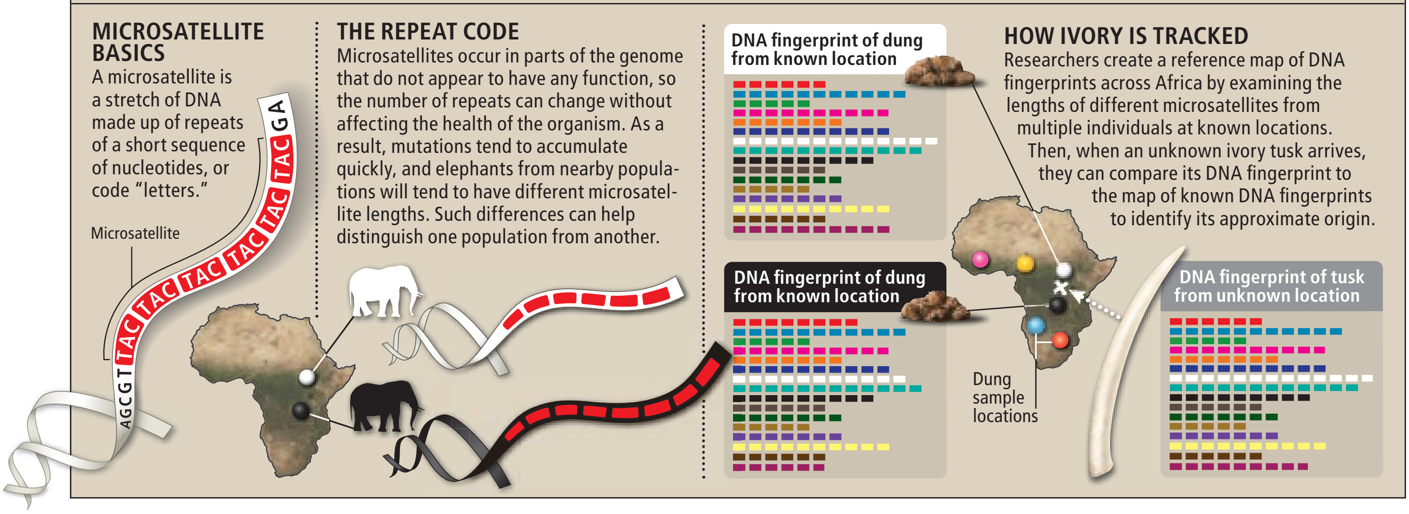
KEY CONCEPTS

- After the near elimination of elephant poaching following the 1989 ban on ivory, demand has returned. Elephant populations are now being decimated like never before.
- Researchers can now accurately map elephant populations over the entire African continent using the DNA in their scat.
- Scientists use this map and DNA extracted from ivory to trace illegal shipments back to their source. The first results from three major seizures show that sophisticated criminal networks are targeting specific groups for intense exploitation. *—The Editors*

[TRACKING TOOL]

DNA FINGERPRINTING

Investigators can trace stolen ivory to a particular population of elephants by applying DNA fingerprinting, a technique that analyzes sequences of DNA known as microsatellites.



Until recently, though, investigators were generally unable to track a container of contraband back to the location where the elephants were killed. An illegal shipment could be poached in one country, processed in another and shipped out of a third.

Knowing where elephants are being killed also helps to bring pressure to bear on countries with ineffective antipoaching operations. In addition, the pattern of geographic origin can provide clues about how poachers operate. If, for example, most of the ivory in a shipment comes from a common locale, we can conclude that poachers are targeting a specific elephant population. In this case, law enforcement should look for a well-organized and exclusive poaching ring. On the other hand, if the ivory in a given shipment comes from widely separated locations, the traffickers may be acquiring their stock via a network of opportunistic purchases from small-time dealers.

In an effort to connect a shipment with its source, we have developed DNA forensic methods to determine where elephant poaching is most concentrated in Africa. Our molecular methods are similar to those used to match crime scene evidence, such as human blood and other tissues, to specific suspects. In this case, though, the crime scene material is elephant ivory, and we are attempting to match it to elephant populations in Africa.

Here we present the first evidence from three seizures all made within two months of one another in 2006. Combined, these seizures constituted nearly 11 metric tons of contraband elephant ivory, representing more than a third of the record-breaking haul of between 25,000 and 29,000 kilograms of ivory confiscated in 2006. Few populations can sustain that level of poaching. If this ivory came from elephants living in a relatively constrained geographic area, it would provide evidence that one of the largest ivory syndicates in the world is behind the killing.

The Seizures

Monday, July 3, 2006, Kaohsiung Harbor, Taiwan—A routine automated scan of shipping manifests alerts Taiwanese customs officials at Kaohsiung to two suspicious containers. Both had departed Tanzania and are at the port en route to the Philippines, having passed through Kaohsiung once before during the same voyage. The containers seem to be shuttling back and forth between ports in the Far East with no apparent final destination. Officials check the hard-copy shipping documents, which report that the containers hold sisal fiber. Yet exporting sisal fiber from Africa to the Philippines is like sending snowballs from Sweden to Siberia. The Philippines grows tons of the fibrous plant. The inspectors decide to crack open one of the containers. There, hidden behind 60 bales of sisal, they uncover 744 elephant tusks. The second container holds another 350 tusks. The cache totals 5.2 metric tons of illegal African ivory, with an

JEN CHRISTIANSEN (*illustration*); NASA/THE VISIBLE EARTH (*base map*)

[THE AUTHORS]

Samuel K. Wasser is a professor of biology and director of the Center for Conservation Biology at the University of Washington. He conceptualized and has coordinated the ivory DNA forensics project. **Bill Clark** is chair of the Interpol Working Group on Wildlife Crime and a law-enforcement officer at the Israel Nature and Parks Authority. He has led the application of these forensics methods to criminal investigations. **Cathy Laurie**, a statistical geneticist at the University of Washington, conducted the statistical analyses of the Taiwan and Hong Kong seizures.

Two other individuals contributed significantly to the work. Celia Mailand is a research scientist at the Center for Conservation Biology and conducted all the laboratory DNA analyses. Matthew Stephens, a professor in human genetics and statistics at the University of Chicago, developed all the statistical methods and software used in the project.

estimated wholesale value of $4.6 million and a retail "street value" upward of $21 million.

Saturday, July 8, 2006, Sai Ying Pun, Hong Kong Island—Five days after the Taiwanese seizure, a local resident reports a terrible burning stench coming from a neighbor's apartment. Police and fire units respond quickly. No one replies to their knocks on the door, so the units force their way in. They discover seven people cutting and packing what turns out to be 2.6 metric tons of elephant ivory. Hong Kong authorities seize 390 tusks plus another 121 cut pieces. Some clues indicate an East African origin.

Monday, August 28, 2006, Osaka Harbor, Japan—Japanese customs agents discover 608 pieces of raw ivory, which, when carefully matched, produce 260 whole tusks. At 2.8 metric tons, this is the largest ivory seizure ever reported in Japan. Many of the tusks are numbered with Swahili writing [*see illustration on page 63*], suggesting an East African shipping source. Also in the incoming consignment are 17,928 carved ivory cylinders, obviously intended for the signature seal, or *hanko,* market. The Japanese and Chinese engrave their individual seal at one end of these signature seals—also called chops—and use them to stamp their personal checks, legal documents and letters. (Though currently among the most common uses of ivory, this is a relatively recent development; *hanko*s were historically made of materials such as jade.) Yet the Japanese do not report the seizure at the 2006 CITES standing committee meeting that was to decide whether to allow Japan to be a purchaser of a one-time ivory sale from southern Africa. On October 7, 2006, the newspaper *Asahi Shimbun* breaks the story, and Japanese authorities acknowledge the shipment soon thereafter.

When we learned of the seizures, we requested samples of the ivory so that we could subject them to DNA analysis at the University of Washington Center for Conservation Biology. The results would be shared among the donor countries, the International Criminal Police Organization (Interpol) and the Lusaka Agreement Task Force, an agency of African countries cooperating to fight wildlife crime. Hong Kong and Taiwan voluntarily agreed to provide ivory samples. Despite numerous requests, Japanese authorities have not yet supplied any samples.

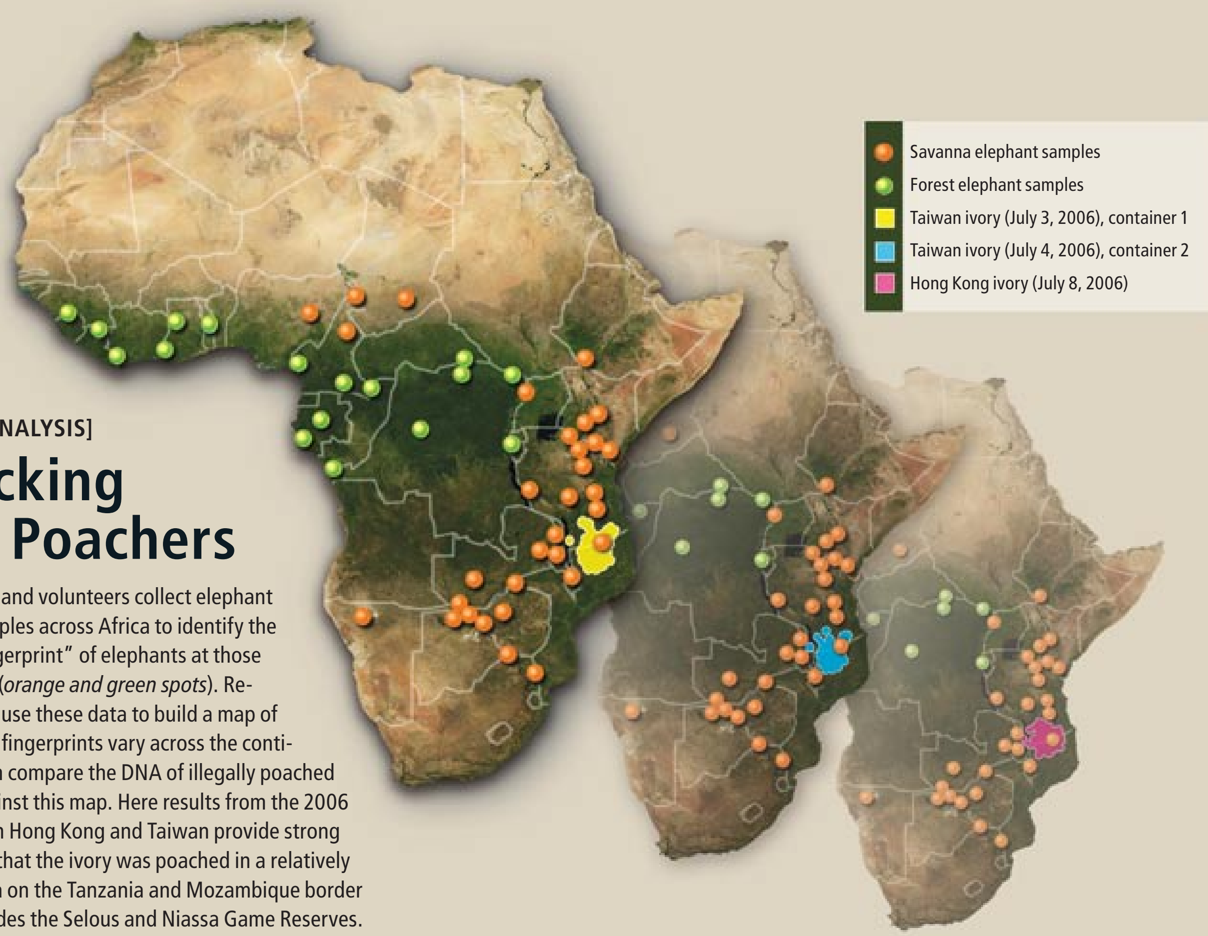
DNA Map

We extract DNA from ivory using a pulverization technique borrowed from dental forensics. We place a piece of ivory about the size of a peanut inside a polycarbonate tube along with a magnet, then seal the tube with stainless steel plugs. Next, we drop the sample into liquid nitrogen at –240 degrees Celsius inside a device called a freezer mill. There a magnetic field oscillates rapidly back and forth, smashing the ivory against the plugs and breaking it into a fine powder. Throughout this process the low temperature maintains the integrity of the DNA. Using now standard techniques, we isolate the DNA from the powder and obtain a profile of variation in DNA segments called microsatellites to get a DNA fingerprint [*see box on opposite page*]. Microsatellites consist of anywhere from

The pattern of geographic origin can provide clues about how poachers operate.

WHITE MARKET: Open ivory markets such as the one below in Kinshasa, Democratic Republic of Congo, have expanded to support the rising ivory trade. But the real surge in ivory demand is driven by the industrial nations of the Far East, where individuals use signature seals called *hankos* (*below left*) to stamp documents.

MICHAEL FREEMAN *Aurora Photos* (seals); PATRICK ROBERT *Corbis* (market)



[DATA ANALYSIS]

Tracking the Poachers

Scientists and volunteers collect elephant dung samples across Africa to identify the DNA "fingerprint" of elephants at those locations (*orange and green spots*). Researchers use these data to build a map of how DNA fingerprints vary across the continent, then compare the DNA of illegally poached tusks against this map. Here results from the 2006 seizures in Hong Kong and Taiwan provide strong evidence that the ivory was poached in a relatively small area on the Tanzania and Mozambique border that includes the Selous and Niassa Game Reserves.

NASA/THE VISIBLE EARTH (*base map*)

HOW MANY ELEPHANTS ARE BEING KILLED?

Rampant poaching in the period between 1979 and 1989 reduced the elephant population across Africa from 1.3 million to fewer than 600,000 individuals, a loss of 7.4 percent a year. Fast-forward to 2006, and the illegal ivory trade had once again escalated to levels few people anticipated. Between August 2005 and August 2006, authorities seized more than 25 metric tons of ivory. Customs commonly assumes that a 10 percent seizure rate for "general goods" contraband is successful, and so the authors estimate that more than 250 metric tons of ivory were smuggled that year. Using the commonly accepted estimate of 6.6 kilograms of ivory per elephant, they conclude that 38,000 elephants—8 percent of the entire African elephant population—are being killed annually.

two to four nucleotides repeated from 10 to 100 times. Unlike functional genes, microsatellite DNA does not code for proteins. Thus, the number of repeats in the microsatellite can vary without affecting the health of the organism or its ability to reproduce, and changes in the repeat number tend to arise frequently and persist. Over time, then, microsatellites in one population come to differ among geographically separated populations.

With a DNA fingerprint of microsatellite repeats from a tusk in hand, we now compare this to a map of DNA fingerprints from elephants across Africa. A decade ago we set out to create a reference map across the whole of the continent that would plot the variation in microsatellite DNA. This project turned out to be a much bigger challenge than we anticipated.

Africa is a huge continent and the precision of our ivory assignments is directly tied to the comprehensiveness of our DNA map. To facilitate the collection of reference DNA, we extracted it from elephant populations in the least invasive way possible—through their feces. Each gram of elephant feces contains DNA from millions of sloughed off intestinal mucosal cells. Collecting enough feces to create a reference map across Africa required the help of many scientists and wildlife wardens, and we are indebted to them for their efforts. But no matter how many elephant dung samples we are able to collect, we will never have enough to completely cover the entire continent.

To knit together swatches of patchy data, we use a statistical technique we devised called the smoothed continuous assignment technique (SCAT). Software employing the SCAT method extrapolates data gathered at discrete locations to compose a continuous geographic distribution of DNA fingerprints—the microsatellite DNA lengths at each of the 16 loci—across the entire elephant range. This method relies on the fact that populations close to one another tend to be genetically more similar than populations that are more distant. We validated the SCAT procedure by using it to determine the origin of dung samples taken from known locations.

Anatomy of a Shipment

We first applied our DNA assignment method to a case that exemplifies the magnitude and complexity of the modern ivory trade. In February 2002 authorities in Malawi, working with Zambian authorities and the Lusaka Agreement Task Force, raided a family ivory-carving factory that was ostensibly using ivory legally acquired from the Malawi government. The factory, however, had far more ivory than it had legal documentation for, and very few of the samples had the requisite government stamp. The haul included many residual scraps of ivory with bored holes from which short cylinders had been cut. These cylinders were thought to be *hanko* signature seals destined for Japan. (Japanese traditionally prefer cylindrical seals, whereas Chinese prefer square ones.)

Detailed records recovered in the Malawi raid described 19 separate shipments made by these traffickers during the preceding nine years. All shipments identified the same shipper, the same shipping codes (either soapstone or sawn timber) and the same origin. Nearly all had the same destination. One of these consignments included a 6.5-metric-ton shipment of ivory (recorded as soapstone), which was at a hidden location, waiting to be delivered.

That June authorities suddenly learned that the missing ivory had been trucked to Beira, Mozambique, and loaded on a ship to Durban, South Africa, where it was transferred onto another ship destined for Singapore. Local authorities were notified of the shipment just four hours before its arrival and confiscated the container. The shipment included 532 tusks, with an atypically large average weight of 12 kilograms per tusk, and 42,000 *hanko* seals. The signature seals were cylindrical, and their diameters matched the bored holes in the ivory scraps seized in Malawi. Several tusks in the seizure were marked with "Yokohama," a port city near Tokyo.

The shipping documents recovered in the Malawi raid did not list the weights of the 18 other illegal ivory shipments. If we assume that each shipment was similar in size to the Singapore seizure, however, they would collectively represent close to 110 metric tons of ivory, or approximately 17,000 poached elephants.

The huge quantity of seized contraband was a striking indicator of the growth of the illicit ivory trade. It also revealed how much of it is controlled by major crime syndicates. Moving this much ivory requires expertise in commodity trade, international finance and other commercial disciplines. The business requires significant infrastructure in the Far East capable of receiving and processing tons of ivory, factories that can produce tens of thousands of *hankos* a year, and a marketing, distribution and retail network to sell them. The millions of U.S. dollars generated in sales must be illegally laundered through legitimate business channels and then moved around the world to pay for new shipments. Further, high-level bribery is evident. There have been reports of poachers using large volumes of wildlife products as barter currency for the weapons and ammunition needed to keep corrupt officials in power.

And while profit is high, the risk to traffickers is low. Few major wildlife traffickers ever get prosecuted, because wildlife crime is generally considered a low priority among law-enforcement agencies when compared with terrorism, drug trafficking, murder and financial crime. Virtually no one involved in the Singapore seizure was ever prosecuted, including the customs agents who signed their names to the manifest declaring the ivory to be soapstone. In several other countries, penalties for getting caught are cheaper than paying sales tax.

The huge quantity of contraband revealed how much of the illicit ivory trade is controlled by major crime syndicates.

Hard and Fast

Although investigators strongly suspected that the ivory confiscated in Singapore was processed at the facility in Malawi, DNA analysis was necessary to determine whether the samples came

Elephants Are Not Alone

Illegal wildlife trafficking of many species and their products is burgeoning throughout the world, far exceeding current monitoring and enforcement capacity. Credible studies from multiple sources indicate that illegal trade in wildlife can be valued at tens of billions of U.S. dollars annually. The liberalization of global trade has helped spread the market for illegal wildlife products, as has technology: recent research indicates significant amounts of dubious elephant ivory are being offered for sale on the Internet. The considerable legal trade in rare wildlife—more then 100 million individuals of rare species are bought and sold every year under CITES—also provides an ideal conduit for illegal trade. And as with ivory, it is becoming clear that criminal syndicates are behind much of it. In just the past few years, authorities have made a series of disconcertingly large busts, confiscating 55,000 reptile skins in India, 19,000 bigeye thresher shark fins in Ecuador, 23 metric tons of pangolins in Asia, 3,000 Tibetan (*shahtoosh*) shawls from at least 12,000 antelopes in India, and 2,000 Indian star tortoises (*below*), also in India. —*S.K.W.*

KWAI CHOW WONG *Getty Images*

If the trade is not brought under control soon, most of Africa will lose the majority of its free-ranging elephants.

from the same source. The results provided strong evidence that all the ivory had a common origin. The tusks and *hanko* seals from the Singapore seizure as well as the ivory scraps seized in the Malawi factory raid all originated from a population of savanna elephants centered on Zambia. Linking the *hanko*s to the same population as the tusks in the Singapore seizure explained the mysterious absence of small to medium tusks in that seizure. Smaller tusks were likely carved into *hanko*s at the ivory-carving facility in Malawi. This strategy almost certainly served to increase the value of the consignment to a Japanese market, as the Japanese historically prefer large tusks. It also indicated that animals of all ages fell victim to these poachers. It takes a very large number of young elephants to provide enough ivory to manufacture 42,000 signature stamps.

This 2002 seizure occurred in the same year that Zambia petitioned CITES to allow its stockpiled ivory to be included in a one-time sale to the Far East. Yet CITES ultimately rejected this proposal, in some degree because of suspicions that some of the ivory recovered in Singapore came from Zambia. Our results help to validate that decision.

Analysis of the ivory in the Singapore seizure showed for the first time how poachers were targeting specific populations for intense exploitation. Populations were hit hard and fast, presumably to satisfy specific purchase orders from buyers. This finding contradicted the more common belief that traffickers were employing a decentralized plan of assembling large consignments by opportunistically procuring ivory stockpiles as they became available across Africa. It also meant that using these techniques to focus law enforcement on identified hotspots should prove to be a viable antipoaching strategy.

Business as Usual

Our more recent studies of the summer 2006 seizures in Taiwan and Hong Kong show just how much the current destruction mirrors the slaughter of the 1980s. The 2006 operations also involved a high level of organization and much political intrigue. Our DNA analysis revealed that the tusks came from an area centered on the Selous ecosystem in Tanzania, spilling over into the Niassa Game Reserve in northern Mozambique [*see box on page 60*]. It appears that Tanzania has once again become a hotbed of illegal poaching activity. This is the country that is home to Serengeti National Park; Gombe Stream, where Jane Goodall carried out her famed chimpanzee research; Mount Kilimanjaro; the Eastern Arc Mountains, a world-renowned hotspot on the edge of the Selous that has more endemic

Are There Too Many Elephants?

Following the ivory ban, some people became caught up in the myth that Africa now has too many elephants. Media reports focused on a small number of southern African countries that demanded to legally cull elephants because of high population densities in protected areas such as wildlife refuges; escalating human-elephant conflict seemed to back those claims. Yet the problem is far more complicated than it appears.

Most of the protected areas with high elephant densities in southern Africa are fenced, which severely restricts the elephants' natural movements. Far more countries throughout Africa, including several countries in southern Africa, are experiencing substantial poaching-related declines among elephants. The raging debates over culling frequently overshadow these points, yet they offer a simpler solution: tearing down those fences and creating megaparks that transcend international boundaries. Many of the now fenced populations border countries with low human and elephant population densities that offer considerable land for elephant movement. The megaparks would dilute any high-density pockets of elephant activity and thus blunt the impact on the rest of the food chain.

There is also disagreement as to the causes of human-elephant conflict. Such conflict most often happens when elephants wander outside their protected areas and into nearby farms. Loss of habitat is usually cited as the prime cause, but the effect of poaching on elephant social structure also plays a large role. Older adult females have consistently been among the first to be poached—aside from big adult males, they have the largest tusks, and female social groups are a lot easier for poachers to find than solitary adult males. A 1989 study found that 80 percent of the skulls recovered from poached elephants were females, with a mean age of 32 years. These old females, called matriarchs, play a pivotal role in elephant society, directing group movements and maintaining the group's competitive standing and social cohesion. With their leaders lost and "protected areas" no longer offering safe haven because of poaching, elephants wander. Indeed, massive elephant exoduses have been well documented during the slaughters that occurred in the civil wars of Mozambique, Angola and elsewhere. These leaderless elephants move out of their protected areas, encounter rich crops, mistake the poor people defending them for poachers, and fight for their lives. *—S.K.W.*

JOHN HRUSA *Corbis*

UNSOLVED BUST: **Just weeks after the Hong Kong and Taiwan seizures, authorities in Osaka, Japan, confiscated 608 pieces of raw ivory totaling 2.8 metric tons (*left*). The authorities have not yet provided samples for DNA analysis, so it is impossible to say with certainty where the ivory originated; however, circumstantial evidence such as Swahili lettering on many of the tusks (*below*) implies Tanzania as an origin (Swahili is primarily spoken in Tanzania and Kenya).**

JAPAN WILDLIFE CONSERVATION SOCIETY

species per square kilometer than any other place in the world; and of course the Selous Game Reserve itself. Tanzania petitioned CITES to sell its stockpiled ivory that same year but withdrew its application in response to international pressures.

One open question is whether the ivory impounded in Osaka also originated in Tanzania. While our lab was analyzing the seizures from Taiwan and Hong Kong, Japanese authorities concluded their work on the bust—the biggest ivory-smuggling attempt in Japanese history. In 2007 a Japanese court convicted a man of attempting to smuggle the 2.8 metric tons of ivory. He received a suspended sentence and a fine equivalent to less than 1 percent of the customs estimate of the ivory's retail street value. Japanese authorities then incinerated the ivory, thereby making it unavailable for DNA analysis. They did retain a collection of about 100 small pieces, each weighing an average of 0.3 gram. Yet these pieces have not been made available and, even if they were, we are uncertain that they could yield enough DNA for analyses. Earlier that year Japan received final CITES approval to purchase ivory from a legal sale that would occur in 2008.

These sales are problematic, no matter how carefully they are monitored. The existence of legal domestic ivory markets, particularly in the Far East, influences public perceptions and legitimizes the fashion for ivory. Legal markets likely absorb a large portion of the smuggled ivory and provide an easy way to launder the rest. How else can hundreds of thousands of ivory carvings be entered into retail consumer trade, if not via conventional retail merchants?

Industrial consumer countries with markets for contraband ivory have not been providing credible support for wildlife agencies in African elephant habitat countries, despite the fact that it is their citizens who provide the financial incentive for nearly all the poaching. Developing countries in Africa are left extremely vulnerable to the power and money that wildlife crime syndicates wield, power that is fueled by the wealth of industrial economies. Although DNA analysis can help concentrate law-enforcement efforts, more help is needed to stop the slaughter. As we write, the killing continues: on March 9, 2009, Vietnam authorities confiscated a shipment of 6.2 metric tons of ivory, which was reportedly smuggled from Tanzania. This constitutes the second-largest ivory seizure since the ban.

Public sentiment contributed significantly to stopping the illegal ivory trade in 1989, and improved public awareness of the elephant's peril could achieve this again. By our estimates, more than 38,000 African elephants were killed for ivory in 2006 alone. All evidence suggests that the poaching rate has still not slowed, and indeed there are reports of intensified poaching from some countries. If the illegal ivory trade is not brought under control soon, most of Africa will lose the majority of its free-ranging elephants, and Africa will never be the same. That is too great a price to pay for a commodity whose principal use is vanity. ■

MORE TO EXPLORE

Elephant Reflections. Photographs by Karl Ammann. Text by Dale Peterson. University of California Press, 2009.

The Center for Conservation Biology. University of Washington. **www.conservationbiology.net**

Animal Investigators: How the World's First Wildlife Forensics Lab Is Solving Crimes and Saving Endangered Species. Laurel A. Neme. Scribner, 2009.

Combating the Illegal Trade in African Elephant Ivory with DNA Forensics. Samuel K. Wasser et al. in *Conservation Biology,* Vol. 22, No. 4, pages 1065–1071; 2008.

THE SCIENCE OF BUBBLES & BUSTS

The worst economic crisis since the Great Depression has prompted a reassessment of how financial markets work and how people make decisions about money

By Gary Stix

KEY CONCEPTS

- The worldwide financial meltdown has caused a new examination of why markets sometimes become overheated and then come crashing down.
- The dot-com blowup and the subsequent housing and credit crises highlight how psychological quirks sometimes trump rationality in investment decision making. Understanding these behaviors elucidates the genesis of booms and busts.
- New models of market dynamics try to protect against financial blowups by mirroring more accurately how markets work. Meanwhile more intelligent regulation may gently steer the home buyer or the retirement saver away from bad decisions.

—The Editors

It has all the makings of a classic B movie scene. A gunman puts a pistol to the victim's forehead, and the screen fades to black before a loud bang is heard. A forensic specialist who traces the bullet's trajectory would see it traversing the brain's prefrontal cortex—a central site for processing decisions. The few survivors of usually fatal injuries to this brain region should not be surprised to find their personalities dramatically altered. In one of the most cited case histories in all of neurology, Phineas Gage, a 19th-century railroad worker, had his prefrontal cortex penetrated by an iron rod; he lived to tell the tale but could no longer make sensible decisions. Cocaine addicts may actually self-inflict similar damage. The resulting dysfunction may cause even abstaining addicts to crave the drug any time, say, the thudding bass of a techno tune reminds them of when they were stoned.

Even people who do not use illicit drugs or get shot in the head have to contend with the reality that some of the decisions cooked up by the brain's frontal lobes may lead them astray. A specific site within the prefrontal cortex, the ventromedial prefrontal cortex (VMPFC) is, in fact, among the suspects in the colossal global economic implosion that has recently rocked the globe.

The VMPFC turns out to be a central location for what economists call "money illusion." The illusion occurs when people ignore obvious information about the distorting effects of inflation on a purchase and, in an irrational leap, decide that the thing is worth much more than it really is. Money illusion may convince prospective buyers that a house is always a great investment because of the misbegotten perception that prices inexorably rise. Robert J. Shiller, a professor of economics at Yale University, contends that the faulty logic of money illusion contributed to the housing bubble: "Since people are likely to remember the price they paid for their house from many years ago but remember few other prices from then, they have the mistaken impression that home prices have gone up more than other prices, giving a mistakenly exaggerated impression of the investment potential of houses."

Economists have fought for decades about whether money illusion and, more generally, the influence of irrationality on economic transactions are themselves illusory. Milton Friedman, the renowned monetary theorist, postulated that consumers and employers remain undeluded and, as rational beings, take inflation into account when making purchases or paying wages. In other words, they are good judges of the real value of a good.

BUSTS

But the ideas of behavioral economists, who study the role of psychology in making economic decisions, are gaining increasing attention today, as scientists of many stripes struggle to understand why the world economy fell so hard and fast. And their ideas are bolstered by the brain scientists who make inside-the-skull snapshots of the VMPFC and other brain areas. Notably, an experiment reported in March in the *Proceedings of the National Academy of Sciences USA* by researchers at the University of Bonn in Germany and the California Institute of Technology demonstrated that some of the brain's decision-making circuitry showed signs of money illusion on images from a brain scanner. A part of the VMPFC lit up in subjects who encountered a larger amount of money, even if the relative buying power of that sum had not changed, because prices had increased as well.

The illumination of a spot behind the forehead responsible for a misconception about money marks just one example of the increasing sophistication of a line of research that has already revealed brain centers involved with the more primal investor motivations of fear (the amygdala) and greed (the nucleus accum-

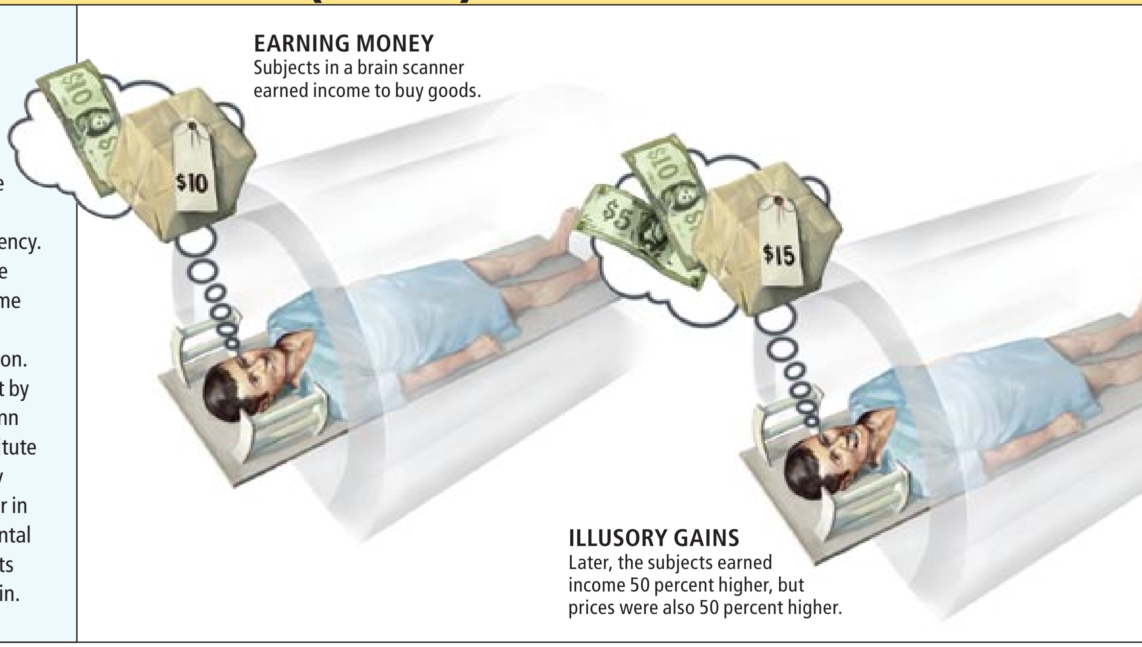
AARON GOODMAN

[WHAT HAPPENS IN YOUR BRAIN]

DO YOU UNDERSTAND (REAL) MONEY?

A psychological phenomenon called money illusion may have contributed to the housing bubble at the root of today's global economic crisis. This illusion is the confusion that results when people fail to acknowledge the effects of inflation on the real value of a currency. Increases in the price of one's home or a salary, for instance, may become nothing more than an illusion once those prices are adjusted for inflation.

A recent experiment carried out by researchers at the University of Bonn in Germany and the California Institute of Technology (*right*) traced money illusion to a decision-making center in the brain. The ventromedial prefrontal cortex became active when subjects were presented with an illusory gain.



EARNING MONEY
Subjects in a brain scanner earned income to buy goods.

ILLUSORY GAINS
Later, the subjects earned income 50 percent higher, but prices were also 50 percent higher.

MATT COLLINS

bens, perhaps, not surprisingly, a locus of sexual desire as well). A high-tech fusing of neuroimaging with behavioral psychology and economics has begun to provide clues to how individuals, and, aggregated on a larger scale, whole economies may run off track. Together these disciplines attempt to discover why an economic system, built with nominal safeguards against collapse, can experience near-catastrophic breakdowns. Some of this research is already being adopted as a guide to action by the Obama administration as it tries to stabilize banks and the housing sector.

The fusing of neuroimaging with behavioral psychology and economics has begun to provide clues to how individuals, and, aggregated on a larger scale, whole economies may run off track.

The Rationality Illusion

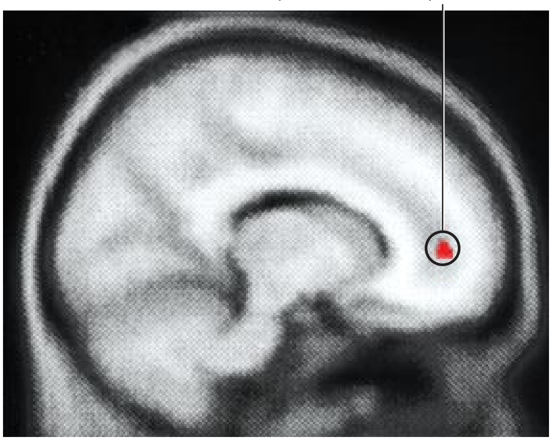
The behavioral ideas now garnering increased attention take exception to some central ideas of modern economic theory, including the view that each buyer and seller constitute an exemplar of *Homo economicus,* a purely rational being motivated by self-interest. "Under all conditions, man in classical economics is an automaton capable of objective reasoning," writes financial historian Peter Bernstein.

Another central tenet of the rationalist credo is the efficient-market hypothesis, which holds that all past and current information about a good is reflected in its price—the market reaches an equilibrium point between buyers and sellers at just the "right" price. The only thing that can upset this balance between supply and demand is an outside shock, such as unanticipated price setting by an oil cartel. In this way, the dynamics of the financial system remain in balance. Classical theory dictates that the internal dynamics of the market cannot lead to a feedback cycle in which one price increase begets another, creating a bubble and a later reversal of the cycle that fosters a crippling destabilization of the economy.

A strict interpretation of the efficient-market hypothesis would imply that the risks of a bubble bursting would be reflected in existing market prices—the price of homes and of the risky (subprime) mortgages that were packaged into what are now dubbed "toxic securities." But if that were so and markets were so efficient, how could prices fall so precipitously? Astonishment about the failure of conventional theory was even expressed by former chair of the Federal Reserve Board Alan Greenspan. A persistent cheerleader for the notion of efficient markets, he told a congressional committee in October 2008: "Those of us who looked to the self-interest of lending institutions to protect shareholder's equity, myself especially, are in a state of shocked disbelief."

Animal Spirits

The behavioral economists who are trying to pinpoint the psychological factors that lead to bubbles and severe market disequilibrium are the intellectual heirs of psychologists Amos Tversky and Daniel Kahneman, who began studies in the 1970s that challenged the notion

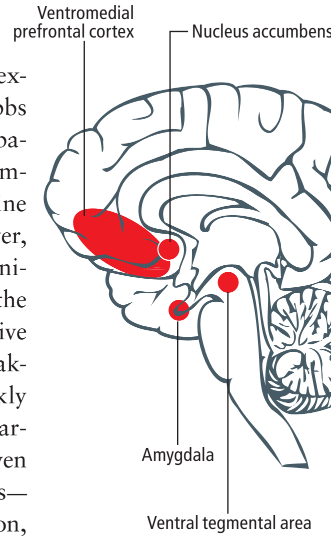


BRAIN REACTS
Activation in one region of the brain involved with decision making, the ventromedial prefrontal cortex, was higher in subjects who irrationally perceived the higher income as a gain, even though the real buying power was not changed.

of financial actors as rational robots. Kahneman won the Nobel Prize in Economics in 2002 for this work; Tversky would have assuredly won as well if he were still alive. Their pioneering work addressed money illusion and other psychological foibles, such as our tendency to feel sadder about losing, say, $1,000 than feeling happy about gaining that same amount.

A unifying theme of behavioral economics is the often irrational psychological impulses that underlie financial bubbles and the severe downturns that follow. Shiller, a leader in the field, cites "animal spirits"—a phrase originally used by economist John Maynard Keynes—as an explanation. The business cycle, the normal ebbs and peaks of economic activity, depends on a basic sense of trust for both business and consumers to engage one another every day in routine economic dealings. The basis for trust, however, is not always built on rational assessments. Animal spirits—the gut feeling that, yes, this is the time to buy a house or that sleeper stock—drive people to overconfidence and rash decision making during a boom. These feelings can quickly transmute into panic as anxiety rises and the market heads in the other direction. Emotion-driven decision making complements cognitive biases—money illusion's failure to account for inflation, for instance—that lead to poor investment logic.

The importance of both emotion and cognitive biases in explaining the global crisis can be witnessed throughout the concatenation of events that, over the past 10 years, left the financial system teetering. Animal spirits propelled Internet stocks to indefensible heights during the dot-com boom and drove their values earthward just a few years later. They were present again when reckless lenders took advantage of low-interest rates to proffer adjustable-rate mortgages on risky, subprime borrowers. A phenomenon like money illusion prevailed: the borrowers of these mortgages failed to calculate what would happen if interest rates rose, which is exactly what happened during the middle of the decade, causing massive numbers of foreclosures and defaults. Securitized mortgages, debt from hundreds to thousands of homeowners packaged by banks into securities and then sold to others, lost most of their value. Banks witnessed their lend-

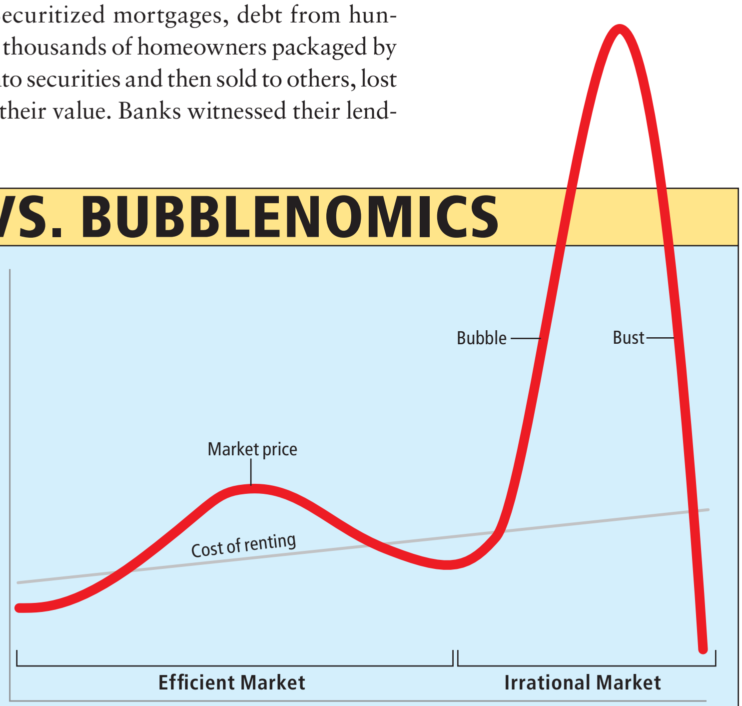


BRAIN AREAS that become activated in response to reward or risk include those shown above, among others.

[OLD THEORY VS. NEW]

EFFICIENT MARKETS VS. BUBBLENOMICS

Classical economic theory fails to consider that people's irrationality can influence their financial decisions. A cornerstone of financial orthodoxy, the efficient-market hypothesis, asserts that most individuals will make a purchase when a good, such as a home, is undervalued and will refrain from incurring the expense if the item gets too costly (*left side of graph*). But classical theory has great difficulty explaining economic bubbles—in which prices rise far beyond the true value of an asset, whether a house or a security. In contrast, behavioral economic theories, which focus on the psychology of finance, predict that, at times, irrational thinking and emotion will prevail, leading hordes of people to spend more and more on investments instead of recognizing that they are overpaying only to later stampede out of the market in a panic, precipitating a crash (*right*).



MELISSA THOMAS (*graph* and *brain illustration*); "THE MEDIAL PREFRONTAL CORTEX EXHIBITS MONEY ILLUSION," BY BERND WEBERA, ANTONIO RANGELB, MATTHIAS WIBRALC AND ARMIN FALKC, IN *PNAS*, VOL. 106, NO. 13; MARCH 31, 2009 (*brain scan*)

[WHEN THE BRAIN ERRS]

OUR INNER BIASES

The brain has two systems for making judgments about money and a whole array of other decisions that allow us to navigate our everyday lives. One system is intuitive, the other rational. The intuitive system sometimes produces errors in thinking, cognitive biases, which can lead us into trouble when dealing with financial matters. A few of the basic errors in using money that have been described by behavioral economists follow.

OVERCONFIDENCE: We consistently overrate our prowess in doing everything from driving cars to investing in real estate or the stock market.

HERDING: A tendency to follow the crowd can causes massive numbers of investors to share the same belief about a financial asset, driving prices up or down.

MATT COLLINS

ing capital decline. Credit, the lifeblood of capitalism, vanished, bringing on a global crisis.

Rules of Thumb

Behavioral economics and the related subdiscipline of behavioral finance, which pertains more directly to investment, have also begun to illuminate in more detail how psychological quirks about money can help explain the recent crisis. Money illusion is only one example of irrational thought processes examined by economists. Heuristics, or rules of thumb that we need to react quickly in a crisis, are perhaps a legacy that lingers from our Paleolithic ancestors. Measured reasoning was not an option when facing down a wooly mammoth. When we are not staring down a wild animal, heuristics can sometimes result in cognitive biases.

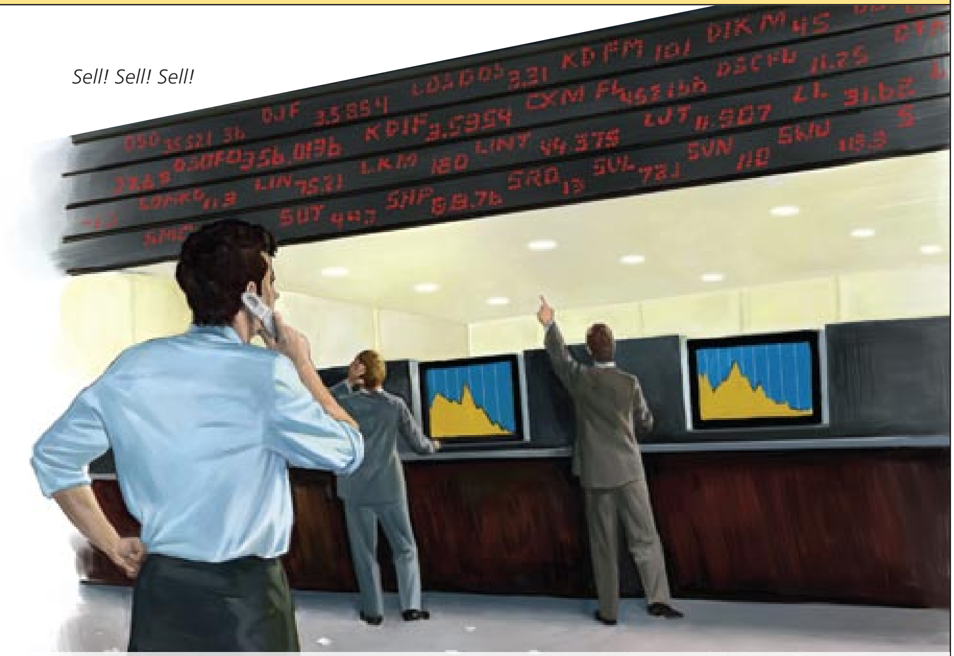
Behavioral economists have identified a number of biases, some with direct relevance to bubble economics. In confirmation bias, people overweight information that confirms their viewpoint. Witness the massive run-up in housing prices as people assumed that rising home prices would be a sure bet. The herding behavior that resulted caused massive numbers of people to share this belief. Availability bias, which can prompt decisions based on the most recent information, is one reason that some newspaper editors shunned using the word "crash" in the fall of 2008 in an unsuccessful attempt to avoid a flat panic. Hindsight bias, the feeling that something was known all along, can be witnessed post-crash: investors, homeowners and economists acknowledged that the signs of a bubble were obvious, despite having actively contributed to the rise in home prices.

An appetite for taking risks with money changes in response to even subtle, emotional cues, undercutting the myth of the steely, cold investor.

Neuroeconomics, a close relation of behavioral economics, trains a functional magnetic resonance imaging device or another form of brain imaging on the question of whether these idiosyncratic biases are figments of an academician's imagination or actually operate in the human mind. Imaging has already confirmed money illusion. But investigators are exploring other questions as well; for instance, does talking about money or looking at it or merely thinking about it activate reward and regret centers inside the skull?

In March at the annual meeting of the Cognitive Neuroscience Society in San Francisco, Julie L. Hall, a graduate student of Richard Gonzalez at the University of Michigan at Ann Arbor, presented research showing that our willingness to take risks with money changes in response to even subtle emotional cues, again undercutting the myth of the steely, cold investor. In the experiment, 24 participants—12 men and 12 wom-

Sell! Sell! Sell!



AVAILABILITY BIAS: Recall of recent events and other thoughts that spring readily to mind can turn into preoccupations that cause an investor to focus on short-term results—and perhaps sell in a panic if the market goes down.

en—viewed photographs of happy, angry and neutral faces. After exposure to happy faces, the study's "investors" had more activation in the nucleus accumbens, a reward center, and consistently invested in more risky stocks rather than embracing the relative safety of bonds.

"Happy faces" were a constant presence during the real estate boom earlier in this decade. The smiling visage and happy talk of Carleton H. Sheets, the late-night real estate infomercial pitchman, promised fortunes to those who lacked cash, credit or previous experience in owning or selling real estate. Lately, Sheets's pitch now highlights "Real Profit$ in Foreclosures."

Behavioral economics has gone beyond just trying to provide explanations for why investors behave as they do. It actually supplies a framework for investing and policy making to help people avoid succumbing to emotion-based or ill-conceived investments.

The arrival of the Obama administration marks a growing acceptance of the discipline. A group of leading behavioral scientists provided guidance on ways to motivate voters and campaign contributors during the presidential campaign. Cass Sunstein, a constitutional scholar who wrote the well-regarded book *Nudge,* which President Barack Obama has reportedly read, was appointed head of the Office of Information and Regulatory Affairs, which reviews federal regulations. Other officials who are either behavioral economists or aficionados of the discipline are now populating the White House.

Sunstein and his *Nudge* co-author Richard Thaler, the latter one of the founders of behavioral economics, came up with the term "libertarian paternalism" to describe how a government regulation can nudge people away from an inclination toward poor decision making. It relies on a heuristic called anchoring—a suggestion of how to begin thinking about something in the hope that thought carries over into behavior. People, for example, might be prodded into saving more for retirement if they were enrolled automatically in a pension plan from the outset, rather than merely being given an option to sign up. "Employees are enrolled if they do nothing, but they can opt out," Thaler remarks. "This assures that absentmindedness does not produce poverty when old." This idea was reflected in the Obama administration's plans to automatically enroll people in a retirement plan in their workplace.

Decision making can be more complex than simply responding to a gentle push down a given path. In those circumstances, a "choice architecture" is needed to help someone decide among various options. In buying a house, for instance, purchasers need clearer information about money illusion and the like. "When all mortgages were of the 30-year, fixed-rate variety, choosing the best one was simple—just pick the lowest interest rate," Thaler says. "Now with variable rates, teaser rates, balloon payments, prepayment penalties, and so forth, choosing the best mortgages requires a Ph.D. in finance." A choice architecture would require that lenders "map" options clearly for borrowers, reducing an imposing stack of paperwork when buying a house into two neat columns, one that lists the various fees, the other that notes interest payments. Captured in a digital format, for instance, these two spreadsheet columns could be uploaded and compared with offerings from other lenders.

Along similar lines, Yale's Shiller outlines an intricate strategy designed to avoid the excesses of bubble economics by educating against errors in "economic thinking." Shiller suggests adopting new units of measurement akin to the *unidad de fomento* (UF) put in place by the Chilean government in 1967 and also embraced by other Latin American governments. The UF is a safeguard against money illusion, allowing a buyer or seller to know whether a price has increased in real terms or is just an inflationary mirage. It

FAMOUS BUBBLES OF YESTERYEAR

The phenomenon of prices rising to unsustainable levels only to crash suddenly has occurred repeatedly for hundreds of years. Here are a few early examples:

Tulip mania: The Dutch succumbed to a frenzy of purchasing tulip bulbs from 1634 to 1637. They went as far as bidding land and jewels to assuage their passion for these flowers.

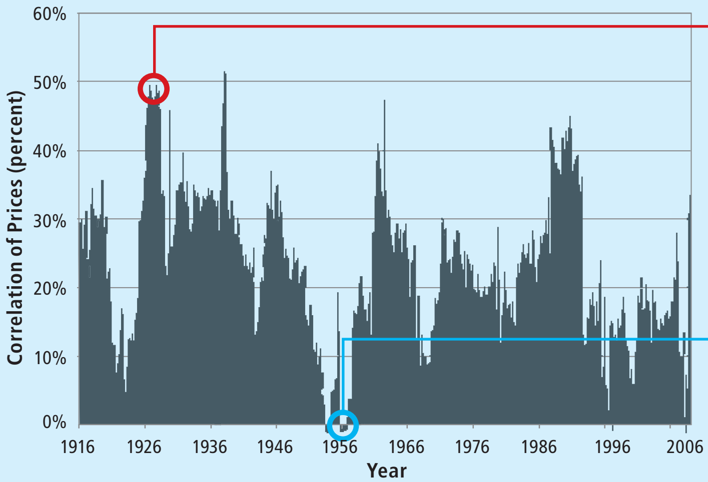
South Sea bubble: It was the 18th century's equivalent of the dot-com boom. The British poured money into a company that was granted monopoly rights to all trade involved with the South Seas. The South Sea Company's success at raising money bred a host of imitators, including one firm that desired to extract sunlight from cucumbers.

The Hoover bull market: Naive investors flooded into the market in 1928 and after President Herbert Hoover was inaugurated in March 1929. The run-up in prices ended with the infamous crash of October 1929.

[AN EVOLUTIONARY PERSPECTIVE]

A NEW WAY TO PREDICT BUBBLE MANIAS

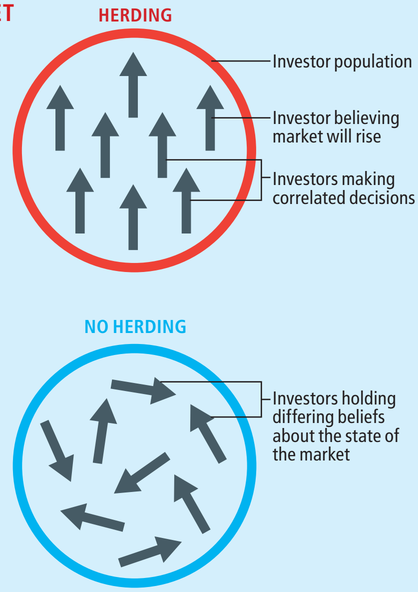
Researchers at the Massachusetts Institute of Technology have combined several descriptions of how markets work—and borrowed from evolutionary theory—in an attempt to make better predictions about when buying and selling activity will become volatile and which investors will survive the turmoil. Their conception is called the adaptive-market hypothesis.



CORRELATION: ONE PRICE LEADS TO ANOTHER
A computational analysis based on the adaptive-market hypothesis tracks the degree to which price changes that occur on one day influence how much prices are altered on the next—in essence, how closely price changes are correlated.

IRRATIONAL MARKET
Upward price movements with a high degree of correlation imply that many investors are herding into the market and that a bubble may be forming, a trend that may be driven by an irrational belief that prices will go up indefinitely.

RATIONAL MARKET
After a bubble bursts and herding activity subsides, the market returns to the more "efficient" state modeled by classical economists; in an efficient market, investors hold independent beliefs about the direction of the market.



MELISSA THOMAS

represents the price of a market basket of goods and is so commonly used that Chileans often quote prices in these units. "Chile has been the most effectively inflation-indexed country in the world," Shiller says. "House prices, mortgages, some rentals, alimony payments, and executive incentive options are often expressed in these inflation units."

Shiller also remains an ardent advocate of new financial technology that could serve as antibubble weapons. Regulators are now scrutinizing the sophisticated financial instruments that were supposed to protect against default on the mortgage-backed securities that fueled the housing boom. Shiller, however, argues that derivatives (a class of financial instruments that is meant to shield against risk but whose misuse for speculation contributed to the credit crisis) can help guarantee that there are enough buyers and sellers in housing markets. Derivatives are financial contracts "derived" from an underlying asset, such as a stock, a financial index or even a mortgage.

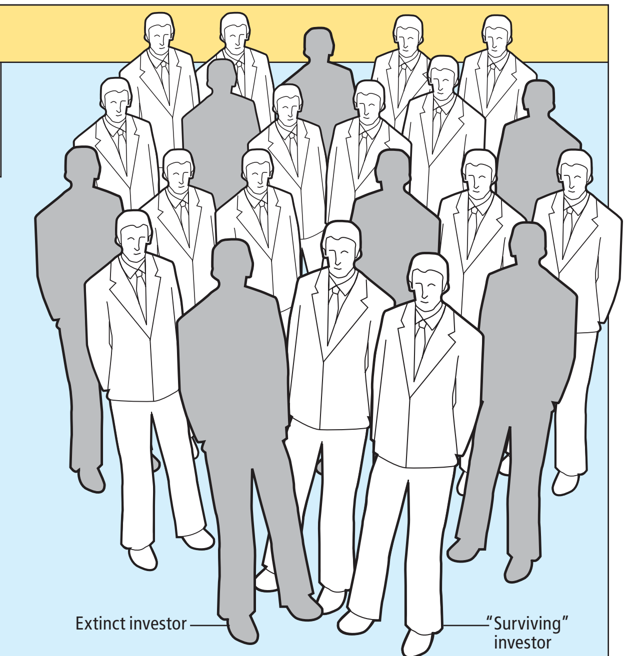
Despite the potential for abuse, Shiller perceives derivatives as prudent "hedges" against dire economic scenarios. In the housing market, homeowners and lenders might use these financial instruments to insure against falling prices, thereby providing sufficient liquidity to keep sales moving.

Economists have begun to adopt ideas from evolutionary theory to better represent how markets shift from placid to turbulent and how some investors survive while others just vanish.

Can Biology Save Us?

Ultimately, a solution to the current crisis will have to be informed by new ways of thinking about how investors act. One particularly creative approach would correct deficiencies in existing economic theory by melding the old with the new. Andrew Lo, a professor of finance at the Massachusetts Institute of Technology and an official at a hedge fund, has devised a theory that gives equilibrium economics and the efficient-market hypothesis their due while also acknowledging that classic theory does not reflect the way markets work in all circumstances. It attempts a grand synthesis that combines evoutionary theory with both classical and behavioral economics. Lo's approach, in other words, builds on the idea that incorporating Darwinian natural selection into simulations of economic behavior can help yield useful insights into how markets operate and provide more accurate predictions than usual of how financial actors—both individuals and institutions—will behave.

Similar ideas have occurred to economists before. Economist Thorstein Veblen proposed that economics should be an evolutionary science as



SURVIVAL OF THE FINANCIALLY FITTEST
The adaptive-market hypothesis also combines evolutionary theory with information about correlations and data related to the financial health of individual and institutional investors. This synthesis can predict who may adapt as market conditions change and who may fall by the wayside.

early as 1898; even earlier Thomas Robert Malthus had a profound influence on Darwin himself with his musings on a "struggle for existence."

Just as natural selection postulates that certain organisms are best able to survive in a particular ecological niche, the adaptive-market hypothesis considers different market players from banks to mutual funds as "species" that are competing for financial success. And it assumes that these players at times use the seat-of-the-pants heuristics described by behavioral economics when investing ("competing") and that they sometimes adopt irrational strategies, such as taking bigger risks during a losing streak.

"Economists suffer from a deep psychological disorder that I call 'physics envy,' " Lo says. "We wish that 99 percent of economic behavior could be captured by three simple laws of nature. In fact, economists have 99 laws that capture 3 percent of behavior. Economics is a uniquely human endeavor and, as such, should be understood in the broader context of competition, mutation and natural selection—in other words, evolution."

Having an evolutionary model to consult may let investors adapt as the risk profiles of different investment strategies shift. But the most important benefit of Lo's simulations may be an ability to detect when the economy is not in a stable equilibrium, a finding that would warn regulators and investors that a bubble is inflating or else about to explode [*see box at left*].

An adaptive-market model can incorporate information about how prices in the market are changing—analogous to how people are adapting to a particular ecological niche. It can go on to deduce whether prices on one day are influencing prices on the next, an indication that investors are engaged in "herding," as described by behavioral economists, a sign that a bubble may be imminent. As a result of this type of modeling, regulations could also "adapt" as markets shift and thus counter the type of "systemic" risks for which conventional risk models leave the markets unprotected. Lo has advocated the establishment of a Capital Markets Safety Board, similar to the institution that investigates airline accidents, to collect data about past and future risks that could threaten the larger financial system, which could serve as a critical foundation for adaptive-market modeling.

As brain science unravels the roots of investors' underlying behaviors, it may well find new evidence that the conception of *Homo economicus* is fundamentally flawed. The rational investor should not care whether she has $10 million and then loses $8 million or, alternatively, whether she has nothing and ends up with $2 million. In either case, the end result is the same.

But behavioral economics experiments routinely show that despite similar outcomes, people (and other primates) hate a loss more than they desire a gain, an evolutionary hand-me-down that encourages organisms to preserve food supplies or to weigh a situation carefully before risking encounters with predators.

One group that does not value perceived losses differently than gains are individuals with autism, a disorder characterized by problems with social interaction. When tested, autistics often demonstrate strict logic when balancing gains and losses, but this seeming rationality may itself denote abnormal behavior. "Adhering to logical, rational principles of ideal economic choice may be biologically unnatural," says Colin F. Camerer, a professor of behavioral economics at Caltech. Better insight into human psychology gleaned by neuroscientists holds the promise of changing forever our fundamental assumptions about the way entire economies function—and our understanding of the motivations of the individual participants therein, who buy homes or stocks and who have trouble judging whether a dollar is worth as much today as it was yesterday. ■

THORSTEIN VEBLEN suggested at the end of the 19th century that economics should be considered an evolutionary science, an inspiration for current endeavors that pursue the spirit of Veblen's idea.

THE GRANGER COLLECTION (*Veblen*)

➥ MORE TO EXPLORE

Your Money and Your Brain: How the New Science of Neuroeconomics Can Help Make You Rich. Jason Zweig. Simon & Schuster, 2007.

The Mind of the Market. Michael Shermer. Times Books/Henry Holt, 2008.

The Subprime Solution: How Today's Global Financial Crisis Happened and What to Do about It. Robert J. Shiller. Princeton University Press, 2008.

Animal Spirits: How Human Psychology Drives the Economy and Why It Matters for Global Capitalism. George A. Akerlof and Robert J. Shiller. Princeton University Press, 2009.

Nudge: Improving Decisions about Health, Wealth and Happiness. Richard H. Thaler and Cass R. Sunstein. Penguin Books, 2009.

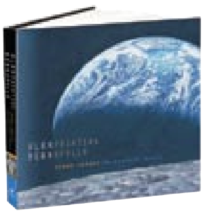
Moon Walking ▪ Becoming Human ▪ Amazing Animals

BY KATE WONG

The books highlighted below commemorate the 40th anniversary this month of the first manned landing on the moon.

➔ PAINTING APOLLO: FIRST ARTIST ON ANOTHER WORLD

by Alan Bean. Smithsonian Books, 2009 ($39.99)



Alan Bean is the only artist to have set foot on the moon. This book pairs 107 of his evocative paintings with essays from experts ranging from art critic Donald Kuspit to Apollo flight director Gene Kranz. The volume is a companion to an exhibit of Bean's work at the Smithsonian Institution's National Air and Space Museum that will run from July 16, 2009, until January 13, 2010.

➔ VOICES FROM THE MOON: APOLLO ASTRONAUTS DESCRIBE THEIR LUNAR EXPERIENCES

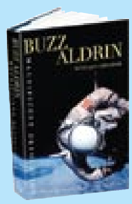
by Andrew Chaiken, with Victoria Kohl. Studio, 2009 ($29.95)

Veteran space writer Andrew Chaiken has interviewed 23 of the 24 astronauts who flew on the Apollo moon missions and chronicles their explorations in their own words. Included are 160 rarely seen photographs shot by the astronauts themselves.

EXCERPT

➔ MAGNIFICENT DESOLATION: THE LONG JOURNEY HOME FROM THE MOON

by Buzz Aldrin, with Ken Abraham. Harmony, 2009 ($27)



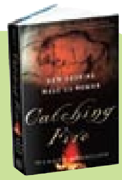
On July 20, 1969, Apollo 11 *astronauts Buzz Aldrin and Neil Armstrong became the first men to walk on the moon. The fact that their spacecraft very nearly did not make it there is one of many revelations in Aldrin's new memoir, which recounts his rise to stardom, his painful descent into alcoholism and depression, and his reemergence as a passionate advocate of human space travel.*

"… we weren't thinking about aborting; we did not want to get this close to landing on the moon and have to turn back; we were intent on fulfilling our mission. On the other hand, the alarm was ominous.… Either the computer's programs were incapable of managing all the landing data coming in to it at once, or perhaps there was a hardware problem caused by all the jostling around since we'd left Earth four days ago. Maybe something inside the computer had broken, just as might happen to a home computer. In any case, we had no time to fix it. The potential for disaster was twofold: First, maybe the computer could not give us accurate information we needed to land; or, second, if in fact we succeeded in landing, would the computer's malfunction prevent us from blasting off the moon and making our rendezvous with Mike the next day? The demands on the computer then would be even greater.

"While we grappled silently with these possibilities, we continued descending toward the moon, pushing through 27,000 feet. The large red ABORT STAGE button on the panel loomed large in front of us. If either Neil or I hit the button, the *Eagle* would instantly blast back up toward *Columbia,* and America's attempt to land on the moon would be dubbed a failure."

ALSO NOTABLE

BOOKS



- ➔ **Catching Fire: How Cooking Made Us Human** by Richard Wrangham. Basic Books, 2009 ($26.95)
- ➔ **What's Next? Dispatches on the Future of Science** edited by Max Brockman. Vintage, 2009 ($14.95)
- ➔ **Life Ascending: The Ten Great Inventions of Evolution** by Nick Lane. W. W. Norton, 2009 ($26.95)
- ➔ **You Are Here: Why We Can Find Our Way to the Moon but Get Lost in the Mall** by Colin Ellard. Doubleday, 2009 ($24.95)
- ➔ **How Sex Works: Why We Look, Smell, Taste, Feel and Act the Way We Do** by Sharon Moalem. HarperCollins, 2009 ($26.99)
- ➔ **Khubilai Khan's Lost Fleet: In Search of a Legendary Armada** by James P. Delgado. University of California Press, 2009 ($29.95)
- ➔ **The Dangerous World of Butterflies: The Startling Subculture of Criminals, Collectors and Conservationists** by Peter Laufer. Lyons Press, 2009 ($24.95)
- ➔ **Paradise Found: Nature in America at the Time of Discovery** by Steve Nicholls. University of Chicago Press, 2009 ($30)

WEB SITE

- ➔ **Photo Synthesis** (a science photography blog launched in April 2009) **http://scienceblogs.com/photosynthesis**

EXHIBIT

- ➔ **Extreme Mammals: The Biggest, Smallest and Most Amazing Mammals of All Time** May 16, 2009–January 3, 2010, at the American Museum of Natural History in New York City. The exhibit is currently scheduled to then travel to San Francisco, Cleveland and Ottawa.

D. FINNIN *American Museum of Natural History (Chinese pangolin)*

ASK THE EXPERTS

www.ScientificAmerican.com/asktheexperts

Why haven't humans evolved ***eyes in the back of the head?***

—B. Craft, Wills Point, Tex.

S. Jay Olshansky, a biodemographer at the University of Illinois at Chicago, looks into this query:

As much as we might appreciate the value of detecting predators that approach from behind—or of keeping an eye on the offspring who follow us—it is important to remember that selection is not directed toward the development or formation of anything, let alone "perfect" organs. In other words, just because some feature seems like a good idea, random mutation and selection will not necessarily fashion it.

Body parts that enable us to detect the sights, sounds, smells, tastes, temperature and tactile elements of our environment did not arise from some master plan or blueprint. Rather selection crafted body parts from available components of cells and tissues within existing forms of life, molding ancient and intermediate versions of sensory cells and organs—each elegant in its own right—like lumps of clay over aeons into the shape and form of our modern bodies. There have never been perfectly formed organs for sight or hearing—just versions that get the job done.

PHOTOILLUSTRATION BY SCIENTIFIC AMERICAN; REDCHOPSTICKS *Getty Images* (eyes); RUBBERBALL *Getty Images* (back of head)

The first light-sensitive cell most certainly arose through random mutation among the earliest multicellular creatures. This mechanism of detecting light conferred a selective advantage, however minute, to those individuals possessing these cells. The best evidence for this advantage is the fact that variations on the theme of visual acuity evolved dozens of times, independently, in various invertebrates, with at least nine variations of the eye having emerged—including the camera lens version we know so well.

Although light-sensitive cells are likely to have appeared on different parts of early forms of life, selection seems to favor those that enable creatures to detect light in the direction they are headed rather than the direction from which they came. Forward locomotion probably was a driving force for the current location of light-sensitive cells. Besides, with a simple 90-degree pivot of the head and peripheral vision, we already can see behind us without turning our bodies around. It would appear, however, that rearward vision is already present in parents and teachers—or at least it would seem so to their children and students.

Instead of ***sequestering carbon dioxide*** *to reduce its effects on global climate, why don't we split it into harmless carbon and oxygen?*

—J. Henderson, Devon, Pa.

James E. Miller, a chemical engineer at Sandia National Laboratories, breaks it down:

Splitting carbon dioxide (CO_2) into carbon and oxygen can in fact be accomplished, but there is a catch: doing so requires energy. If hydrocarbon fuels, which produce the greenhouse gas in the first place, supply that energy, thermodynamics tells us that the net result will be more CO_2 than you started with.

Consider the proposal as a chemical reaction: CO_2 plus energy yields carbon and oxygen. This formula essentially reverses coal combustion (carbon plus oxygen yields CO_2 and energy). If energy from coal were applied to drive the decomposition reaction, more CO_2 would be released than consumed, because no process is perfectly efficient.

Another option would be to harness a carbon-free energy source to drive a reaction that does not merely undo the combustion process but instead uses carbon dioxide as an input to generate useful, energy-rich products. At Sandia National Laboratories, we are working to apply concentrated sunlight to drive high-temperature thermal reactions that yield carbon monoxide, hydrogen and oxygen from CO_2 and water. Carbon monoxide and hydrogen are basic chemical building blocks that find use in producing synthetic fuels, so we call this process "sunshine to petrol." ■

HAVE A QUESTION?... *Send it to experts@SciAm.com or go to* **www.ScientificAmerican.com/asktheexperts**