RETHINKING "HOBBITS"
What They Mean for Human Evolution

THE EVERYTHING TV
Get Ready for the Wide-Screen Web

SCIENTIFIC AMERICAN

November 2009 www.ScientificAmerican.com

The Long-Lost Siblings of OUR SUN
page 24

A Plan for a Sustainable Future

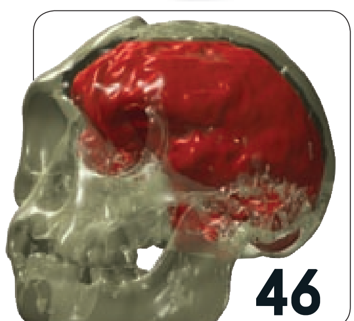
How to get all energy from wind, water and solar power by 2030

Chronic Pain
What Goes Wrong

Plus:
- The Future of Cars
- Farms in Skyscrapers

CONTENTS FEATURES

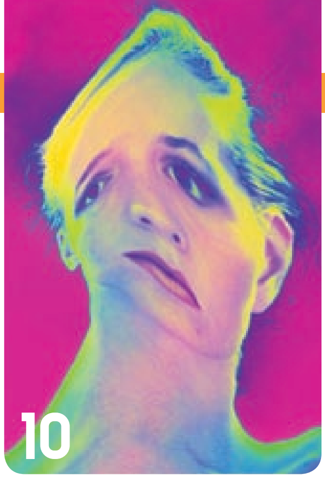
SCIENTIFIC AMERICAN November 2009 ▪ Volume 301 Number 5

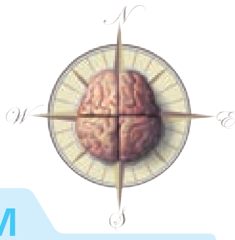


ON THE COVER

A common perception is that it is impossible to provide for all energy needs with renewable sources. But the math suggests otherwise. Image by Jean-Francois Podevin.

CONTENTS DEPARTMENTS





GO TO SCIENTIFICAMERICAN.COM

Galileo, 400 Years Later

In November 1609 Italian astronomer Galileo Galilei built a high-power telescope and began his landmark studies of the moon, part of a series of observations that forever changed our view of the heavens.

More at **www.ScientificAmerican.com/nov2009**

THE FRANKLIN INSTITUTE

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. **Individual Subscription rates:** 1 year $39.97 (USD), Canada $49.97 (USD), International $61 (USD). **Institutional Subscription rates:** Schools and Public Libraries: 1 year $69 (USD), Canada $74 (USD), International $81 (USD). Businesses and Colleges/Universities: 1 year $299 (USD), Canada $304 (USD), International $311 (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.

From the Sources

The headlines were different when the biweekly broadsheet began, but the engine of innovation behind them was the same as it is today: science. Readers of *Scientific American*'s first issue, dated August 28, 1845, must have been struck by the front-page story on "Improved Rail-Road Cars" that were "calculated to avoid atmospheric resistance." They may have marveled at the item about Morse's telegraph, which speculated: "This wonder of the age, which has for several months past been in operation between Washington and Baltimore, appears likely to come into general use through the length and breadth of the land."

Reflecting the profound changes in science and society in the past century and a half, the top stories today have changed—global warming, stem cells, and technologies for energy independence, to name a few. But science is still at their roots. Indeed, it is clearer than ever that it is not some remote endeavor that occurs in walled-off ivory towers, removed from the concerns of humankind. Far from it. Science, and the technologies that grow out of it, touches the lives of all people. And as advances have arisen, *Scientific American* has been there to explain and enlighten.

We could not do so without the generous amounts of time provided by our scientist sources and contributors. The researchers who author articles for us are at the pinnacles of their fields; more than 120 Nobel laureates are among them. The scientists spend hours explaining their research and findings to our reporters and editors. They help to check the accuracy of informational graphics, charts and tables. And they, along with our expert journalists and editors, suggest ideas for stories that deserve coverage in the pages of the magazine and online at ScientificAmerican.com. That working relationship has always been implicit in everything we do.

Continuing in that tradition of close collaboration, we have now expanded our board of advisers. At the left, you will see the names of people who have agreed, as friends of the magazine, to assist in our mission of being for you, our readers, the best source for information about science and technology advances and how they will affect our lives. The advisers give us feedback on story proposals and manuscripts from time to time. We may tap their expertise for planning. I personally hope that they will critique and challenge us as well, holding us up to the kind of scrutiny that every endeavor requires to excel.

In responding to my invitation, many of the advisers reacted with warm words about *Scientific American,* telling me how it had inspired them as readers or reminding me of its critical role in informing the public. That is a daunting level of expectation to live up to, but in those same scientists and experts we also have a powerful tool toward that end. Our goal, of course, is to better serve you, our readers. ■

MARIETTE DiCHRISTINA
acting editor in chief

ETHAN HILL (*DiChristina*); ILLUSTRATION BY MATT COLLINS

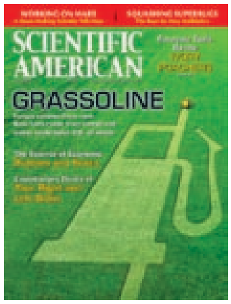
editors@SciAm.com

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

Grassoline ▪ Science and God ▪ Left and Right



JULY 2009

> **"Energy creation is important, but so is our abilityto feed the world."**
> —*Camille Florence Coers* CHARLOTTE, N.C.

Feed the World

As a retired farmer, I know that the information in "Grassoline at the Pump," by George W. Huber and Bruce E. Dale, about agricultural residues is false in a most dangerous way. There is NO extra residue from the corn harvest. Sure, you can take it away and use it to create fuel. But that residue is desperately needed right where it fell, to renew the soil. All of it and more are needed to sustain our already low organic matter levels created by years of plowing and other unsustainable agricultural practices. Soil can and does "die," and then it is unable to produce food. Energy creation is important, but so is our ability to feed the world.

Camille Florence Coers
Charlotte, N.C.

THE AUTHORS REPLY: *Biofuels researchers are striving to improve soil fertility as much as possible during biofuels production. Fortunately, there are ways to remove crop residues for use as biofuels while increasing soil fertility. For example, the organic matter can be balanced by reduced tillage practices; by double cropping, where two crop varieties are planted in succession in the same growing season; and by the use of cover crops that replenish the soil. The Dale lab Web site (www.everythingbiomass.org) details some of our work showing how such practices can provide both biofuels and fertile soil.*

Your July cover story could not be timelier as oil prices remain volatile. The types of fuels envisioned by "Grassoline" have great potential for aircraft usage. Several U.S. carriers, including Continental Airlines, have conducted successful test flights using alternative fuels, but significant hurdles remain before these can be certified for commercial use. It is critical that we support further research and development for alternative jet fuels.

James C. May
President and CEO
Air Transport Association

Burden of Proof

As an admirer of the Skeptic column, I find it unfortunate that Michael Shermer's opus 100, "I Want to Believe," contains what I believe is a serious fault. Shermer cites negative results of tests of the power of prayer to heal. What if God simply declines to cooperate with our tests of His existence? Shermer asks what existed before our universe began. Why should we assume that God did not exist before our universe or before all universes?

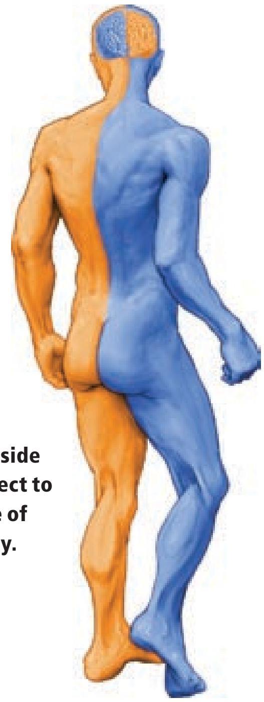
I have never seen a scientific test that can prove or disprove God's existence. In scientific terms, Shermer is correct; the null hypothesis is no argument. In religious terms, faith is everything. In my opinion, separation of church and science is as important as separation of church and state. Scientists who want to prove scientifically that God does not act in our lives play into the hands of religious spokespeople who want to prove that God controls our lives.

Roger Eiss
Ridgefield, Wash.

The Vision Thing

In "Origins of the Left and Right Brain," Peter F. MacNeilage, Lesley J. Rogers and Giorgio Vallortigara mention Rogers's experiments involving keeping a hen's eggs in darkness so the right eye is not stimulated and consequently the left hemisphere does not develop normally. In humans information from the left visual field of each eye is processed in the right hemisphere, and vice versa. Is this not the case with chickens, or does this fact cast doubt on Rogers's conclusions?

George F. Feissner
Cortland, N.Y.



NERVES from one side of the body connect to the opposite side of the brain—mostly.

ANDREW SWIFT

THE AUTHORS REPLY: *The projections from eye to brain are different in birds and humans. In birds each eye projects virtually entirely to the opposite hemisphere, whereas in humans the left side of the visual world relative to the point where the eyes are fixating projects to the right side of the eye and then to the same side of the brain, and vice versa. This difference is irrelevant to the point we made about the relative efficiency of lateralized and unlateralized bird brains. It was simply that when lateralization does not develop, unlateralized birds are less efficient at concurrent feeding and predator evasion.*

Don't Do as I Say

"The Science of Bubbles and Busts," by Gary Stix, delves into the psychology of the marketplace, which makes for an interesting article. But by focusing on the behavior of small individual investors, it completely misses the largest contributions to the bubble. Propping up real estate with artificially low interest rates and bogus appraisals, institutionalized accounting fraud within corporate America, easy rating of securities as "AAA," highly leveraged derivatives gambling, swaps in excess of target companies' net worth followed by selling those targets short, suspect trading programs such as PRIMEX, and a deliberately paralyzed regulatory community all contributed more to the fleecing of workers' 401Ks than the herd mentality. Fraudsters were merely taking advantage of those human traits.

Lars Olavson
Salt Lake City

Benoît Mandelbrot has been very vocal on the faulty assumptions that are regularly employed in economics. I contend, however, that it is actually the false belief in determinism that is at fault. And the illusion of predictability afforded by the deterministic view is every bit as potent as the money illusion.

Jonathan J. Dickau
Poughkeepsie, N.Y.

ERRATA The box "The Fat of the Matter," in "Grassoline at the Pump," states that the High Plains Bioenergy refinery is expected to turn 30 million *pounds* of lard into 30 million gallons of biodiesel every year. In fact, the plant expects to turn 30 million *gallons* of lard into the equivalent amount of biodiesel.

The caption to a photograph in the box "Responding to Surprise," in "Origins of the Left and Right Brain," identifies two birds as blue-footed boobies. Instead the birds are masked boobies or possibly the closely related Nazca boobies.

In "Working on the Railroad" [News Scan], Charles Q. Choi relied on a press release in reporting that a paper appeared in the June 1 *Environmental Science & Technology.* The paper came out in the May 15 issue.

CLARIFICATION In "New Ways to Squash Superbugs," Christopher T. Walsh and Michael A. Fischbach write that almost 20 percent of people who contract methicillin-resistant *Staphylococcus aureus* die from it. The figure refers to the invasive (systemic) form of the infection; most other cases, such as infections confined to the skin, are benign.

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.

Nutcracker Man ▪ Hookworm Target ▪ Nascent Oil Industry

Compiled by Daniel C. Schlenoff

NOVEMBER 1959

NERVE GROWTH—"No longer do physicians encourage the patient with a regenerated facial nerve to try to regain control of facial expression by training; their advice today is to inhibit all expression, to practice a 'poker face' in order to make the two sides of the face match in appearance. The outlook is equally dim for restoration of coordination in cases of severe nerve injury in other parts of the body. This changed viewpoint reflects a revision in the picture of the entire nervous system. According to the new picture, the connections necessary for normal coordination arise in embryonic development. —R. W. Sperry"

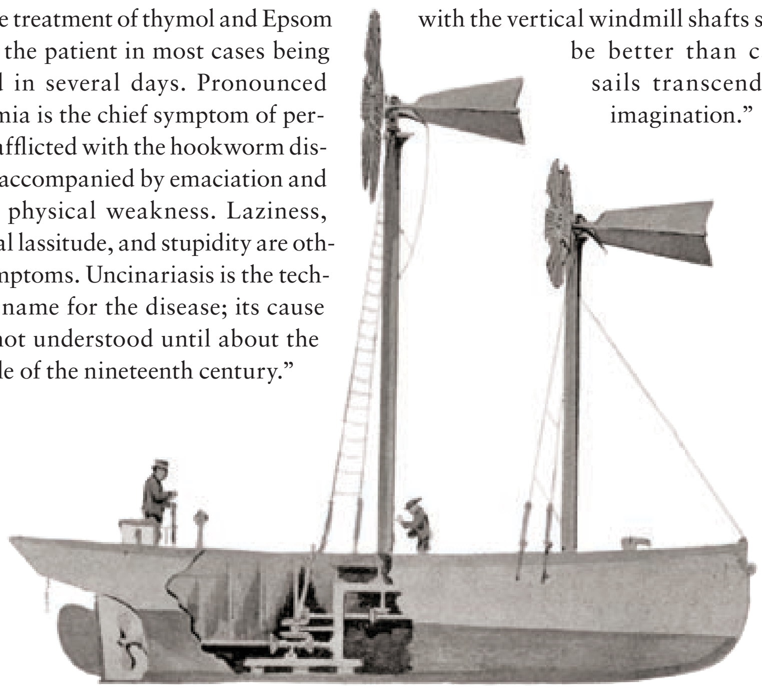
[NOTE: Roger W. Sperry won the 1981 Nobel Prize in medicine.]

FIRST TOOLMAKER—"At Olduvai Gorge in Tanganyika, L.S.B. Leakey has uncovered, almost intact, a skull that may furnish 'the connecting link between the South African near-man or ape-man—*Australopithecus* and *Paranthropus*—and true man as we know him.' Leakey believes that his find is between 600,000 and a million years old. If this estimate is supported by radioactive-dating tests soon to be undertaken at the University of California, the skull is the oldest yet discovered of the toolmaking man. The skull, that of a youth of about 18, was found with 'examples of the very primitive stone culture called Oldowan.' According to Leakey, the skull is in some respects (its large teeth and palate [which gave the fossil the nickname 'nutcracker man']) more primitive than that of *Australopithecus*, but in other respects closer to *Homo sapiens*."

NOVEMBER 1909

HOOKWORM—"The $1,000,000 given by John D. Rockefeller will go a long way toward eradicating the 'hookworm.' The worm was identified in 1903 by Dr. Charles Wardell Stiles of the Rockefeller Commission. Soil pollution is responsible for the existence and spread of the worm. It can be eliminated from the human body by a simple treatment of thymol and Epsom salts, the patient in most cases being cured in several days. Pronounced anaemia is the chief symptom of persons afflicted with the hookworm disease, accompanied by emaciation and great physical weakness. Laziness, mental lassitude, and stupidity are other symptoms. Uncinariasis is the technical name for the disease; its cause was not understood until about the middle of the nineteenth century."

WINDMILL BOAT—"A boat that is driven by windmills is certainly a mechanical curiosity [*see illustration*]. However, just why this complicated arrangement of bevel gears connecting the propeller shaft with the vertical windmill shafts should be better than canvas sails transcends our imagination."



SAILBOAT WITHOUT SAILS—an overly complex design from 1909

ICE TRADE—"Three-quarters of the ice used in France is artificial. Fifteen years ago considerable quantities of Norwegian ice were still brought to Paris via Dieppe. This commerce has now entirely ceased, and Norwegian ice is used only in cities on or near the seacoast. The annual consumption of ice for cooling purposes in France amounts to 200,000 tons, of which 150,000 tons are manufactured. Natural ice is not wholesome, as the majority of microbes survive temperatures of from –60 to –170 deg. F. At the instigation of the Paris health board, the prefect of the Seine issued an ordinance which restricted the use of natural ice to industrial establishments and admitted as 'edible' only artificial ice made either from sterilized water or water drawn from the city mains."

NOVEMBER 1859

FIRST OIL WELLS—"Recent news on Pennsylvania rock oil: in most counties a troublesome process must be undergone to extract oil from mineral substances, such as from coral and asphalt; but Pennsylvania seems to be so favorably dealt with by Dame Nature, that the very rocks distill oil into her lap. The north-western part of that State seems to contain quite a number of subterranean springs which yield a limpid oil, some of which we have examined, and quite recently there was a considerable excitement caused by the discovery of a rich oil spring while sinking a shaft to find a salt spring. The yield of the Seneca oil spring near Titusville, up to the period of the recent fire, was up to 1,600 gallons per day. This excitement is unabated."

SCIENTIFIC AMERICAN, VOL. CI, NO. 19; NOVEMBER 6, 1909

How does the Coast Guard find people lost at sea?

Arthur A. Allen, a physical oceanographer with the U.S. Coast Guard Office of Search and Rescue in Washington, D.C., answers (as told to Adam Hadhazy):

We begin by interviewing the people who reported the problem. We try to find out where and when the boaters got in trouble, when they left port, where they intended to go, and where else they may have headed—what their plan B was. We also want to know what boat they were in and what survival gear they had. We basically determine all the possible scenarios about the incident and establish what it is we are looking for.

Then, based on that information, we build a strategy with the help of search-planning software called the Search and Rescue Optimal Planning System (SAROPS), which simulates the trajectory of various kinds of objects as they drift. SAROPS is a Monte Carlo–based system that simulates units called particles. Some particles will represent people in the water; others, the boat. They can all start drifting at different times and locales. With SAROPS, we can make more than 10,000 guesses about where boaters got in trouble and when and where they might end up. The program then assesses which scenario is most probable. There is always uncertainty, of course.

To begin devising the search in SAROPS, we pick from a list of objects whose rates of drifting under various conditions have already been modeled mathematically. We have information on the drift characteristics of many different items, from people to 55-gallon oil drums to various kinds of vessels, such as life rafts, sea kayaks, sailboats, skiffs and refugee rafts. In a recent case, for instance, we knew that the lost individuals had taken off in a sports boat with a center console, so we fed that option into the model.

SAROPS also considers the effects of wind on various currents in the ocean. Say I'm sitting at my desk at 10:30 A.M. and planning a 12 to 3 P.M. helicopter flight. I need to know the wind patterns from when the accident happened all the way through this afternoon to predict where survivors may have drifted in the intervening time. For that information, we have developed a powerful tool called the Environmental Data Server, which draws on a great variety of National Oceanic and Atmospheric Administration, U.S. Navy and academic sources of wind and current data that are updated several times a day. The server translates all these data into a common format, so that we


COAST GUARD helicopter in the midst of a search

TIME & LIFE PICTURES/GETTY IMAGES

can plug the information into SAROPS.

With our best projections in hand as to where the victims might be, we generally deploy helicopters, C-130 planes, boats called cutters and motor lifeboats to try to find them. For each kind of aircraft and boat, we know the probability of detection if we take a given path. We account for such effects as white caps on waves in these predictions, because whitecaps decrease visibility. The ocean surface is a very tough place to find someone. Although we are searching many, many square miles, the ocean is very, very large, and you are very small. It is like looking for a soccer ball—a person's head above water—in an area the size of the state of Connecticut.

If search and rescuers do locate someone, then we interview that person, if feasible, and go all the way back to the beginning of the scenarios and readjust them accordingly. In any case, we continuously update our models and optimize search patterns to account for time passing and conditions changing.

Another aspect of our search-and-rescue procedures involves survival models. We have models, for instance, that calculate the net temperature a person in cold water is likely to have when heat loss to the water and heat generated by shivering are considered. This is a situation where being big and fat or muscular is helpful. People can also become dehydrated, which exacerbates hypothermia. Besides losing heat, a victim also loses water through metabolism, respiration and sweating, which comes into play in warmer waters. Other threats to life include predation and running out of food; we do not have models for those yet.

Even if weather conditions would allow a search to continue, we may call it off if our models tell us the victims have virtually no chance of still being alive. Unfortunately, despite our technology and best efforts, not everyone who is lost at sea is found. ■

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

Medicine & Health

Putting Madness in Its Place

Growing evidence points to birthplace as a risk factor for schizophrenia BY JR MINKEL

Schizophrenia hides its heritability well. Although fewer than 1 percent of the general population will be diagnosed as schizophrenic based on symptoms such as hallucination and disorganized thought, for children of a schizophrenic parent, those odds jump to about one in 10. And yet the condition's genetic underpinnings have stubbornly resisted discovery. In the latest attempt, three crack teams of investigators pooled genomic data from 8,000 schizophrenics of European ancestry but could lay claim to only a handful of weak genetic risk markers.

Analyses such as these, which appeared online July 1 in *Nature* (*Scientific American* is part of the Nature Publishing Group), have led researchers to question the value of brute-force genomics for analyzing schizophrenia. "I think we need to pause and think through the risk pathways to disease more clearly," says Dolores Malaspina, director of the social and psychiatric initiatives program at New York University Langone Medical Center. In particular, devotees of genetics might want to cede a little ground to their colleagues in epidemiology, who over the past decade have amassed a provocative, interlocking set of studies implicating urban birthplace and migrant status as persistent risk factors.

Researchers believe the potential for schizophrenia starts to emerge during early brain development, beginning in the womb. Rates tick up slightly for offspring whose mothers were infected with influenza or undernourished during pregnancy, for newborns who suffered obstetric complications such as oxygen deprivation, and for offspring born in the winter or spring.

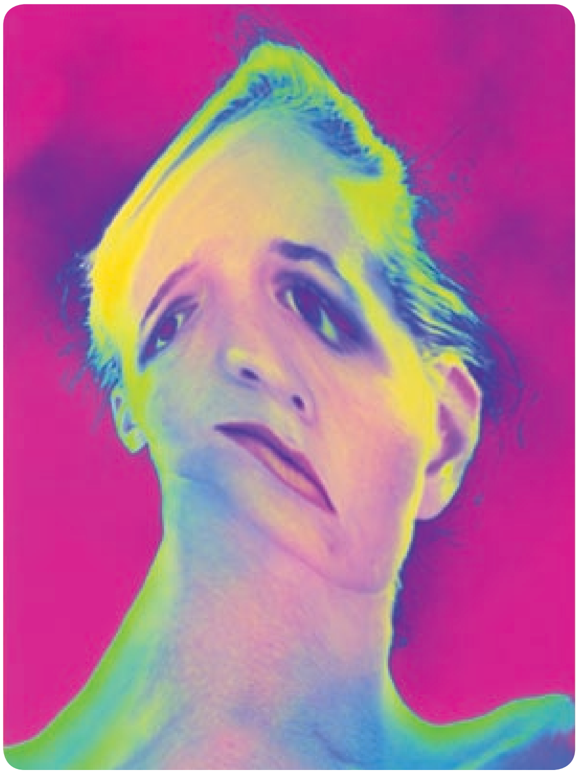
Starting in the 1990s, studies from Denmark, the Netherlands and Sweden began making the case for urban life as a distinct risk factor. In the largest of these, out of a cohort of 1.75 million Danes, being born in Copenhagen was associated with a 2.5-fold greater risk of schizophrenia than being born in rural areas. Danes who were born in smaller cities showed intermediate risk. Although the nature of the exposure remains obscure, researchers were able to narrow down its timing: Danes who lived in urban centers for the first 15 years of life had the most elevated risk.

A second wave of findings has documented that immigrants to European countries are at heightened risk of schizophrenia as compared with native-born residents. Second-generation immigrants show increased risk relative to their parents, and rates are highest among those of African heritage. In a study of three cities in the U.K., Afro-Caribbeans were nine times as likely as the general population to be treated for schizophrenia. Neighborhood composition seems to play a role. In South London epidemiologist James Kirkbride of the University of Cambridge and his colleagues at King's College London have found that in neighborhoods with higher measures of "social cohesion," such as voter turnout, the incidence of schizophrenia is proportionally lower.

Despite the consistency of the findings, epidemiologists who work in the field say scientific journals in the U.S. have shown reluctance to consider papers that explore the relation between race and schizophrenia. Hence, it was not until 2007 that Michaeline Bresnahan, Ezra Susser and their colleagues at the Columbia University Mailman School of Public Health cautiously published data from a cohort of 12,000 Californians enrolled in the Kaiser Permanente health plan, which showed that the rate of hospital admission for schizophrenia was twice as high for African-Americans as for whites, even after controlling for socioeconomic status of the parents. Because the cohort was part of the same health plan, reduced access to health services was unlikely to account for the discrepancy, Susser says.

Given that schizophrenia has no clear biological markers, skeptics may question whether diagnostic criteria have been applied rigorously across diverse cultural groups. For epidemiologists, such arguments miss the point. "The strategy is to identify important risk or protective factors within a given group," observes Dana March, a Ph.D. candidate in Susser's group.

March says her preliminary



DISTORTED VIEW: Artist's interpretation of schizophrenia, which has hereditary features that are hard to elucidate.

M. KULYK Photo Researchers, Inc.

work shows that of Kaiser cohort members born in Oakland County, those born into more densely populated neighborhoods are at twofold to threefold greater risk of schizophrenia than those born in less dense areas, irrespective of race. Residents of more run-down or overcrowded city neighborhoods could be more exposed to toxic chemicals and infections, she says, and may have less access to social capital that would blunt the effects of a predisposition to mental illness acquired early in life.

In an attractive synthesis, such neighborhood-level risk factors might impart lasting epigenetic changes—the chemical overwriting of the genome in response to environmental cues. If true, the roots of schizophrenia would lie where geography and genetics meet.

JR Minkel is based in Nashville, Tenn.

Pandemic Payoff

Legacy of the vicious 1918 flu: a tamer H1N1 virus today BY CHRISTINE SOARES

ALTHOUGH THE SWINE FLU OUTBREAK OF 2009 IS STILL IN FULL swing, this global influenza epidemic, the fourth in 100 years, is already teaching scientists valuable lessons about pandemics past, those that might have been and those that still might be. Evidence accumulated this summer indicates that the novel H1N1 swine flu virus was not entirely new to all human immune systems. Some researchers have even come to see the current outbreak as a flare-up in an ongoing pandemic era that started when the first H1N1 emerged in 1918.

As soon as the newest H1N1 virus burst onto the scene in the spring, it conspicuously assaulted the young and left the old mostly unscathed. To date, 79 percent of confirmed U.S. cases have been in people younger than 30 years and only 2 percent in people older than 65. In light of that lopsided attack pattern, investigators at the Centers for Disease Control and Prevention quickly started testing hundreds of human serum samples stored between 1880 and 2000, looking for evidence of past human experience with the novel H1N1 virus.

Data published in May showed a powerful antibody response to the new virus in a third of the samples from subjects older than 60 and in a smaller number (6 to 9 percent) of samples from younger adults. The authors theorized that exposure to post-1918 H1N1 human flu viruses had primed the oldest subjects' immune system to recognize the novel H1N1.

The CDC group procured serum samples collected from 83 adults and a handful of children who had received the vaccine against swine H1N1 that was given in 1976 to 43 million Americans. More than half of the samples from adults who received a single shot of that vaccine displayed a powerful immune response to the 2009 H1N1 virus, whereas little recognition of the new virus was seen in the serum of inoculated children, all younger than four at the time.

The discrepancy was an important clue, according to senior author Jackie Katz of the CDC's influenza division, who published those particular findings in September. The adults, who were between 25 and 60 years old in 1976, would have been exposed to H1N1 flu before 1957, the year it stopped circulating for the next two decades. "We assume that by the age of five a person would have had at least one exposure to influenza," Katz explains. That prior encounter with H1N1 seemed to be the key to a robust recognition of the 1976 vaccine virus, just as having had the 1976 vaccine seems to produce a strong response to the 2009 H1N1 virus. The very young children, in contrast, represent the responses of immune systems that have no past history with H1N1.

Katz cautions that high antibody levels in serum do not guarantee immunity from infection, but they serve as good indicators of protection when testing vaccines and are a fairly sure sign of earlier exposure to the pathogen. For people with some measure of previous immunity, a subsequent vaccine could act as a "booster shot." Indeed, trial results published in September surprised health officials by showing that a single shot of vaccine against the new H1N1 produced a strong response, even among some children older than six, hinting at broad recognition of the vaccine virus by the trial subjects' immune system.

Analyses of infection rates in modern seasonal flu epidemics suggest that with age comes a subtle buildup of immunity to flu viruses in general. Although the external viral proteins hemagglutinin and neuraminidase (the H and N that designate a flu strain) are the main targets of vaccines, the human immune system may also recognize other viral parts. The resulting responses may not prevent infection, but they may reduce symptoms to a degree that people do not even realize they are infected.

PAST VACCINATIONS and previous infection by interrelated viruses may account for the mildness of the new H1N1 swine flu.

BETTMANN CORBIS

Indeed, the seasonal flu peaks in kids and "then sort of declines with age," says Jeffery Taubenberger, a virus expert at the National Institute of Allergy and Infectious Diseases. "The elderly have the highest mortality because they often have underlying conditions," he adds, "but you find that people in their 40s and 50s get a lot less clinical flu than kids, so one possibility is that there's a slow accrual of a wide variety of flu immunity."

Taubenberger, who isolated the full 1918 pandemic virus in 1997, notes that even 20th-century seasonal strains such as the H2N2 virus that appeared in 1957 and the H3N2 pandemic strain that began circulating in 1968 are built on the chassis of the origi-

nal H1N1, as is the 2009 H1N1 virus. In effect, every human flu strain in the past 90 years has been a member of a dynasty founded by the 1918 virus, he concludes.

Those family ties are likely contributing to the relative mildness of the current pandemic. Avian flu viruses bearing H5, H7 or H9 hemagglutinins, widespread in domesticated poultry, have not yet managed to gain traction in the human population. If they did, they might produce a flu as ferocious as the one induced by the H1N1 virus in 1918, when it was truly new to people and killed at least 40 million worldwide.

Long-standing fears of that worst-case scenario engendered pandemic-planning efforts that are paying off today. They also prompted the 1976 vaccination campaign, which has been called a fiasco for the adverse events that accompanied the mass inoculations against a pandemic that never materialized. But even that brush with a version of H1N1, it seems, is paying an unexpected dividend now.

Shelling Out for Eggs

A decision to pay for eggs for stem cell studies sparks debate BY KATHERINE HARMON

Paying a woman for her eggs to use in stem cell research has been a bioethical no-no for years. But this past June, New York State decided to allow just that, becoming the first state to permit public money to be used in this way. The decision, which allows payment of up to $10,000, will likely jump-start donations—and thereby research. Many bioethicists, however, worry that the financial incentive could exploit women and compromise their health.

Ethical issues surround egg donation because the process is not without risk. It requires a series of hormonal stimulation injections as well as an invasive procedure to retrieve the eggs. The long-term health effects and risks of complication are not well known. A woman who provides eggs for research is "assuming unknown risk for unknown benefits," says Debra Mathews, a pediatrician at Johns Hopkins University. The lingering unknowns prompted the National Academy of Science to issue in 2005 nonbinding guidelines to prohibit payment (but allow direct reimbursement for expenses), as a means to protect underprivileged women in particular.

Various research teams have observed those guidelines and tried to recruit women to donate their eggs for free. But these altruism-dependent attempts failed to find any takers. Instead scientists have primarily relied on eggs left over from in vitro fertilization (IVF) procedures. The secondhand supply, however, is small, and some question the quality of these eggs. Many may have been rejected for implantation because they were subpar to begin with. Storage and transport can also be problematic; as Mathews explains, "We're not good at freezing and thawing eggs yet."

The lack of quality eggs, along with an 11-year, $600-million directive from the New York State legislature to further stem cell research, persuaded New York's Empire State Stem Cell Board to allow payment to women for egg donation. The board governs publicly funded stem cell work and is in charge of overseeing grants for related research.

Proponents of the board's decision note that payment for similar services is not unheard of. "We pay people to participate in research that has zero benefit to them [but carries] risk all the time, and we trust people to make that decision for themselves," says Mathews, who is also a member of the Johns Hopkins Berman Institute of Bioethics. Other bioethicists, including Insoo Hyun of the Case Western Reserve University School of Medicine, echo that sentiment. Hyun wrote a 2006 commentary piece in *Nature* in which he argued that just like others who volunteer for research, women should be paid to donate eggs for stem cell studies. (*Scientific American* is part of the Nature Publishing Group.) Moreover, research donations do not have to be seen as something different from fertility donations, points out Ronald Green, director of the Ethics Institute at Dartmouth College. "In a sense, infertility is a disease, so women are helping [other] women overcome a disease," just as they could be helping to find treatments for additional diseases.

FOR SALE: Human egg cells.

M. I. WALKER *Photo Researchers, Inc.*

Opponents worry that offering up large sums of money for egg donation may be too good an offer for some women to pass up—especially those who might not qualify for paid fertility donation, which screen women based on intellectual and physical attributes. The financial incentives might also drive some to overdonate, Green notes. He says that some "serial egg donors" have donated some 20-odd times, risking their own health and reproductive abilities. He recommends some kind of national register to keep track of donations and ensure that women give no more than a few times.

The move to pay for eggs destined for research may also reflect changing mores. In 1978 the birth of Louise Brown, the world's first baby to be conceived by IVF, set off much debate about the control of embryos, women's reproductive rights and ominous *Brave New World* correlations. Yet test-tube babies became common, and since 1978 more than three million have been born worldwide. Except when it is used to select and screen embryos for certain characteristics, the procedure brings along little ethical hand-wringing today—even with its hefty financial rewards to female donors.

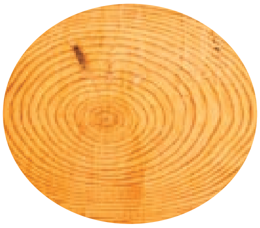
The debate might eventually be a moot point, as researchers

continue to make convincing headway with induced pluripotent cells, which seem to have all the properties of embryonic stem cells but which are created from adult cells. But both Mathews and Green acknowledge that creating a functional egg from skin or other cells still looks to be a long way off. "Generally the science moves pretty slowly and incrementally," Mathews says. "It's always difficult to predict, but if we could predict it, it wouldn't be science."

Energy & Environment

Still Hotter Than Ever

A new analysis creates a better "hockey stick" of rising temperatures BY DAVID APPELL



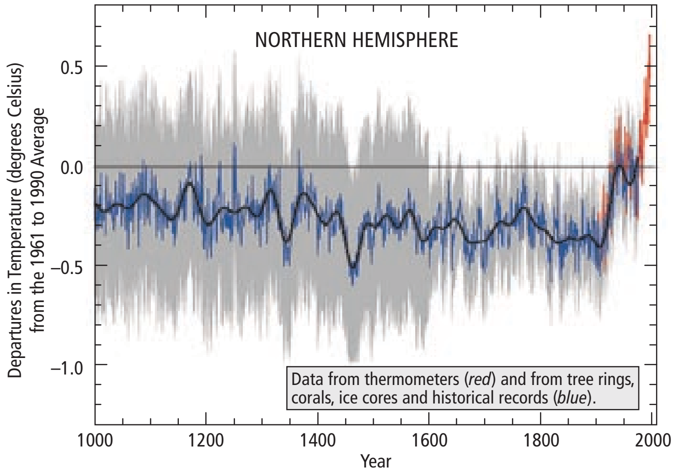
THE "HOCKEY STICK" GRAPH HAS BEEN BOTH A LINCHPIN AND target in the climate change debate. As a plot of average Northern Hemisphere temperature from two millennia ago to the present, it stays relatively flat until the 20th century, when it rises up sharply, like the blade of an upturned hockey stick. Warming skeptics have long decried how the temperatures were inferred, but a new reconstruction of the past 600 years, using an entirely different method, finds similar results and may help remove lingering doubts.

The hockey stick came to life in 1998 thanks to the work of Michael Mann, now at Pennsylvania State University, and his colleagues (and many other climate scientists who subsequently refined the graph). Reconstructing historical temperatures is difficult: investigators must combine information from tree rings, coral drilling, pinecones, ice cores and other natural records and then convert them to temperatures at specific times and places in the past. Such proxies for temperature can be sparse or incomplete, both geographically and through time. Mann's method used the overlap, where it exists, of recent proxy data and instrument data (such as from thermometers) to estimate relations between them. It calculates earlier temperatures using a mathematical extrapolation technique [see "Behind the Hockey Stick," by David Appell, Insights; SCIENTIFIC AMERICAN, March 2005].

Martin Tingley of Harvard University calls his approach "much easier to handle and to propagate uncertainties"—that is, to calculate how the inherent limitations of the data affect the temperature calculated at any given time. The method can easily be modified to answer other questions in climate science, such as about precipitation and drought, and can even make projections into the future given rates of buildup of carbon dioxide in the atmosphere. Written with his thesis adviser Peter Huybers, his paper was submitted to the *Journal of Climate*.

Tingley and Huybers's new method, which Mann describes as "promising," makes the assumption that nearby proxies can be simply related, or "chained," either to data from nearby places or to data from the same place taken a few years before or after. For example, temperatures at neighboring places as measured in the last century seem correlated in a way that drops off approximately exponentially, with a "half-distance" (akin to the concept of half-life) of about 4,000 kilometers.

Tingley assumes a simple, linear relation between the proxy data values and the true temperature. This relation is then determined from proxy data and (where they exist) instrument data, using a methodology known as Bayesian statistics. Huybers explains that with Bayesian descriptions, "we attempt to estimate how probable certain temperatures were in the past given the sets of observations available to us."



GRAPHIC VIEW: "Hockey stick" plot of the variation in temperature, sometimes inferred from natural records such as tree rings (*above*), shows a 20th-century warming spike.

The sheer amount of computation, however, is daunting, involving heavy matrix algebra. Initial values for proxies and temperatures (where they have a known overlap) are input, and the methodology works backward to refine the relations at other times. To determine past temperatures, Tingley typically had to manipulate about one million matrices, each consisting of 1,296 columns and 1,296 rows.

Focusing on the past 600 years of proxy data between 45 and 85 degrees north latitude, Tingley's initial results, presented at a conference earlier this year, find that the 1990s were the warmest decade of the period and that 1995 was the warmest year. (The El Niño year 1998 was the warmest year for North America and Greenland but not for northern Eurasia.) He also found that the 20th century had the largest rate of warming of any century and that the 1600s had the largest rate of change overall (and larger than previous reconstructions), albeit in the cooling

TOM GRILL *Getty Images (tree rings)*; SOURCE: INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE *(graph)*

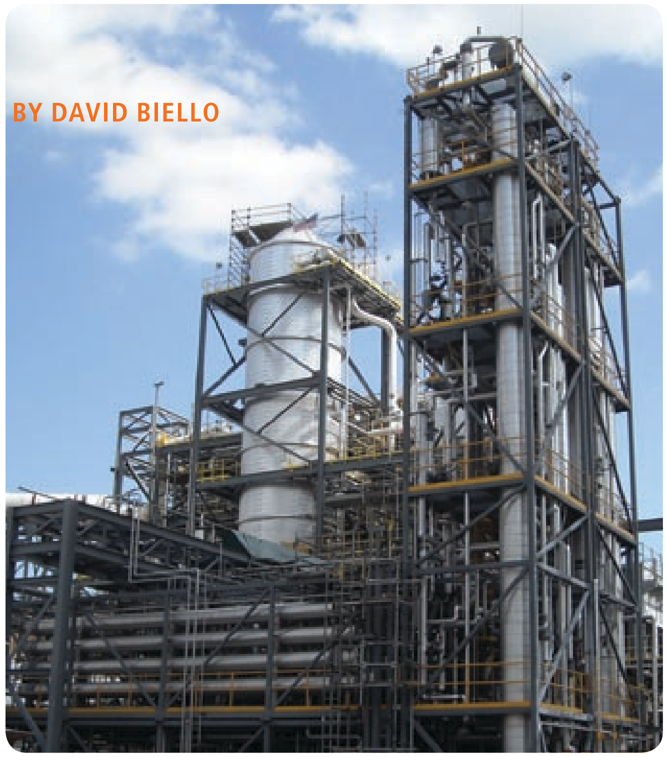
direction thanks to the so-called Little Ice Age.

Qualitatively, Tingley's result resembles the same basic hockey-stick shape as previous reconstructions, except that it has more variability in the past. Perhaps more important, his analysis suggests that a similar treatment of all available proxy data in the Northern Hemisphere in the past two millennia should produce a statistically superior hockey-stick result. Tingley, now a postdoctoral student at the Statistical and Applied Mathematical Sciences Institute in Research Triangle Park, N.C., plans to extend his method to examine the history of droughts in the southwestern U.S., as well as temperatures over wider areas and times.

David Appell, based in St. Helens, Ore., writes frequently about climate issues.

Burying Climate Change

Efforts begin to sequester carbon dioxide from power plants BY DAVID BIELLO



CARBON CAPTURE UNIT **at the Mountaineer power plant near New Haven, W.Va., uses chilled ammonia scrubbers to grab carbon dioxide from coal burning for subsequent storage underground.**

COURTESY OF AMERICAN ELECTRIC POWER

Over the next five years at least half a million tons of carbon dioxide will be injected into rock deep underneath the Mountaineer power plant near New Haven, W.Va. Although that is less than 0.00001 percent of global emissions of the greenhouse gas and less than 2 percent of the plant's own CO_2 output, the sequestration, which began in September, marks the first commercial demonstration of the only available technological fix for the carbon problem of coal-fired power plants, one that many coal facilities around the world hope to emulate.

Coal accounts for roughly 50 percent of the electricity generated in the U.S. and as much as 75 percent of the electricity generated by American Electric Power, says Nick Akins, executive vice president of generation at the utility, which owns Mountaineer. The plant can pump out 1,300 megawatts of electricity, making it one of the single largest coal-fired power plants in the U.S. and a leading source of CO_2 emissions. (The top emitters of global-warming pollution—China and the U.S.—burn nearly four billion tons of the dirty black rock a year.)

As a result, everyone from coal companies to environmental groups have identified carbon capture and storage, or CCS, as critical in enabling significant and rapid cuts in greenhouse gases. But there have been only a handful of demonstrations of the technology to capture the gas and, outside of using CO_2 to pump more oil out of the ground, even fewer attempts to store it.

To capture CO_2 from its smokestacks, Mountaineer will employ so-called chilled ammonia technology, which relies on ammonium carbonate chemistry to pull CO_2 out of the exhaust gases. (The other two basic capture technologies either burn coal in pure oxygen to produce a CO_2-rich emissions stream or siphon off the CO_2 made during the gasification of coal.)

Mountaineer takes the captured CO_2 and compresses it to at least 2,000 pounds per square inch, liquefying it and pumping it about 8,000 feet down into the ground. At that depth, the liquid CO_2 flows through the porous rock formations, adhering to the tiny spaces, slowly spreading out over time and, ultimately, chemically reacting with rock or brine. "We're not going into a salt cavern; we're not going into an underground river. We're going into microscopic holes," explains geologist Susan Hovorka of the University of Texas at Austin, referring to CCS in general. "Add it up, and it's a large volume." In fact, the Department of Energy estimates that the U.S. has the geologic room for 3.9 trillion tons of CO_2 underground, more than enough for the 3.2 billion tons that is emitted every year by large industrial sources.

The two geologic formations below Mountaineer are the Rose Run Sandstone and Copper Ridge Dolomite, which run underneath layers of relatively impermeable rock that will keep the CO_2 trapped. "Part of our project is to kind of take those through their paces and get an idea of their acceptance of CO_2," says Gary Spitznogle, a CCS engineering manager at American Electric Power. After all, a similar effort in Ohio revealed that formations there stored less CO_2 than expected. The company will monitor the CO_2 via three specially drilled wells, in addition to the two wells for pumping the CO_2 down in the first place.

The process of capturing and storing carbon dioxide may be simple chemistry and geology, but it has significant industrial costs. American Electric Power alone will pay $73 million for just the capture technology at Mountaineer and has asked for $334

million in federal stimulus—half the total cost, the company says—to scale up the project to nab roughly 20 percent of the plant's emissions in future years.

Despite the steep price of CCS, Mountaineer is not alone. In the U.S., utilities are planning multibillion-dollar power plants that will incorporate CCS; by 2011 Alabama Power may outsequester Mountaineer and bury 150,000 tons of CO_2 from its Plant Barry in the Citronelle Oil Field. Abroad, China has several test facilities, and in Iceland an international consortium of researchers will pump CO_2 into underground basalt where it will react to form a carbonate mineral.

But even if CO_2 is permanently locked away in rock, other environmental problems surrounding coal remain. The technology does nothing to remedy the impacts of coal mining, particularly mountaintop removal, or residual toxic fly ash, among other issues. Moreover, although the Environmental Protection Agency has begun to craft rules to regulate the CO_2-injection wells, it is still unclear who owns the pore space resource as well as who assumes liability in the event of an accident, such as a sudden, geyserlike release of the gas.

Nevertheless, given looming regulation on emissions, utilities are anticipating extensive CCS installation in just the next few decades. "Our first full scale would be around 2015, and by 2025 we would have a pretty considerable amount constructed on large coal units," Spitznogle says.

That means one thing: higher electricity prices. In May 2007 the Department of Energy estimated that capturing 90 percent of the CO_2 with amine scrubbers would make electricity at a cost of more than $114 per megawatt-hour, compared with just $63 per megawatt-hour without CO_2 capture. For the consumer, the extra cost would amount to about $0.04 per kilowatt-hour—a necessary price, perhaps, for less of the warming gas in the atmosphere.

Easy Go, Easy Come

What spoils quantum entanglement can also restore it

BY GEORGE MUSSER

WOULDN'T IT BE NICE TO BE AN ELECTRON? THEN YOU, TOO, COULD TAKE ADVANTAGE of the marvels of quantum mechanics, such as being in two places at once—very handy for juggling the competing demands of modern life. Alas, physicists have long spoiled the fantasy by saying that quantum mechanics applies only to microscopic things.

Yet that is a myth. In the modern view that has gained traction in the past decade, you don't see quantum effects in everyday life not because you are big, per se, but because those effects are camouflaged by their own sheer complexity. They are there if you know how to look, and physicists have been realizing that they show up in the macroscopic world more than they thought. "The standard arguments may be too pessimistic as to the survival of quantum effects," says Nobel laureate physicist Anthony Leggett of the University of Illinois.

In the most distinctive such effect, called entanglement, two electrons establish a kind of telepathic link that transcends space and time. And not just electrons: you, too, retain a quantum bond with your loved ones that endures no matter how far apart you may be. If that sounds hopelessly romantic, the flip side is that particles are incurably promiscuous, hooking up with every other particle they meet. So you also retain a quantum bond with every loser who ever bumped into you on the street and every air molecule that ever brushed your skin. The bonds you want are overwhelmed by those you don't. Entanglement thus foils entanglement, a process known as decoherence.

To preserve entanglement for use in, say, quantum computers, physicists use all the tactics of a parent trying to control a teenager's love life, such as isolating the particle from its environment or chaperoning the particle and undoing any undesired entanglements. And they typically have about as much success. But if you can't beat the environment, why not use it? "The environment can act more positively," says physicist Vlatko Vedral of the National University of Singapore and the University of Oxford.

One approach has been suggested by Jianming Cai and Hans J. Briegel of the Institute for Quantum Optics and Quantum Information in Innsbruck, Austria, and Sandu Popescu of the University of Bristol in England. Suppose you have a V-shaped molecule you can open and close like a pair of tweezers. When the molecule closes, two electrons on the tips become entangled. If you just keep them there, the electrons will eventually decohere as particles from the environment bombard them, and you will have no way to reestablish entanglement.

The answer is to open up the molecule and, counterintuitively, leave the electrons even more exposed to the environment. In this position, decoherence resets the electrons back to a default, lowest-energy state. Then you can close the molecule again and reestablish entanglement afresh. If you open and close fast enough, it is as though the entanglement was never broken. The team calls this "dynamic entanglement," as opposed to the static kind that endures as long as you can isolate the system from bombardment. The oscillation notwithstanding, the researchers say dynamic entanglement can do everything the static sort can.

A different approach uses a group of particles that act collectively as one. Because of the group's internal dynamics, it can have multiple default, or equilibrium, states, corresponding to different but comparably energetic arrangements. A quantum computer can store data in these equilibrium states rather than in individual particles. This approach, first proposed a decade ago by Alexei Kitaev, then at the Landau Institute for Theoretical Physics in Russia, is known as passive error correction, because it does not require physicists to supervise the particles actively. If the group deviates from equilibrium, the

environment does the work of pushing it back. Only when the temperature is high enough does the environment disrupt rather than stabilize the group. “The environment both adds errors as well as removes them,” says Michał Horodecki of the University of Gdańsk in Poland.

The trick is to make sure it removes faster than it adds. Horodecki, Héctor Bombín of the Massachusetts Institute of Technology and their colleagues recently devised such a setup, but for geometric reasons it would require higher spatial dimensions. Several other recent papers make do with ordinary space; instead of relying on higher geometry, they thread the system with force fields to tilt the balance toward error removal. But these systems may not be able to perform general computation.

This work suggests that, contrary to conventional wisdom, entanglement can persist in large, warm systems—including living organisms. “This opens the door to the possibility that entanglement could play a role in, or be a resource for, biological systems,” says Mohan Sarovar of the University of California, Berkeley, who recently found that entanglement may aid photosynthesis [see “Chlorophyll Power,” by Michael Moyer; Scientific American, September 2009]. In the magnetism-sensitive molecule that birds may use as compasses, Vedral, Elisabeth Rieper, also at Singapore, and their colleagues discovered that electrons manage to remain entangled 10 to 100 times longer than the standard formulas predict. So although we may not be electrons, living things can still take advantage of their wonderful quantumness.

Monopole Position

A sighting, of sorts, of separate north-south magnetic poles BY JOHN MATSON

Magnets are remarkable exemplars of fairness—every north pole is invariably accompanied by a counterbalancing south pole. Split a magnet in two, and the result is a pair of magnets, each with its own north and south. For decades researchers have sought the exception—namely, the monopole, magnetism’s answer to the electron, which carries electric charge. It would be a free-floating carrier of either magnetic north or magnetic south—a yin unbound from its yang.

Two research groups—one led by Tom Fennell of the Laue-Langevin Institute in Grenoble, France, and the other by Jonathan Morris of the Helmholtz Center Berlin for Materials and Energy—have offered experimental evidence that such monopoles do in fact exist, albeit not as electronlike elementary particles. Rather they exist as unbound components inside so-called spin ices. These man-made materials take their name from their similarity to water ice in terms of their magnetic nature. The French-led team experimented with holmium titanate and the Germany-based group, dysprosium titanate.

Claudio Castelnovo, a physicist at the University of Oxford on the Morris team, explains that the compounds offer a peculiar combination of order and freedom that facilitates the dissociation of the poles. Internally, the tiny magnetic components in spin ices arrange themselves head to tail in strings, like chains of bar magnets stretching across a table in different directions. In a very cold, clean sample, those strings form closed loops.

But then the physicists gave a little kick to the system by increasing the temperature. The rise excited the components and introduced defects in these chains, Castelnovo explains—in the bar-magnet analogue, one of the mag-nets is flipped, breaking the head-to-tail continuity.

On either side of that defect, then, are two norths at one end and two souths at the other. Those concentrations of charge can float free along the string, acting as—voilà—magnetic monopoles, which the teams conclude they saw based on the way neutrons scattered off the spin ices. “The beauty of spin ice is that the remaining degree of disorder in this low-temperature phase makes these two points independent of each other, apart from the fact that they attract each other from a magnetic point of view because one is a north and one is a south,” Castelnovo points out. “But they are otherwise free to move around.”

FIELD DAY: Magnets always have a north pole and a south pole. Physicists have managed to separate them in unusual materials called spin ices, enabling each pole to move freely.

CORDELIA MOLLOY *Photo Researchers, Inc.*

Of course, this method of synthesizing monopoles cannot bring a north into existence without also generating a south—the key is their dissociation. “They always have to come in pairs,” Castelnovo says, “but they don’t have to be anywhere specifically in relation to each other.”

But Kimball Milton, a University of Oklahoma physicist who reviewed the status of monopole searches in 2006, is not convinced. A genuine magnetic monopole “implies to me it’s a point particle, and it’s not” in the studies, Milton says. “It’s an effective excitation that at some level looks like a monopole, but it’s not really fundamentally a monopole.”

He also asserts that it is “completely wrong” to describe, as the researchers do, the chain of magnetism within spin ices as a Dirac string, a hypothetical invisible tether with a monopole at its end that was envisioned in the 1930s by English physicist Paul Dirac. The magnetic strings in the spin ice do not fit the Dirac definition, Kimball feels, because they are, in fact, observable and merely carry flux between two opposing so-called monopoles. “Real monopoles, if they existed, would be isolated, and the string would run off to infinity,” he insists.

“I’m not trying to put down the experiment or the work in any way,” says Milton, noting that the findings are important in condensed-matter physics. But “they’re not important from a fundamental point of view.”

Technology

Sewage's Cash Crop

How flushing the toilet can lead to phosphorus for fertilizers BY KATHERINE TWEED

WASTEWATER WONDER: **Ostara's Crystal Green, a slow-release fertilizer, incorporates phosphorus retrieved from sewage streams.**

COURTESY OF CLEANWATERSERVICES.ORG

Tucked away in Oregon's Willamette Valley, three massive metal cones could help address the world's dwindling supply of phosphorus, the crucial ingredient of fertilizers that has made modern agriculture possible. The cones make consistently high-quality, slow-release fertilizer pellets from phosphorus recovered at the Durham Advance Wastewater Treatment Facility, less than 10 miles from downtown Portland. By generating about one ton of pellets every day, they are changing the view that such recycling could not be done efficiently. Ostara, the firm that makes the reactors and sells the pellets as Crystal Green, thinks that Durham is one of hundreds of facilities that could use the technology.

Humans excrete some 3.3 million tons of phosphorus annually. In fact, phosphorus from domestic sewage, in addition to fertilizer runoff, has traditionally been a nuisance, because it triggers blooms of algae that deplete local waters of oxygen. In some wastewater plants the element can also bind with ammonia and magnesium to form a mineral called struvite, which keeps phosphorus out of waterways but clogs pipes at the facilities. The growing recognition that cheap supplies of phosphorus will grow scarce in the coming decades has led some nations to consider conservation. Sweden has mandated that 60 percent of phosphate be recycled from wastewater by 2015. In 2008 China slapped a 135 percent export tariff on phosphate.

These pressures have made struvite a hot topic in sewage circles. Japan has been recycling struvite for a decade, but the cost-effectiveness and quality of the pellets varied, according to Don Mavinic, professor of civil engineering at the University of British Columbia (U.B.C.) and co-inventor of Ostara's technology. "There's always been a problem of struvite removal," Mavinic says. "I wanted to build a better mousetrap."

To take up phosphates and nitrogen, many sewage facilities use bacteria, which settle down after ingesting the nutrients and are ultimately removed with the sludge. But dying bacteria rupture and release a little of the phosphate back into the wastewater, potentially leading to struvites.

Mavinic got interested in the struvite problem because of the maintenance issue at the plants, but ultimately a grant to find local nutrient sources jump-started the work. U.B.C.'s "mousetrap" pumps treated effluent and magnesium chloride into a 24-foot-tall reactor, where the cone shape acts to create essentially a turbulent thundercloud, tossing around the particles until they form pellets. Mavinic is now fine-tuning the system so that reactors can be sized to make a specific pellet grade for local industries.

In Oregon interest comes primarily from nurseries, where farmers have traditionally bought polymer-coated slow-release fertilizer. Wilco, a farmer-owned co-op about 30 miles from the Durham plant, has been selling Crystal Green since the reactors went online in May. "Having a local source of high-quality slow-release sustainable fertilizer is a great thing," says Jeff Freeman, a regional sales manager at Wilco. "It's something our customers are looking for, and the product has performed outstandingly."

Because of the demand for such fertilizer, the estimated payback of the investment is about five years. Mark Poling, wastewater treatment director at Durham, says it could be faster, because the reactors are functioning better than expected.

The company has sent prototype reactors to wastewater plants in Israel, the U.K. and various cities in the U.S. Shanghai was expected to get a delivery this fall. But Ostara says it is looking to corner the U.S. market first, where the Environmental Protection Agency has been pushing states to more heavily regulate nutrient pollution, including phosphate in sewage effluent.

Wastewater represents a ripe, but small, low-hanging fruit for phosphate recycling, according to experts. It holds only a small fraction of recoverable phosphate, and not all facilities create struvite. "Unfortunately, the phosphorus in human waste is only about 10 percent" of mined phosphate rock, explains David A. Vaccari, director of civil, environmental and ocean engineering at the Stevens Institute of Technology. "Even if you got 8 percent, it would be one piece of the puzzle. And it's one part we should do, but it's only a slim fraction of what we need."

Approximately 80 percent of mined phosphate rock used in food production does not even lead to consumed food. The element is leached from farm fields and lost in food manufacturing. So although U.B.C. has already commercialized one small corner of the market, it has its eyes on a larger prize: agricultural waste.

The scientists have a pilot effort using the same basic reactor to process nutrients from dairy and pig waste while removing methane. They're not alone. Researchers are scaling up a variety of projects to minimize livestock's carbon and water footprint: the nutrient load of one cow is equal to about 25 people. "The domestic wastewater industry has enormous potential," Mavinic says, "but boy, oh, boy, it's nothing compared with the agricultural industry."

Katherine Tweed is based in New York City.

Keys to Copenhagen

The U.S. can lead the world to a historic emissions agreement by committing to its own sweeping energy transformation

BY THE EDITORS

In a few short weeks, world leaders will assemble in Copenhagen for the much anticipated United Nations Climate Change Conference. Their goal: to draft an agreement that will limit global warming, chiefly by reducing greenhouse gas emissions. As the 12-day meeting gets closer, the chorus from jaded pundits and politicians gets louder: "It can't be done."

Nonsense. The naysayers have two reasonable concerns. One: Countries will never agree on limits because they are out to protect their own interests, which differ. Two: Even if they reach an agreement, it will never hold because it will raise energy prices, which people will resist. Fortunately, both worries can be resolved.

The path to overcoming the diplomatic hurdle is daunting but clear. Leaders from China, Japan, the European Union and elsewhere have stated plainly that the U.S. must prove it will clean up its own backyard before they will agree to international limits. In June the U.S. House of Representatives passed the American Clean Energy and Security Act, also known as the Waxman-Markey bill. Originally a dictate to reduce fossil-fuel use, the bill was weakened as it was hammered out, so much so that some leading supporters claimed it no longer did enough. A bill that the Senate took up in September, introduced by John Kerry and Barbara Boxer, aimed to fix many of the problems.

But the important point is that Congress is finally acting. In his influential blog ClimateProgress.org, policy expert Joseph Romm wrote: "The original Clean Air Act didn't do enough. And the 1987 Montréal protocol ... would not have saved the ozone layer. But [each of these measures] began a process and established a framework that ... could be strengthened over time." Commitment in Congress and President Barack Obama's personal attendance in Copenhagen may be enough to prompt nations to seek a meaningful agreement.

As politicians and diplomats begin to clear the first hurdle, scientists and engineers have been dismantling the second: the claim that an aggressive goal can never be achieved economically because developed countries will never cut back on their lavish existence and developing nations will never slow their rise in living standards. In fact, reducing emissions does not mean cutting lifestyles. It does not mean punitive strategies. Rather it means replacing fossil fuels with clean, sustainable energy sources.

This notion is not naive ideology; it is hard-headed pragmatism. As Mark Z. Jacobson and Mark A. Delucchi show in their article "A Path to Sustainable Energy by 2030," starting on page 58, wind, water and solar resources could supply 100 percent of the world's energy by 2030. Step by step, the authors prove that more than enough sustainable energy exists, that the needed technologies are available now, and that they can produce power at the same or lower cost than traditional fossil and nuclear plants.

Wind power is already as cheap as coal power. Other renewables are not, but incremental improvements are steadily making them competitive. The key is to subsidize renewable sources, for a limited time, in a way that brings down their per-watt cost and hastens the day when they will be competitive on their own. Not all subsidies do that; in the U.S., a requirement that each state obtain a certain fraction of its energy from renewable sources, or a nationally mandated price for renewable power, could encourage builders to put up wind turbines in windless valleys and solar panels in sunless climes. A better approach would be a national renewable portfolio standard and state-by-state incentives to encourage renewables where they would be most productive, such as wind in North Dakota and solar in Arizona. An alternative is direct cash grants to boost installation of renewables, which the Department of Energy and other agencies have begun to make through the federal stimulus plan.

At the same time, the price of fossil fuels must be raised to account for their environmental damage. And existing subsidies for fossil energy should be eliminated. Some fossil-energy companies are shifting to renewables, but on the whole, the coal, natural gas and oil industries will not give up the government largesse meekly, so politicians will have to resist intense lobbying from them.

Now that the world has a plan to transform the global energy system economically, leaders in Copenhagen can commit to cutting emissions without diminishing their citizens' standard of living. The missing piece is leadership, which the U.S. can provide if Congress acts definitively. ■

ILLUSTRATION BY MATT COLLINS

A Clunker of a Climate Policy

The recent car-upgrade program is an example of how not to address CO_2 reduction prudently

BY JEFFREY D. SACHS

The Cash for Clunkers program offers a cautionary tale for the future of climate change control. The federal program paid individuals up to $4,500 to replace their "clunker" automobiles with new, higher-mileage vehicles. Part of the purpose was to give a lift to the ailing auto industry. Another part, at least it was claimed, was to mitigate climate change by getting old high-carbon-emissions vehicles off the road. But billions of dollars were spent quickly without clear answers on what we were getting for our money.

The broad principle of climate change mitigation is to reduce greenhouse gas emissions, including carbon dioxide (CO_2) from the combustion of fossil fuels, to target levels at the minimum net cost to society. There are many ways to reduce emissions: drive more efficient or electrically powered vehicles; produce electricity with renewable energy sources; capture CO_2 from power plants and store it geologically; restart the nuclear power sector; weatherproof homes to reduce energy for heating and cooling.... The list is long, with different time horizons, costs and uncertainties.

Clearly, not every method of reducing emissions makes equal sense. Consulting firm McKinsey & Company has recently published estimates of the abatement costs of various technologies (www.mckinsey.com/clientservice/ccsi/greenhousegas.asp). Highly efficient lighting, appliances and vehicles, along with better insulation and other technologies, can save more in energy costs during their lifetime than the upfront capital for installing them: they are *better than free* to society. Other options—notably, renewable energy sources, forest conservation programs and carbon capture and storage—tend to come in below $60 per ton of avoided CO_2 emissions.

Some carbon-reduction ideas are so expensive they should play no part in the policy mix. Yet because lobbyists overrun our legislative processes, every climate idea will have its corporate backers, and lots of terrible ideas will no doubt be advocated.

Let's make a rough calculation of how much mitigation per dollar the Cash for Clunkers program really achieved. The typical trade-in was reportedly a 15.8-miles-per-gallon (mpg) vehicle for a 24.9-mpg vehicle. Assuming that the average vehicle is driven around 12,000 miles a year, the clunker annually required 759 gallons of gasoline compared with the new vehicle's 482 gallons. Because each gallon of burned gasoline produces 8.8 kilograms of CO_2, every car saving 278 gallons a year signifies a reduction of 2.4 metric tons of CO_2 a year.

Assuming that a clunker would have been driven on average another five years, the annual budget cost per car is $900 ($4,500 divided over five years, and ignoring the interest factor for simplicity). If we value gasoline pretax at roughly $2 per gallon, we are saving around $555 a year. The net annual cost of the CO_2 reduction is therefore $345, or $141 per ton of CO_2. Note that a full life-cycle analysis would also account for the CO_2 emitted in the production of the new car, which would modestly diminish the net CO_2 reduction and modestly *raise* its net unit cost.

This crude calculation is subject to many refinements but shows that Cash for Clunkers represented a very high cost per ton of CO_2 avoided. Countless ways to reduce CO_2 emissions are less expensive than smashing up autos five years before their natural demise.

We will blunder badly and repeatedly in climate change control unless we put some transparent control systems in place. We should rely heavily on price signals rather than one-by-one subsidized programs, except for the subsidies needed to bring new technologies such as electric vehicles to the commercial phase. An economywide tax on each ton of CO_2 emissions, programmed to rise gradually over time at an appropriate social discount rate, would induce the marketplace to take actions that are less expensive per ton than the tax and to leave behind measures such as Cash for Clunkers or corn to ethanol. A carbon tax would be far more effective in this regard than the cumbersome cap-and-trade system proposed by the House of Representatives.

We'll need to spend trillions of dollars over time to save the planet from climate change. All the more reason not to let lobbyists make a financial game out of this deadly serious effort. ■

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

An extended version of this essay is available at **www.ScientificAmerican.com/nov2009**

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

Will E.T. Look Like Us?

Evolution helps us imagine what aliens might be like

BY MICHAEL SHERMER

What are the odds that intelligent, technically advanced aliens would look anything like the ones in films, with an emaciated torso and limbs, spindly fingers and a bulbous, bald head with large, almond-shaped eyes? What are the odds that they would even be humanoid? In a YouTube video, produced by Josh Timonen of the Richard Dawkins Foundation for Reason and Science, I argue that the chances are close to zero (www.youtube.com/watch?v=JKAXrmkx12g). Richard Dawkins himself made this interesting observation in a private communication after viewing it:

> I would agree with [Shermer] in betting against aliens being bipedal primates, and I think the point is worth making, but I think he greatly overestimates the odds against. [University of Cambridge paleontologist] Simon Conway Morris, whose authority is not to be dismissed, thinks it positively likely that aliens would be, in effect, bipedal primates. [Harvard University biologist] Ed Wilson gave at least some time to the speculation that, if it had not been for the end-Cretaceous catastrophe, dinosaurs might have produced something like the attached [referring to paleontologist Dale A. Russell's illustrated evolutionary projection of how a bipedal dinosaur might have evolved into a reptilian humanoid].

I replied to Dawkins that if something like a smart, technological, bipedal humanoid has a certain level of inevitability because of how evolution unfolds, then it would have happened more than once here. In his 2001 book *Nonzero: The Logic of Human Destiny,* Robert Wright argues that our existence precludes other terrestrial intelligences of our level from arising. But Neandertals were as close as one can get to a counterfactual experiment: they had hundreds of thousands of years to themselves in Europe without our interference and showed nothing like the technological and cultural progress of the modern humans who displaced them. Dawkins's rejoinder to me is enlightening:

> But you are leaping from one extreme to the other. In the film vignette, you implied a quite staggering rarity, so rare that you don't expect two humanoid life-forms in the entire universe. Now you are … pointing out, correctly, that a certain inevitability would predict that humanoids should have evolved more than once on Earth! So, yes, we can say that humanoids are *fairly* improbable, but not necessarily all *that* improbable! Anything approaching "a certain inevitability" would mean millions or even billions of humanoid life-forms in the universe, simply because the number of available planets is so huge. Now, my guess is intermediate between your two extremes … I suspect that humanoids are not so very rare as to justify the statistical superlatives that you permitted yourself in the vignette.

Good point. But of the 60 to 80 phyla of animals, only one, the chordates, led to intelligence, and only the vertebrates actually developed it. Of all the vertebrates, only mammals evolved brains big enough for higher intelligence. And of the 24 orders of mammals only one—ours, the primates—has technological intelligence. As the late Harvard evolutionary biologist Ernst Mayr concluded: "Nothing demonstrates the improbability of the origin of high intelligence better than the millions of phyletic lineages that failed to achieve it." In fact, Mayr calculated that even though there have evolved perhaps as many as 50 billion species on Earth, "only one of these achieved the kind of intelligence needed to establish a civilization."

The late astronomer Carl Sagan, in a Planetary Society debate with Mayr (*Bioastronomy News,* Vol. 7, No. 4, 1995), noted that technologically communicating species "may live on the land or in the sea or air. They may have unimaginable chemistries, shapes, sizes, colors, appendages and opinions. We are not requiring that they follow the particular route that led to the evolution of humans. There may be many different evolutionary pathways, each unlikely, but the sum of the number of pathways to intelligence may nevertheless be quite substantial."

Thus, the probability of intelligent life evolving elsewhere in the cosmos may be very high even while the odds of it being humanoid may be very low. I strongly suspect that we are blinded by Protagoras' bias ("Man is the measure of all things") when we project ourselves into the alien Other. ■

Michael Shermer is publisher of Skeptic *magazine (www.skeptic.com) and author of* Why Darwin Matters.

PHOTOGRAPH BY BRAD SWONETZ; ILLUSTRATION BY MATT COLLINS, AFTER AN ILLUSTRATION BY DALE A. RUSSELL IN *RECONSTRUCTIONS OF THE SMALL CRETACEOUS THEROPOD STENONYCHOSAURUS INEQUALIS AND A HYPOTHETICAL DINOSAUROID,* BY D. A. RUSSELL AND R. SÉGUIN, NATIONAL MUSEUMS OF CANADA, NATIONAL MUSEUM OF NATURAL SCIENCES, 1982

How Women Can Save the Planet

Empowering young women through education will help reduce overpopulation in areas that cannot support it and avoid extremism in the children they raise

BY LAWRENCE M. KRAUSS

At six billion plus today, the earth's human population will reach more than nine billion by 2050, according to estimates. If this many people consume energy at the current rate in the developed world, the planet will need more than double the amount of power it consumes today. But energy is just one issue that humankind will have to tackle to create a sustainable future. The root cause of the looming energy problem—and the key to easing environmental, economic and religious tensions while improving public health—is to address the unending, and unequal, growth of the human population. And the one proven way to reduce fertility rates is to empower young women by educating them.

High fertility rates in areas of the developing world that can least cope put tremendous pressure on freshwater and sanitation needs and fuel economic and religious tensions. In response, these countries ramp up their energy production via the only means available to them based on their resources—means that tend to either pollute the environment or contribute to global warming.

For instance, India, Somalia and Sudan have large positive birth rates. The latter two countries struggle to provide adequate food and water resources, and India increased its energy consumption by almost 50 percent between 1992 and 2001. (In contrast, Japan, France and Russia have negative birth rates, and the U.S. is slightly positive.) Indeed, a United Nations study published in August reported that Asia currently does not have the means to feed the extra 1.5 billion expected to live on that continent by 2050.

Empirical work indicating that providing schooling for women and girls will address these problems includes study after study showing that educated women have fewer children, are wealthier and are less likely to accept fundamentalist extremism. If we want a safer world, we should consider the utility of spending dollars on educating young people as an alternative to troops and weapons.

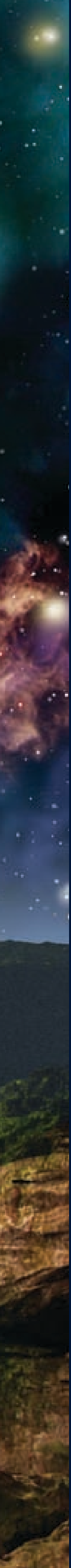
In Afghanistan and Pakistan today the Taliban have created thousands of *madrassas,* where children from poor families with no access to education can receive food and what passes for learning (but what is in fact quite the opposite). At the same time, they restrict access to education for women. In Gaza vulnerable young people are recruited early on to religious extremist training camps. I am not naive enough to believe that building schools and providing access to safe and secure environments for learning will alone solve our problems—we will need to create economic opportunities as well.

Moreover, in paternalistic societies where women have few rights, effecting change will be an uphill battle. For example, the government we are now supporting with troops and infrastructure in Afghanistan has recently passed legislation that food can be withheld from women who do not have sex with their husband and that women cannot go out of the house without their husband's permission. In countries of this sort that now receive significant support from us, we need to make the empowerment of women a higher priority. As difficult and slow as the process might be, the education of women in such countries is a necessary first step to giving them the opportunity and motivation to begin to control their own destiny.

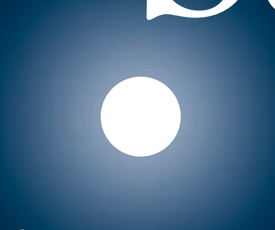
The long-term goal of reducing poverty, religious fundamentalism and overpopulation will be impossible to reach until we free women around the world from the enslavement of ignorance. More fundamental is the fact that education is a basic human right that has been systematically denied too many women for too long. ■

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

PHOTOGRAPH BY JOHN BOSWELL; ILLUSTRATION BY MATT COLLINS



The Long-Lost Siblings of the Sun



The sun was born in a family of stars. What became of them?

By Simon F. Portegies Zwart

People have often sought solitude in the starry night sky, and it is an appropriate place for that. The night is dark because, in cosmic terms, our sun and its family of planets are very lonely. Neighboring stars are so far away that they look like mere specks of light, and more distant stars blur together into a feeble glow. Our fastest space probes will take tens of thousands of years to cross the distance to the nearest star. Space isolates us like an ocean around a tiny island.

Yet not all stars are so secluded. About one in 10 belongs to a cluster, a swarm of hundreds to tens of thousands of stars with a diameter of a few light-years. In fact, most stars are born in such groups, which generally disperse over billions of years, their stars blending in with the rest of the galaxy. What about our sun? Might it, too, have come into existence in a star cluster? If so, our location in the galaxy was not always so desolate. It only became so as the cluster dispersed in due time.

HAD YOU BEEN ALIVE at the dawn of the solar system, the night sky would have been bright enough to read by. A thousand or so stars formed within a few light-years from the same interstellar cloud the sun did.

RON MILLER

KEY CONCEPTS

- The sun is a solitary star, and astronomers have traditionally assumed it formed as such. Yet most stars are born in clusters, and scraps of evidence from meteorites and from the arrangement of comets suggest that our sun was no exception.
- Its birth cluster could have contained 1,500 to 3,500 stars within a diameter of 10 light-years—a big, unhappy family whose larger members bullied the small fry and which broke up not long after our solar system came into being.
- Although the sun's siblings have long since dispersed across the galaxy, observatories such as the European GAIA satellite will be able to look for them. Their properties might fill in the gaps of the solar system's deep history. *—The Editors*

[THE AUTHOR]

Simon F. Portegies Zwart is a professor of computational astrophysics at Leiden Observatory of Leiden University in the Netherlands. His specialties are high-performance computing and gravitational stellar dynamics, in particular the ecology of dense stellar systems. In his spare time, he translates Egyptian hieroglyphs and brews beer.

A growing body of evidence suggests just that. Although conventional wisdom once held that the sun was an only child, many astronomers now think it was one of 1,000 or so siblings all born at nearly the same time. Had we been around at the dawn of the solar system, space would not have seemed nearly so empty. The night sky would have been filled with bright stars, several at least as bright as the full moon. Some would have been visible even by day. Looking up would have hurt our eyes.

The cluster into which the sun was probably born is now long gone. I have pieced together the available data and made an educated guess as to what it might have looked like. From these inferred properties, I have calculated the possible trajectories of former cluster members through the galaxy to figure out where they might have ended up. Although they have scattered and mixed in with millions of unrelated stars, they should be identifiable with the European Space Agency's Global Astrometric Interferometer for Astrophysics (GAIA) satellite, scheduled for launch in 2011. Their orbits and sunlike compositions should give them away. Reuniting with our long-lost stellar siblings should enable astronomers to reconstruct the conditions under which a shapeless cloud of gas and dust gave rise to our solar system.

Memories of Our Birth

The most compelling evidence that the sun has close siblings emerged in 2003, when Shogo Tachibana, now at the University of Tokyo, and Gary R. Huss, now at the University of Hawaii at Manoa, analyzed two primitive meteorites that are thought to be almost pristine leftovers of solar system formation. They detected nickel 60, the product of the radioactive decay of iron 60, in chemical compounds where, by rights, iron should be found. It seems a game of chemical bait and switch took place in the meteorite: the compounds originally formed from iron, the iron metamorphosed into nickel, and the nickel was locked in place, forever an interloper.

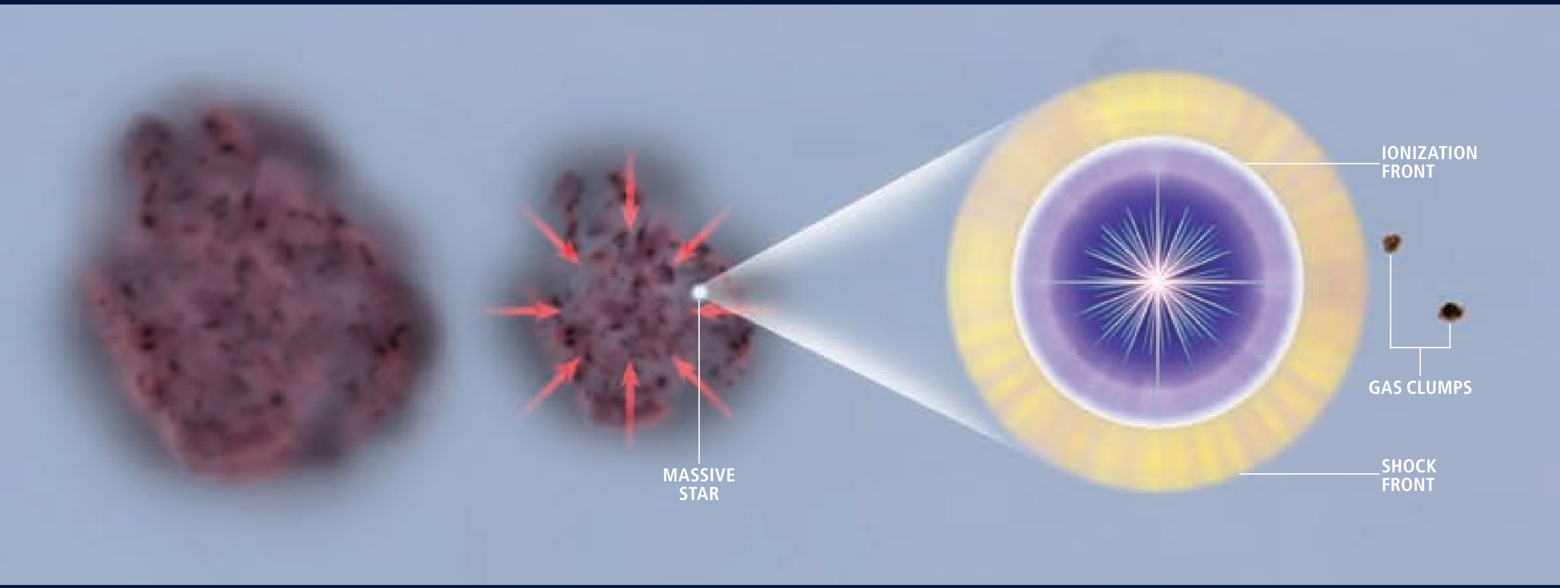
The iron 60 had to be synthesized, injected into the solar system and incorporated into meteorites within its radioactive half-life, which, according to a new estimate published this past August, is 2.6 million years. That is a cosmic eyeblink. Therefore, the iron had to come from very nearby—and the likeliest source is a supernova

COURTESY OF MEREI PORTEGIES ZWART-MASSEE (*Portegies Zwart*); DON DIXON (*illustrations*)

[SOLAR PREHISTORY]

THE BIRTH OF THE SUN'S CLUSTER

Based on observations of star clusters and the inferred properties of the cluster into which the sun was born, J. Jeff Hester and Steven J. Desch of Arizona State University and their colleagues have reconstructed the events leading up to the formation of the sun.



A giant cloud of molecular gas accumulates and begins to collapse under its own weight.

One or more massive stars form in the densest regions of the cloud.

Each massive star pours out ultraviolet radiation, ionizing the surrounding gas and driving out a shock front. The shock expands at a few kilometers per second.

STAR CLUSTER R136, located in a region known as the Tarantula Nebula, is similar to (but much denser than) the cluster into which the sun was born.

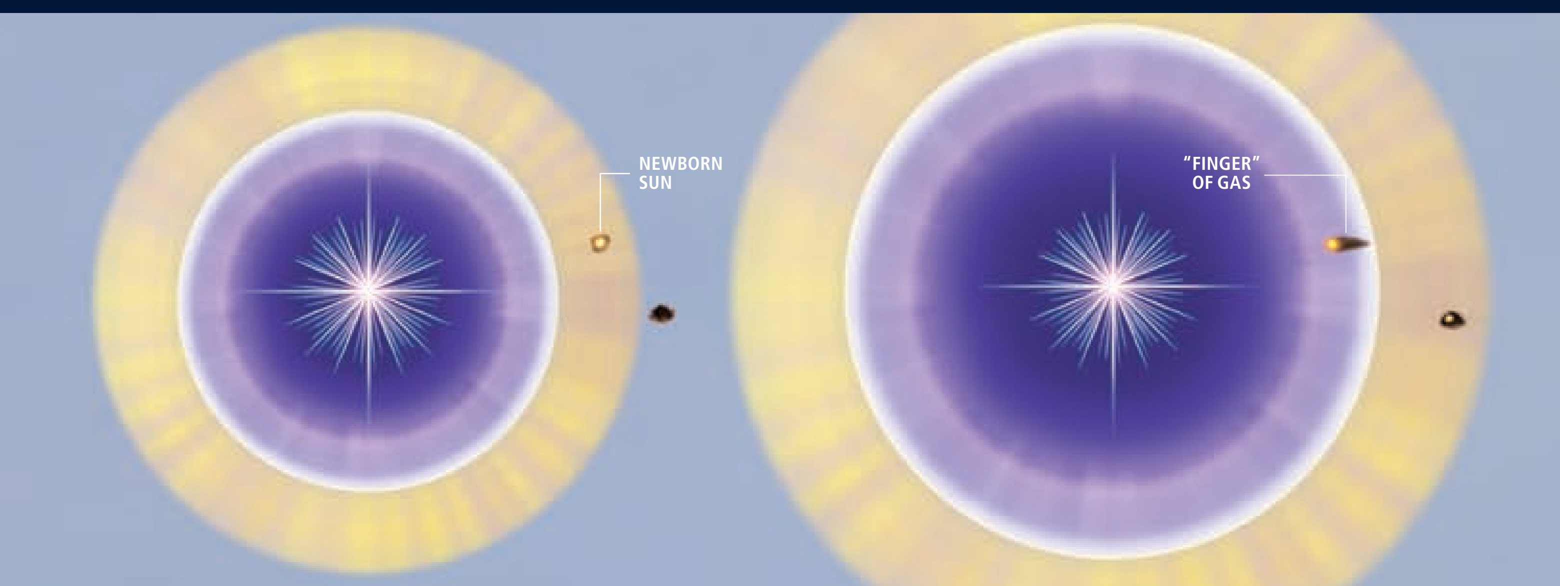
NOLAN WALBORN *Space Telescope Science Institute/NASA,* JESÚS MAÍZ APELLÁNIZ *Institute of Astronomy of Andalucía* AND RODOLFO BARBÁ *University of La Serena*

explosion. Based on this and other isotopic measurements, Leslie Looney of the University of Illinois and his co-workers argued in 2006 that a supernova went off within a distance of five light-years when the sun was scarcely 1.8 million years old. The supernova might have been as close as 0.07 light-year. (The new half-life estimate will change these values, but not substantially.)

If the sun had been as secluded as it is today, the location and timing of the supernova would be quite a coincidence. Was a massive star simply passing by when it decided to blow up? No other supernova has ever gone off at such close range; if it had, it would probably have wiped out life on Earth. A much more plausible explanation is that the newborn sun and the exploding star were fellow members of a cluster. With stars packed so tightly together, a close supernova would not have been so improbable.

The Starry Clusters Bright

The idea that the sun originated in a star cluster is at odds with the classical view of clusters that is still common in textbooks. Astronomers have traditionally classified clusters into two types: so-called galactic, or open, clusters and globular clusters. The former are young, sparsely populated and located primarily in or near the plane of our galaxy. The prototypical example is Praesepe, also known as the Beehive cluster or as M44. It was one of the first objects at which Galileo pointed his telescope 400 years ago, in



Within a few million years the shock front reaches nearby gas clumps and compresses them. They collapse and form stars, including our sun.

Some 100,000 years later the ionization front hits the newborn sun and starts to boil off loose circumsolar gas. A gaseous finger may connect the system to the molecular cloud.

NOT AN ONLY CHILD

Several lines of evidence suggest that the sun was born in a cluster:

- Ancient meteorites contain the decay products of short-lived radionuclides such as iron 60 and aluminum 26. The source of the isotopes (probably a supernova) must have been very nearby, indicating that the early sun was not alone.
- The sun's levels of heavy elements are higher than its location in the galaxy would otherwise indicate—suggesting that it was topped up with debris from a nearby supernova.
- Uranus and Neptune are much smaller than Jupiter and Saturn. One reason might be that the radiation of a nearby star boiled off their outer layers. Planets closer to the sun avoided this fate because residual interplanetary gas shielded them.

1609. What looked like a splotch of light revealed itself as an array of stars—up to 350 of them, all born about 700 million years ago.

In contrast, globular clusters are very old, densely populated and located all around the galaxy, not just in a plane. The first was discovered in 1746 by Italian astronomer Giovanni Maraldi and is now known as M15. It contains about a million stars with an age of about 12 billion years.

The trouble is that neither category fits the sun. Its advanced age of 4.6 billion years suggests it should have been born in a globular cluster, yet its location in the galactic disk points to a galactic cluster. In the past two decades, however, we have realized that not all clusters fall neatly into one of these two classical types [see "The Unexpected Youth of Globular Clusters," by Stephen E. Zepf and Keith M. Ashman; Scientific American, October 2003].

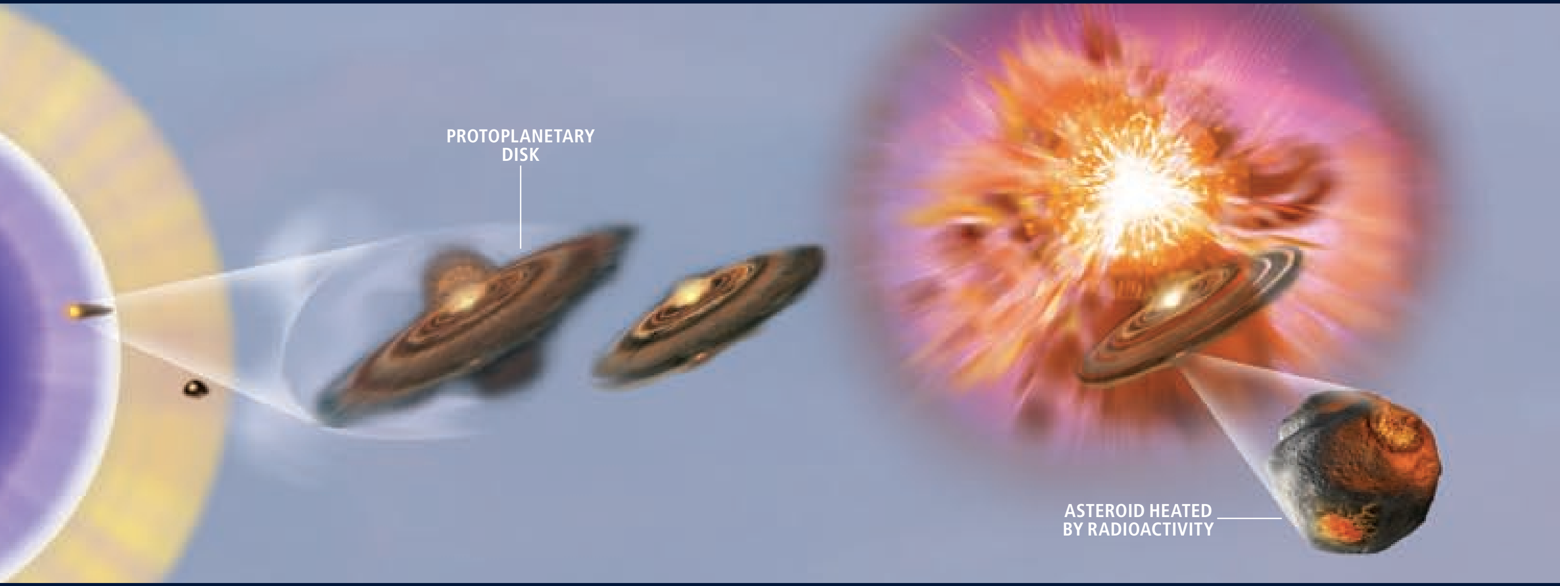
What changed our minds was the star cluster R136, which is located in one of the Milky Way's small satellite galaxies, the Large Magellanic Cloud. First spotted in 1960, R136 was initially thought to be a single, giant star 2,000 times as massive as the sun and 100 million times as bright. But in 1985 Gerd Weigelt and Gerhard Baier, both then at the University of Erlangen-Nürnberg in Germany, used new high-resolution imaging techniques to show that R136 is actually a cluster of about 10,000 stars a few million years old. It is as dense as a globular but as young as a galactic cluster. With characteristics of both types, R136 was the missing link between them. Since then, observers have found several clusters like R136 in our galaxy. Other galaxies such as the Antennae contain hundreds if not thousands of them.

The discovery that stars continue to form in clusters so dense they could be mistaken for a single star was astonishing. It led to considerable consternation among theorists. On the one hand, we were relieved, because we had not been able to explain R136 as a single superstar. On the other hand, we had to reconsider everything we thought we knew about star clusters. We now think that all stars, including the sun, are born in tight clusters such as R136. A cluster forms out of a single interstellar gas cloud and, over time, evolves into either a galactic or globular cluster depending on its mass and environment.

[TIMELINE CONTINUED]

THE DEATH OF THE SUN'S CLUSTER

The sun's birth cluster eventually disperses, but not before helping to shape the solar system. Radiation from other stars acts like a cookie cutter to set the size of the system; a nearby supernova salts the growing planets with radioactive isotopes; and the gravity of a passing star scrambles comets' orbits.



DON DIXON

Within 10,000 years the loose gas boils off entirely. The sun's protoplanetary disk is then directly exposed to ultraviolet radiation.

Over the next 10,000 years or so, this radiation erodes the disk beyond about 50 astronomical units (AU) in radius.

About two million years later the massive star blows up and rains debris onto the solar system, including freshly created radioisotopes. These are incorporated into planetary building blocks and power early geologic activity.

Dreams from Our Stellar Fathers

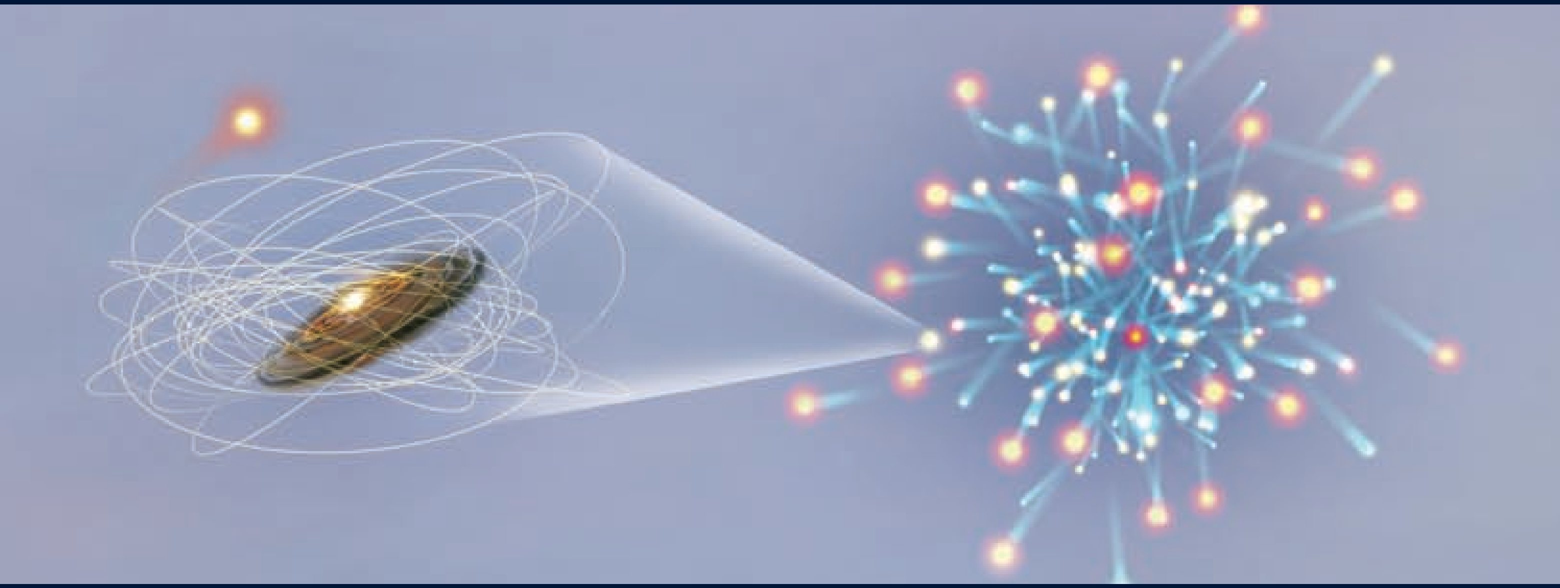
The members of a cluster span a range of masses, with a few heavy stars and a multitude of lightweight ones. The least massive, with a tenth the mass of the sun, are the most common, and for every factor of 10 increase in mass, the abundance of stars drops by about a factor of 20.

Thus, for each star of 15 to 25 solar masses—the size of the one that went supernova near the newborn sun—a cluster contains some 1,500 lesser stars. This number sets the minimum mass of the sun's birth cluster. The maximum mass is set by the fact that the larger a cluster is, the longer it takes for massive stars to settle toward the center, where they have the greatest likelihood of affecting their smaller brethren. Based on my simulations, the cluster probably contained fewer than about 3,500 stars.

A star of 15 to 25 solar masses lives for six million to 12 million years before blowing up, so it must have formed about this long before the sun did. In other clusters, such as the famous Trapezium cluster in the Orion Nebula, astronomers have found that massive stars are usually the first to form, with sunlike stars arising several million years later.

A cluster of the inferred mass was too flimsy to evolve into a globular cluster. Instead it dispersed after 100 million to 200 million years. The massive stars at its center shed gas in stellar winds (similar to but much more intense than the solar wind) and eventually exploded, reducing the density of material in the cluster and thereby weakening its gravitational field. Consequently, the cluster expanded and might have fallen apart. Even if it survived this early outgassing, interactions among stars and the tidal forces exerted by the rest of the galaxy drove its slow dissolution.

Before the cluster disintegrated, stars were so densely packed that one could easily have passed through the solar system. A stellar close encounter would have pulled planets, comets and asteroids from their original circular, planar orbits into highly elliptical and inclined orbits. Many comets beyond a distance of 50 astronomical units (AU), past the orbit of Pluto, have highly skewed orbits. The internal dynamics of the solar system seem incapable of accounting for these peculiar orbits; the bodies are beyond the gravitational influence even of Jupiter. The most likely explanation is that they were stirred



Sometime within the next 100 million years or so, another star in the cluster passes a few thousand AU from the sun, stirring up comets on the outskirts of the solar system and setting them on inclined orbits.

Its gravity weakened by the self-destruction of its most massive members, the cluster disperses in about 100 million to 200 million years. The sun and other cluster members slowly drift apart.

What is puzzling is that the sun's orbit, traced back in time, suggests our solar system was born farther out in the galaxy than it is now.

up by a star passing 1,000 AU away. The planets, though, have very regular orbits, indicating that no stellar intruder ever came within 100 AU of the sun.

From these facts, I have estimated the dimensions of the cluster. For another star in the cluster to pass 1,000 AU away with reasonable probability over the cluster lifetime, the cluster had to be less then 10 light-years in diameter. Conversely, for a star not to come within 100 AU, the cluster had to be greater than three light-years in diameter. In short, the sun's birth cluster looked like R136 but much less dense, so that stars were far enough apart not to interfere with planet formation.

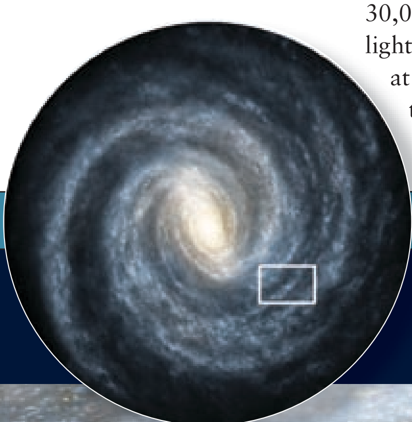
Solar Genealogy

Theorists can go further and ask where exactly in the galaxy the birth cluster was located. The solar system revolves around the galactic center in an almost circular orbit, more or less in the disk. At the moment, we are located about 30,000 light-years from the center and about 15 light-years above the plane of the disk, orbiting at a speed of 234 kilometers per second. At this rate, the sun has done 27 circuits since its formation. Its orbit is not a closed loop but a somewhat more complicated shape determined by the gravitational field of the galaxy, which astronomers infer from the motion of stars and interstellar gas clouds.

Assuming, provisionally, that the gravitational field has not changed over the past 4.6 billion years, I have projected the orbit backward in time and deduced that the sun was born 33,000 light-years from the center and 200 light-years above the galactic plane. What makes this position puzzling is that the outer reaches of the galaxy are poorer in heavy elements than the inner parts. The most distant regions may lack enough material to make planets, let alone life [see "Refuges for Life in a Hostile Universe," by Guillermo Gonzalez, Donald Brownlee and Peter D. Ward; Scientific American, October 2001]. Although the sun's putative birthplace is not quite so impoverished, it is still poorer in heavy elements than the sun is. Based purely on the sun's heavy-element composition, astronomers would have expected it to form 9,000 light-years closer to the center.

Maybe the supernova that seeded meteorites with iron 60 also enriched the sun with heavy

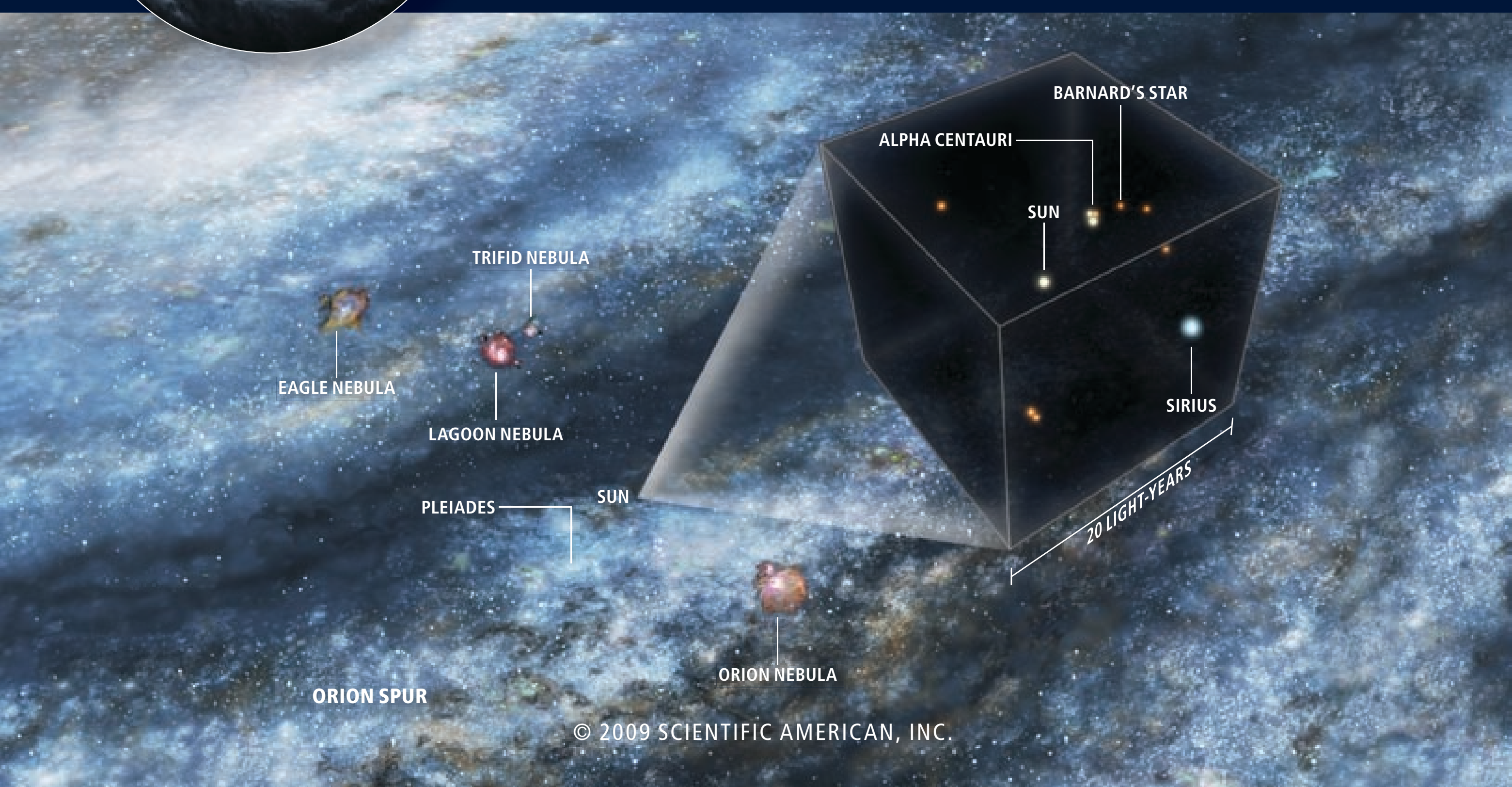
DON DIXON



[GEOGRAPHY OF THE GALAXY]

MEET THE NEIGHBORS

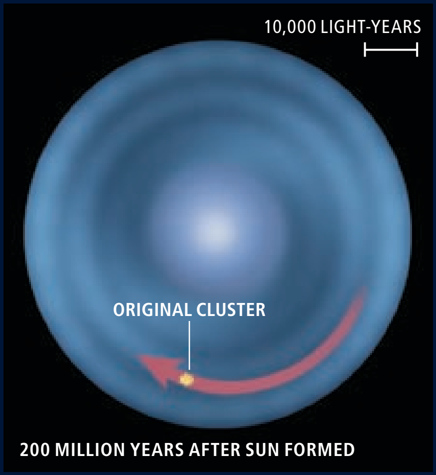
The sun currently lies about 30,000 light-years from the center of the Milky Way galaxy. Astronomers know of only 11 other stars within 10 light-years of the sun. Before the sun's cluster dispersed, the same volume held more than 1,000 stars.



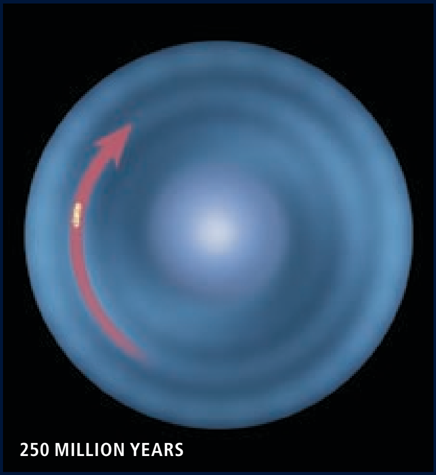
[CLUSTER DISPERSAL]

FAMILY BREAKUP

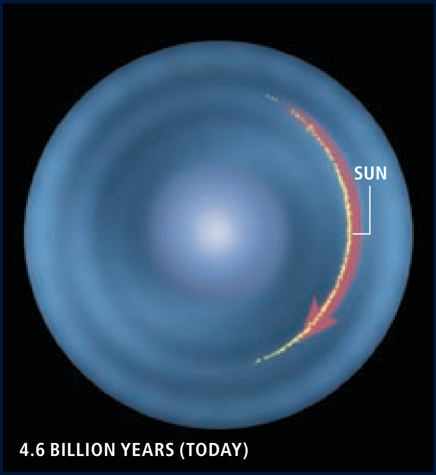
By tracking the likely orbits of the sun's siblings as they dispersed, theorists can estimate where they ended up, so that observers can search for them. The discovery of even one would help reconstruct the origin of the solar system.



The sun and its siblings move apart at a few kilometers per second, while continuing to orbit the galaxy's center at more than 200 kilometers per second.



After doing a fourth of an orbit around the galactic center, the stars have spread out only 100 or so light-years.



After making 27 full orbits, the stars form a stream tens of thousands of light-years long. A few percent of them still lie within 300 light-years of the sun.

elements. Or maybe my orbital calculation went astray because the gravitational field of the galaxy has changed or because the sun's orbital path was diverted slightly by the gravity of nearby stars or gas clouds. In that case, the sun was born closer to the center than I estimated, and its composition is not so anomalous.

The sun's ex-family members, too, should be orbiting around the galactic center at more than 200 kilometers per second. Yet their relative velocity, which is determined by their mutual gravitational forces in the original cluster, is only a few kilometers per second. Like clumps of cars on a highway, they stick together even though they are no longer bound to one another gravitationally. The original swarm has spread into an arc only very gradually. After 27 orbits, it should stretch about halfway around the galaxy.

My calculations suggest that about 50 of the sun's brothers and sisters should still be within 300 light-years of our current location and that about 400 stars are within 3,000 light-years. Depending on the stars' original relative velocity and the timing of their departure from the cluster, the sun either follows in their orbital footsteps or they in ours.

The best place to look for them is in the plane of the galaxy in the direction the solar system is moving or in exactly the opposite direction. One of my students is now looking for them in a catalogue of stars assembled by ESA's Hipparcos satellite in the early 1990s [see "The Star Mapper," by Philip Morrison; Scientific American, February 1998]. But Hipparcos was probably not precise enough to make a positive identification. For that, we will need the GAIA spacecraft. It has a pair of telescopes that will measure the full three-dimensional position and velocity of some one billion stars over five years, creating an essentially complete census of stars within several thousand light-years of the sun. In the data, we can look for stars that lie nearly along the sun's past and future orbital path. Their composition should look like the sun's, because the same supernova that polluted the early solar system will have done the same to other stars in the cluster.

Identifying even a single sibling of the sun will provide some much needed information about the very early days of the solar system, a period otherwise lost to history. Theorists will be able to compute the birthplace of the sun with greater certainty and determine, for example, whether the gravitational field of the galaxy has changed substantially or not. Not least, solar siblings will be excellent places to look for habitable planets. Although we seem very alone in the galaxy, it was not always that way. Many of the sun's seeming idiosyncrasies—not least that it nurtures life—might make sense in the context of its family. ■

DON DIXON

MORE TO EXPLORE

The Formation of Star Clusters. Bruce Elmegreen and Yuri Efremov in *American Scientist,* Vol. 86, No. 3, pages 264–273; May-June 1998.

The Cradle of the Solar System. J. Jeff Hester, Steven J. Desch, Kevin R. Healy and Laurie A. Leshin in *Science,* Vol. 304, pages 1116–1117; May 21, 2004.

Radioactive Probes of the Supernova-Contaminated Solar Nebula: Evidence That the Sun Was Born in a Cluster. Leslie W. Looney, John J. Tobin and Brian D. Fields in *Astrophysical Journal,* Vol. 652, No. 2, pages 1755–1762; December 1, 2006. Available online at **arxiv.org/abs/astro-ph/0608411**

The Lost Siblings of the Sun. Simon F. Portegies Zwart in *Astrophysical Journal Letters,* Vol. 696, No. 1, pages L13–L16; May 1, 2009. **arxiv.org/abs/0903.0237**

NEW CULPRITS IN CHRONIC PAIN

Glia are nervous system caretakers whose nurturing can go too far. Taming them holds promise for alleviating pain that current medications cannot ease

BY R. DOUGLAS FIELDS

KEY CONCEPTS

- Chronic pain that persists after an injury heals is often caused by overly excited pain-sensing neurons that signal without an external stimulus.
- Traditional pain drugs that target neural cells directly rarely quiet these abnormal pain messages because the neurons' heightened sensitivity is driven by a different type of cell called glia.
- Such cells monitor the activity of neurons and attempt to keep them healthy and functioning efficiently. But well-intentioned glial reactions to intense pain can at times prolong that pain.

—The Editors

Helen's left foot slipped off the clutch on impact, twisting her ankle against the car's floorboard. It felt like a minor sprain at the time, she recalls, but the pain never subsided. Instead it intensified. Eventually, the slightest touch, even the gentle brush of bed linen, shot electric flames up her leg. "I was in so much pain I could not speak, yet inside I was screaming," wrote the young Englishwoman in an online journal of the mysterious condition that would torment her for the next three years.

The chronic pain suffered by people like Helen is different from the warning slap of acute pain. Acute pain is the body's most alarming, intense sensation, whose purpose is to stop us from further injuring ourselves. This type of pain is also called pathological pain because an external cause, such as tissue damage, produces the signals that travel the nervous system to the brain, where they are perceived as pain. But imagine if the gut-wrenching agony of a real injury never stopped, even after the wound healed, or if everyday sensations became excruciating: "I was unable to shower … the water felt like daggers," Helen remembers. "The vibrations in a car, someone walking across floorboards, people talking, a gentle breeze … would set off the uncontrollable pain. Common painkillers … even morphine had no effect. It was like my mind was playing tricks on me."

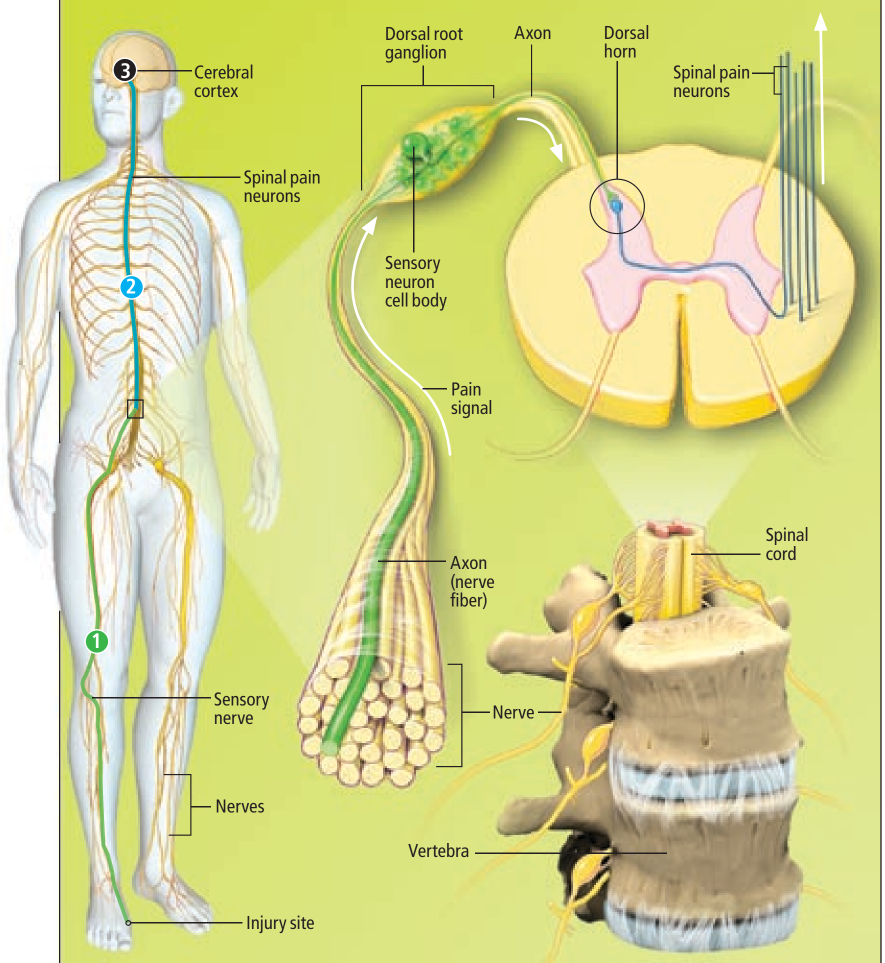
Unfortunately, Helen was right. Her chronic pain stemmed from a malfunction in the body's pain circuits, causing them to continually trig-

GERALD SLOTA

[BASICS]

PAIN CIRCUITRY

Sensations from an injured part of the body travel through three stages of neural circuitry before being perceived as pain by the brain. At the relay point in the spine where messages are passed from the first stage to the next, support cells called glia monitor and regulate the behavior of neurons to ease the transmission of signals.

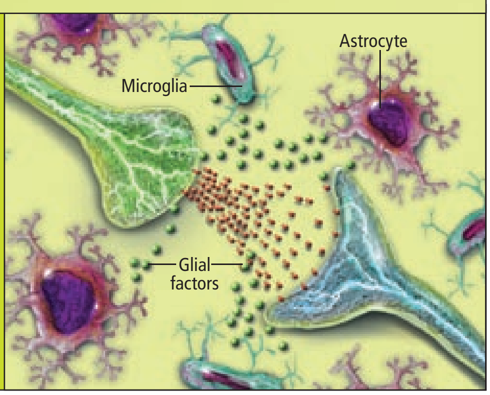


▲ **PAIN SENSATION**

After an injury, such as breaking a toe, sensory nerves 1 responsible for detecting noxious stimuli carry the signals from the leg to the dorsal horn of the spinal cord. Inside the spinal cord those peripheral sensory nerve fibers relay their messages to dedicated pain-transmitting neurons that carry the signals up the spinal cord to the base of the brain 2. When the signals reach the cerebral cortex 3, they are perceived as pain.

EAVESDROPPERS CHIME IN ▸

Neurons are surrounded by astrocytes and microglia, helper cells that provide nourishment and protection. Collectively known as glia, these support cells also monitor and regulate neural activity by contributing sensitizing or dampening factors as needed to sustain neural signaling.



ger a false alarm, one that is termed neuropathic because it arises from the misbehavior of the nerves themselves. When the false signals reach the brain, the agony they inflict is as real as any life-threatening pain, yet it never goes away and doctors are often powerless to quiet it.

Recent research is finally elucidating why traditional pain drugs often fail to quell neuropathic pain: the drugs target only neurons when the underlying source of the pain can be the dysfunction of nonneuronal cells called glia that reside in the brain and spinal cord. New insights into how these cells, whose job is to nurture the activity of neurons, can themselves become unbalanced and disrupt neuronal function are sparking new ideas for treating chronic pain. The work is also providing a surprising perspective on an unfortunate corollary of current pain treatment in some people: narcotic addiction.

Pain Circuits and Breakers

Understanding what could cause pain to persist after an injury has healed requires some knowledge of what causes pain at all. Although the sensation of hurt is ultimately perceived in the brain, the nerve cells that produce it are not located there; rather they line the spinal cord, gathering sensory information from throughout the body. Dorsal root ganglion (DRG) neurons, which represent the first stage of a three-part pain-sensing circuit, have their cell bodies stuffed like clusters of grapes in the seam between each vertebra of the backbone, resembling rows of buttons on a double-breasted jacket running from tailbone to skull. Each DRG neuron, like a person with two outstretched arms, extends one slender feeler, known as an axon or fiber, outward to survey a tiny distant region of the body while reaching its other axon into the spinal cord to touch a neuron that will relay impulses through the second stage in pain circuitry, a chain of spinal cord neurons. These spinal pain-transmitting cells in the cord relay messages from DRG neurons up to the final stage, the brain stem and ultimately the cerebral cortex. Pain signals originating from the left side of the body cross inside the spinal cord to travel to the right brain, and signals from the right side are sent to the left brain.

Interrupting the flow of information at any point along the three-stage pain circuit can blunt acute pain. Local anesthetics, such as the Novocain dentists use to painlessly extract a tooth, numb axon tips around the injection site, preventing the cells from firing electrical impulses.

ANDREW SWIFT

A "spinal block," often used to eliminate pain in childbirth, stops pain impulses at the second stage of the circuit, as bundles of DRG cell axons enter the spinal cord to meet spinal neurons. This blockade leaves the mother fully conscious to experience and assist in the painless delivery of her child. A morphine injection works at the same location, reducing transmission of pain signals by spinal neurons while leaving awareness of nonpainful sensations intact. In contrast, general anesthetics used in major surgery disrupt information processing in the cerebral cortex, rendering the patient completely unaware of any sensory input from neural pathways outside the brain.

Our body's natural painkillers work at these same three links in the pain circuit. A soldier charged with adrenalin in battle may suffer grievous injury while unaware of the wound because the cerebral cortex ignores the pain signals while dealing with a highly emotional and life-threatening situation. In natural childbirth, a woman's body releases small proteins called endorphins that dampen the transmission of pain signals as they enter her spinal cord.

Hormones, emotional states and numerous other factors can also dramatically alter a person's perception of pain by modulating the transmission of messages along pain pathways. In addition, many biological processes and substances that alter the ebb and flow of molecules through ion channels in individual nerve cells all contribute to regulating the sensitivity of nerves themselves. When an injury occurs, these factors can ease controls on neuronal firing, thereby facilitating the neurons' job of transmitting pain signals.

That uninhibited state, however, can last too long, leaving DRG cells hypersensitized and causing them to fire pain messages without an external stimulus. This situation is the primary cause of neuropathic pain. The increased neural sensitivity can also cause abnormal feelings of tingling, burning, tickling and numbness (paresthesia) or, as in Helen's experience of the shower of daggers, can amplify light touch or temperature sensations to painful levels (allodynia).

Efforts to understand how neurons in the pain circuitry become hypersensitive after injury have, not surprisingly, long focused on what goes wrong in neurons—work that has yielded some clues but not a complete picture. My own research and that of many colleagues have demonstrated, for instance, that the very act of firing impulses to send pain signals alters the activity of genes inside pain neurons. Some genes regulated by neuronal firing encode the ion channels and other substances that heighten the cells' sensitivity. The intense activation of DRG cells when tissue is injured can thus cause the kinds of sensitizing changes in those neurons that might result in neuropathic pain later on. Our studies and the work of other laboratories also reveal, however, that neurons are not the only cells responding to painful injury and releasing the substances that promote neural sensitivity.

Glia far outnumber neurons in the spinal cord and brain. They do not fire electrical impulses, as neurons do, but they have some interesting and important properties that influence neuronal firing. Glia maintain the chemical environment surrounding neurons: beyond delivering the energy that sustains the nerve cells, they sop up the neurotransmitters that neurons release when they fire an impulse to a neighboring neuron. Sometimes glia even dispense neurotransmitters to augment or modulate the transmission of neuronal signals. When neurons are injured, glia release growth factors that promote neural survival and healing, and they release substances that call on cells in the immune system to fight infection and initiate healing. And yet recent research is revealing that these activities on the part of glia, to nurture neurons and facilitate their activities, can also prolong the state of neural sensitization.

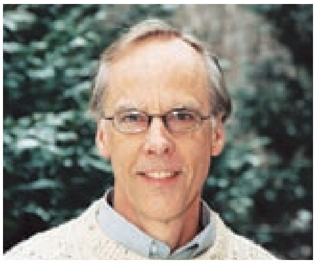
Glia Become Suspect

For more than a century scientists have known that glia respond to injury. In Germany in 1894 Franz Nissl noticed that after a nerve is damaged, glial cells at the spots where nerve fibers connect in the spinal cord or brain change dramatically. Microglia become more abundant, and a larger type, called astrocytes because of their star-shaped cell bodies, becomes much beefier, plumped up with thick bundles of filamentous fibers that fortify its cellular skeleton.

These glial responses were commonly understood to promote nerve repair after injury, but how they did so was unclear. Furthermore, if an injury—such as a twisted ankle—is inflicted far from the spinal pain circuitry, the astrocytes in the spine must be responding not to direct injury but rather to changes in signaling at the relay point between DRG and spinal neurons. This observation implied that astrocytes and microglia were monitoring the physiological properties of pain neurons.

Over the past two decades glia have been

[THE AUTHOR]



R. Douglas Fields is editor in chief of the journal *Neuron Glia Biology* and has written several articles on neuroscience topics for *Scientific American,* most recently in March 2008 about the role of white matter in the brain. His forthcoming book, *The Other Brain* (Simon & Schuster), describes new insights into how glia regulate brain functions in health and disease.

GLOSSARY

NEUROPATHIC PAIN
Persistent pain that develops after nerve damage caused by injury. Can include unpleasant sensations, numbing, burning, prickling, heat, cold and swelling. Other causes of nerve damage that leads to neuropathic pain include viral infection of nerves, diabetic damage to peripheral nerves, or nerve injury resulting from cancer-related surgery, chemotherapy or nutritional deficits.

ALLODYNIA
Perception of nonpainful touch or temperature stimuli as painful.

HYPERALGESIA
Increased sensitivity to painful stimuli.

HYPERESTHESIA
Increased sensitivity to stimulation (hyperalgesia plus allodynia).

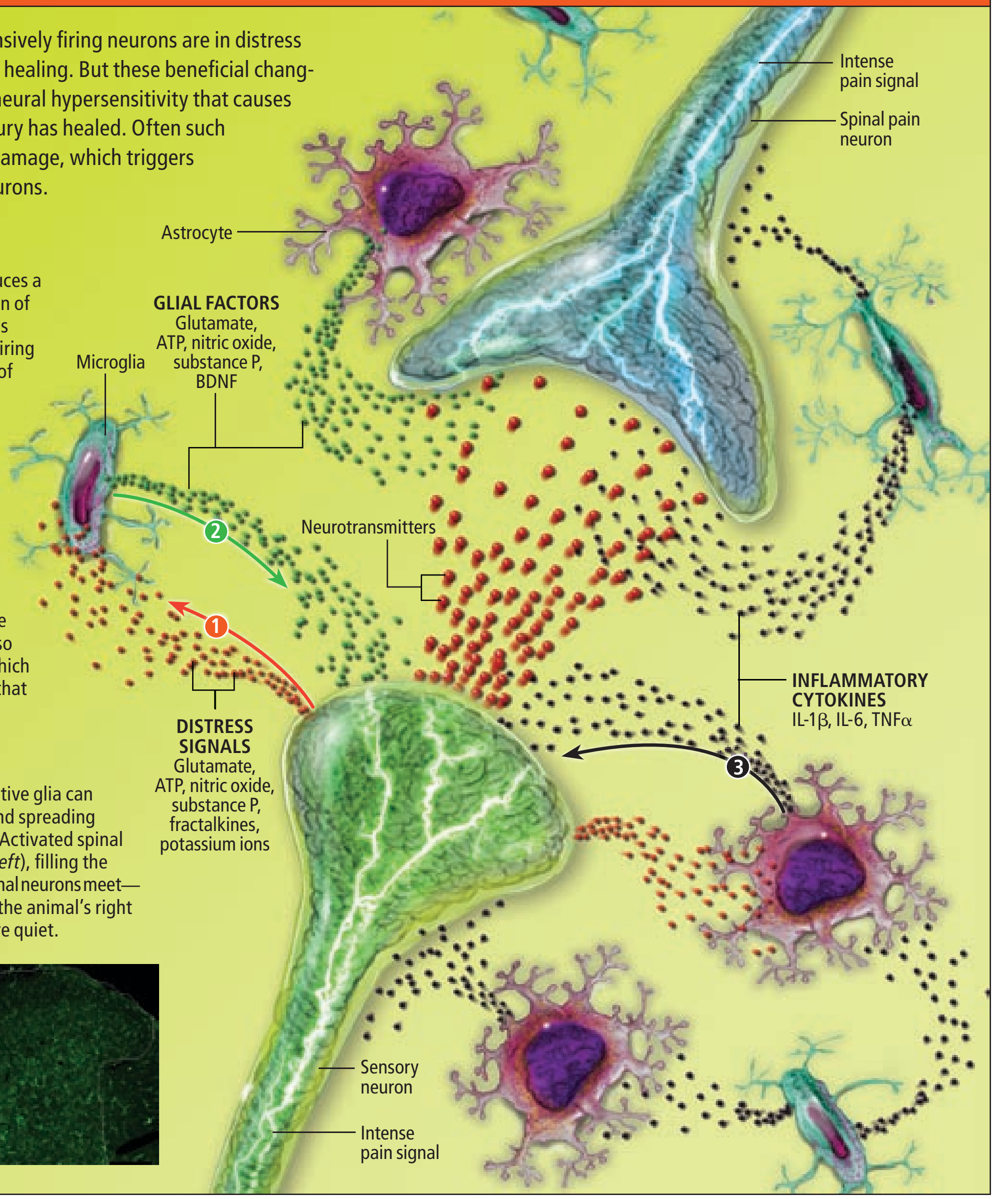
PARESTHESIA
Abnormal sensation, such as burning, in response to touch.

COURTESY OF R. DOUGLAS FIELDS (*Fields*); SOURCE FOR GLOSSARY: INTERNATIONAL ASSOCIATION FOR THE STUDY OF PAIN

[PAIN LOOP]

TOO MUCH OF A GOOD THING

After an injury, glia sensing that intensively firing neurons are in distress react to restore balance and promote healing. But these beneficial changes, if prolonged, can lead to chronic neural hypersensitivity that causes pain to continue after the original injury has healed. Often such neuropathic pain begins with nerve damage, which triggers glial responses that further excite neurons.



GLIA ACTIVATION ▸

An injury that damages nerve fibers produces a barrage of pain signaling in the dorsal horn of the spine, where peripheral sensory nerves meet spinal pain neurons. An intensively firing sensory neuron generates large amounts of neurotransmitters as well as other molecules that glia interpret as signs of distress (1), sending the helper cells into a reactive state. Glia normally mop up excess neurotransmitters, but reactive glia reduce their neurotransmitter uptake and begin producing molecules intended to stabilize and heal the neurons (2). These glial factors act to either reduce inhibitory forces on neurons or to stimulate them, allowing the cells to fire more easily. Neural distress also causes the glia to release cytokines (3), which induce inflammation, a healing response that also further sensitizes neurons.

GLIA-SUSTAINING PAIN

Excitatory/inflammatory signaling by reactive glia can activate neighboring glia, perpetuating and spreading neural hypersensitivity in the spinal cord. Activated spinal astroglia are visible below (*bright green, left*), filling the right dorsal horn of a rat—where DRG and spinal neurons meet—10 days after injury to the sciatic nerve in the animal's right leg. Glia on the left (*image below right*) are quiet.

ANDREW SWIFT (*illustration*); FROM "NERVE CONDUCTION BLOCKADE IN THE SCIATIC NERVE PREVENTS BUT DOES NOT REVERSE THE ACTIVATION OF P38 MITOGEN-ACTIVATED PROTEIN KINASE IN SPINAL MICROGLIA IN THE RAT SPARED NERVE INJURY MODEL," BY YEONG-RAY WEN ET AL., IN *ANESTHESIOLOGY*, VOL. 107; JANUARY 2007 (*micrographs*)

shown to possess many mechanisms for detecting electrical activity in neurons, including channels for sensing potassium and other ions released by neurons firing electrical impulses and surface receptors for sensing the same neurotransmitters that neurons use to communicate across synapses. Glutamate, ATP and nitric oxide are among the significant neurotransmitters released by neurons that are detected by glia, but many others exist. This array of sensors allows glia to survey electrical activity in neuronal circuits throughout the body and brain and to respond to changing physiological conditions [see "The Other Half of the Brain," by R. Douglas Fields; Scientific American, April 2004].

Once scientists recognized the breadth of glial responses to neural activity, attention returned to the support cells' suspicious behavior at pain-relay points. If glia were monitoring neural pain transmissions, were they affecting them, too? Exactly 100 years after Nissl's observation of glia responding to nerve injury, a simple experiment first tested the hypothesis that glia might participate in the development of chronic pain. In 1994 Stephen T. Meller and his colleagues at the University of Iowa injected rats with a toxin that selectively kills astrocytes, then assessed whether the animals' sensitivity to painful stimulation was reduced. It was not, showing that astrocytes have no ob-

vious role in the transmission of acute pain.

Next the scientists treated rats with a nerve-fiber irritant that caused the animals to gradually develop chronic pain, much as Helen experienced long after the car accident irritated the nerves in her ankle. Animals injected with the astrocyte poison developed dramatically less chronic pain, revealing that astrocytes were in some way responsible for the onset of chronic pain after nerve injury. Subsequent research has revealed how.

Glia release many types of molecules that can increase the sensitivity of DRG and spinal cord neurons relaying pain signals to the brain, including growth factors and some of the same neurotransmitters that neurons themselves produce. Scientists have come to realize that glia interpret rapid neural firing and the neural changes it induces as a sign of distress in the neurons. In response, glia release the sensitizing molecules to ease the stress on the neurons by facilitating their signaling and to begin their healing.

Another vital class of molecules that glia generate in response to neuronal damage or distress are cytokines, which is shorthand for "cytokinetic," meaning cell movement. Cytokines act as powerful chemical beacons that cells in the immune system follow to reach the site of an injury. Consider the immense needle-in-the-haystack problem a cell in your immune system faces in finding a tiny splinter embedded in your fingertip. Potent cytokines released from cells damaged by the splinter beckon immune system cells from the blood and lymph to rush to the fingertip to fight infection and initiate repair. They also induce changes in the tissue and local blood vessels that ease the work of immune cells and promote healing but that result in redness and swelling. The collective effects of cytokine signaling are called inflammation.

A splinter demonstrates how effective cytokines are in targeting immune cells to a wound, but even more impressive is how painful a tiny splinter can be—the pain is far out of proportion to the minuscule tissue damage suffered. Soon even the area surrounding the splinter becomes swollen and painfully sensitive, although these neighboring skin cells were unharmed. The pain surrounding an injury is caused by another action of inflammatory cytokines: they greatly amplify the sensitivity of pain fibers. Supersensitizing pain sensors near an injury is the body's way of making us leave the site alone so that it can heal.

Neurons, as a rule, are not the source of cytokines in the nervous system—glia are. And just as cytokines can make the nerve endings surrounding a splinter in your fingertip hypersensitive, the cytokines released by glia in the spinal cord in response to intensive pain signaling can spread to surrounding nerve fibers and make them hypersensitive as well. A cycle may begin of oversensitized neurons firing wildly, which sends glia into a reactive state, in which they pour out more sensitizing factors and cytokines in an attempt to relieve the neurons' distress but end up instead prolonging it. When that occurs, pain can originate within the spinal cord from nerve fibers that are not directly injured.

The initial responses of glia to an injury are beneficial for healing, but if they are too intense or continue too long, unstoppable chronic pain is the result. Several research groups have documented the feedback loops that can cause glia to prolong their release of the sensitizing factors and inflammatory signaling that leads to neuropathic pain, and many are experimenting with ways to reverse those processes. This work has even led to ways of making the narcotics used in treating acute pain more effective.

Stopping Pain at Its Source

In the past, all treatments for chronic pain have been directed toward dampening the activity of neurons, but the pain cannot abate if glia continue to incite the nerve cells. Insights into how glia can fall into their vicious nerve-sensitizing cycle are leading to new approaches to targeting dysfunctional glia in the hope of stopping a fundamental source of neuropathic pain. Experimental efforts to treat neuropathic pain by modulating glia are therefore focusing on quieting glia themselves, blocking inflammatory trigger molecules and signals and delivering anti-inflammatory signals.

In animal experiments, for instance, Joyce A. DeLeo and her colleagues at Dartmouth Medical School have shown that a chemical called propentofylline suppresses astrocyte activation and thereby chronic pain. The antibiotic minocycline prevents both neurons and glia from making inflammatory cytokines and nitric oxide, as well as reducing the migration of microglia toward injury sites, suggesting the drug could prevent glial hyperactivation.

A related approach centers on Toll-like receptors (TLRs), surface proteins on glial cells that recognize certain indicators of cells in distress and prod glia to begin emitting cytokines. Linda R. Watkins of the University of Colorado at

PAIN FACTS

10% to 20%
of the U.S. and European populations report chronic pain.

59%
of chronic pain sufferers are female.

18%
of adults with chronic pain visit an alternative medicine therapist.

Only 15%
of primary care physicians in a recent survey felt comfortable treating patients for chronic pain.

41%
of doctors said they would wait until patients specifically requested narcotic painkillers before prescribing them.

RISK FACTORS FOR CHRONIC NECK OR BACK PAIN

- Advanced age
- Anxiety
- Being female
- Depression
- Heavy lifting
- Living alone
- Nicotine use
- Nonparticipation in sports
- Obesity
- Repetitive work
- Stress
- Work dissatisfaction

GETTY IMAGES (*woman in pain*); SOURCES FOR DATA: "PAIN AS A REASON TO VISIT THE DOCTOR: A STUDY IN FINNISH PRIMARY HEALTH CARE," BY P. MÄNTYSELKÄ ET AL., IN *PAIN*, VOL. 89, NOS. 2–3; JANUARY 2001; "PREVALENCE OF PAIN IN GENERAL PRACTICE," BY J. HASSELSTRÖM ET AL., IN *EUROPEAN JOURNAL OF PAIN*, VOL. 6, NO. 5; OCTOBER 2002; "PERSISTENT PAIN AND WELL-BEING: A WORLD HEALTH ORGANIZATION STUDY IN PRIMARY CARE," BY OYE GUREJE ET AL., IN *JOURNAL OF THE AMERICAN MEDICAL ASSOCIATION*, VOL. 280, NO. 2; JULY 8, 1998; "SURVEY OF CHRONIC PAIN IN EUROPE: PREVALENCE, IMPACT ON DAILY LIFE, AND TREATMENT," BY H. BREIVIK, IN *EUROPEAN JOURNAL OF PAIN*, VOL. 10, NO. 4; MAY 2006 (*"10% TO 20%"*); *1999 NATIONAL PAIN SURVEY EXECUTIVE SUMMARY* (*"59%"*); *COMPLEMENTARY THERAPIES FOR PAIN MANAGEMENT*, BY E. ERNST, M. H. PITTLER AND B. WIDER, ELSEVIER HEALTH SCIENCES, 2007 (*"18%"*); "OPIOIDS FOR CHRONIC NONMALIGNANT PAIN," BY MICHAEL POTTER ET AL., IN *JOURNAL OF FAMILY PRACTICE*, VOL. 50, NO. 2; FEBRUARY 2001 (*"Only 15%"* and *"41%"*)

Boulder and her colleagues have shown in animals that using an experimental compound to block a particular TLR subtype, TLR-4, on glial cells in the spinal cord reversed neuropathic pain that stemmed from damage to the sciatic nerve. Interestingly, naloxone—a drug used to blunt the effects of opiates in addiction treatment, also blocks glial responses to TLR-4 activation. Watkins has demonstrated in rats that naloxone can reverse fully developed neuropathic pain.

Another existing drug, indeed an ancient pain-relieving substance that can work when many others fail, is marijuana, which has been legalized for medicinal use in some states. Substances in the marijuana plant mimic natural compounds in the brain called cannabinoids, which activate certain receptors on neurons and regulate neural signal transmission.

Two types of cannabinoid receptor occur in the brain and nervous system, however: CB1 and CB2. They have different functions. Activating the CB2 receptor brings pain relief, whereas activating CB1 receptors induces the psychoactive effects of marijuana. Remarkably, the CB2 receptor that relieves pain does not appear on pain neurons; it is on glia. When cannabinoids bind to microglial CB2 receptors, the cells reduce their inflammatory signaling. Recent studies have found that as chronic pain develops, the number of CB2 receptors on microglia increase, a sign that the cells are valiantly trying to capture more cannabinoids in their vicinity to provide analgesic relief. Now pharmaceutical companies are vigorously pursuing drugs that can be used to control pain by acting on glial CB2 receptors without making people high.

Blocking inflammatory cytokines with existing anti-inflammatory medicines, such as anakinra (Kineret) and etanercept (Enbrel), has also reduced neuropathic pain in animal models. In addition to stemming inflammatory signals, several groups have demonstrated that adding anti-inflammatory cytokines, such as interleukin-10 and IL-2, can subdue neuropathic pain in animals. Two existing drugs, pentoxyfilline and AV411, both inhibit inflammation by stimulating cells to produce IL-10. Moreover, assorted research groups have reversed neuropathic pain for up to four weeks by delivering the genes that give rise to IL-10 and IL-2 into the muscles or the spine of animals.

A few of these drugs have entered human trials for pain [*see table on opposite page*], including AV411, which is already used as an anti-inflammatory treatment for stroke in Japan. A trial in Australia showed that pain patients voluntarily reduced their dosages of morphine while on the drug, a sign that AV411 was contributing to relieving their pain. But AV411 may be working by mechanisms that go beyond calming pain caused by inflammation, highlighting a surprising twist in the tale of glia and pain.

Restoring Balance

Morphine is among the most potent painkillers known, but doctors are wary of its devilish properties, to the extent that many will undertreat even patients with terminal cancer. Like heroin, opium and modern narcotics, such as OxyContin, morphine blunts pain by weakening communication among spinal cord neurons, thus diminishing the transmission of pain signals.

Unfortunately, the power of morphine and other narcotics to block pain quickly fades with repeated use, a property called tolerance. Stronger and more frequent doses are necessary to achieve the same effect. Patients with chronic pain can become addicts, compounding their misery with debilitating drug dependency. Doc-

[DRUG TOLERANCE]

Glia Oppose Opiates

A stunning discovery made in recent years is that glia play a role in causing opiate painkillers to lose effectiveness. Linda R. Watkins of the University of Colorado at Boulder has demonstrated that morphine, methadone and probably other opiates directly activate spinal cord glia, causing glial responses that counteract the drugs' painkilling effects. The activated helper cells begin behaving much as they do after nerve injury, spewing inflammatory cytokines and other factors that act to overly sensitize neurons. Watkins showed that the effect starts less than five minutes after the first drug dose.

By making neurons hyperexcitable, glial influence overcomes the normal neuron-dampening effects of the drugs, explaining why patients often require ever increasing doses to achieve pain relief. The same mechanism may also underlie the frequent failure of opiates to relieve chronic neuropathic pain when it is driven by reactive glia. —***R.D.F.***

AJ PHOTOS/PHOTO RESEARCHERS, INC.

tors, fearing that they will be suspected of *dealing* rather than *prescribing* such large quantities of narcotics, are often forced to limit patients to dosages that are no longer effective in relieving their agony. Some patients resort to crime to obtain illegal prescriptions to ease their intolerable pain; a few turn to suicide to end their suffering. A new finding at the intersection of pain relief, glia and drug addiction is evidence that glia are responsible for creating tolerance to heroin and morphine.

Suspicions about glial involvement in narcotic tolerance first arose with the observation that just as when an addict quits heroin "cold turkey," patients dependent on narcotic painkillers who stop their medication suddenly suffer classic painful withdrawal symptoms. The patients (and heroin addicts) become hypersensitive to such an extreme that even normal sound and light become excruciatingly painful. The similarity of these symptoms to the hyperesthesia seen in neuropathic pain suggested the possibility of a common cause.

In 2001 Ping Song and Zhi-Qi Zhao of the Shanghai Institute of Physiology tested whether the development of tolerance to morphine involved glia. When the researchers gave rats repeated doses of morphine, they saw the number of reactive astrocytes in the spinal cord increase. The changes in glia caused by repeated morphine injection were identical to those seen in the spinal cord after an injury or when neuropathic pain develops. The scientists then eliminated astrocytes with the same poison that Meller used to dampen the development of chronic pain in rats. Morphine tolerance in these animals was sharply reduced, indicating that glia in some way contribute to it.

Many research groups have since tried blocking various signals between neurons and glia (for example, by inactivating specific cytokine receptors on glia) and testing whether morphine tolerance is affected. This research shows that blocking inflammatory signals to and from glia does nothing to alter normal acute pain sensations, but if the blockers are injected together with morphine, lower doses of morphine are required to achieve the same relief *and* the duration of pain relief is doubled. These findings strongly indicated that glia were counteracting the pain-relieving effect of morphine.

Glia's actions to undermine the potency of morphine are in keeping with the fundamental glial job of maintaining balanced activity in neural circuits. As narcotics blunt the sensitivity of pain circuits, glia respond by releasing neuroactive substances that increase neuronal excitability to restore the normal levels of activity in neural circuits. Over time glial influence ratchets up the sensitivity of pain neurons, and when the blunting effect on pain circuits provided by heroin or narcotic pain medications is suddenly removed by rapid withdrawal from the drug, neurons fire intensely, causing supersensitivity and painful withdrawal symptoms. In experimental animals painful withdrawal from morphine addiction can be reduced dramatically by drugs blocking glial responses.

Modulating the activity of glia, then, could prove to be a key not only to alleviating chronic pain but also to reducing the likelihood that people treated with narcotic painkillers will become addicted. What a boon glia-targeted drugs would be for those who have long sought to control two such major sources of human misery and tragedy. Yet the connections among neurons, pain and addiction eluded scientists in the past who ignored the vital partner of neurons—glia. ■

[DRUGS]

QUIETING OVERACTIVE GLIA

Several substances have been shown to modulate the activity of glia and are being tested as potential treatments for neuropathic pain or for the reduction of opiate tolerance and withdrawal. (Asterisks denote drugs already marketed for other uses.)

SUBSTANCE	MECHANISM	TESTING STAGE
AV411*	Inhibits astrocyte activity	Human tests for efficacy in enhancing morphine action and reducing withdrawal symptoms; safety tests for pain completed
Etanercept*	Anti-inflammatory signals quiet glia	Human tests for postsurgical neuropathic pain reduction
Interleukins* (cytokines)	Anti-inflammatory signals quiet glia	Cell and animal tests for pain
JWH-015	Activates pain-dampening CB2 cannabinoid receptors	Cell and animal tests for pain
Methionine sulfoximine*	Inhibits astrocyte neurotransmitter processing	Cell and animal tests for pain
Minocycline*	Inhibits activation of microglia	Cell and animal tests for pain
Propentofylline	Inhibits astrocyte activity	Human safety tests for pain completed
Sativex*	Activates cannabinoid receptors	Human efficacy tests for cancer-related and HIV-related neuropathic pain and diabetic neuropathy
SLC022	Inhibits astrocyte activity	Human efficacy tests for herpes-related neuropathic pain

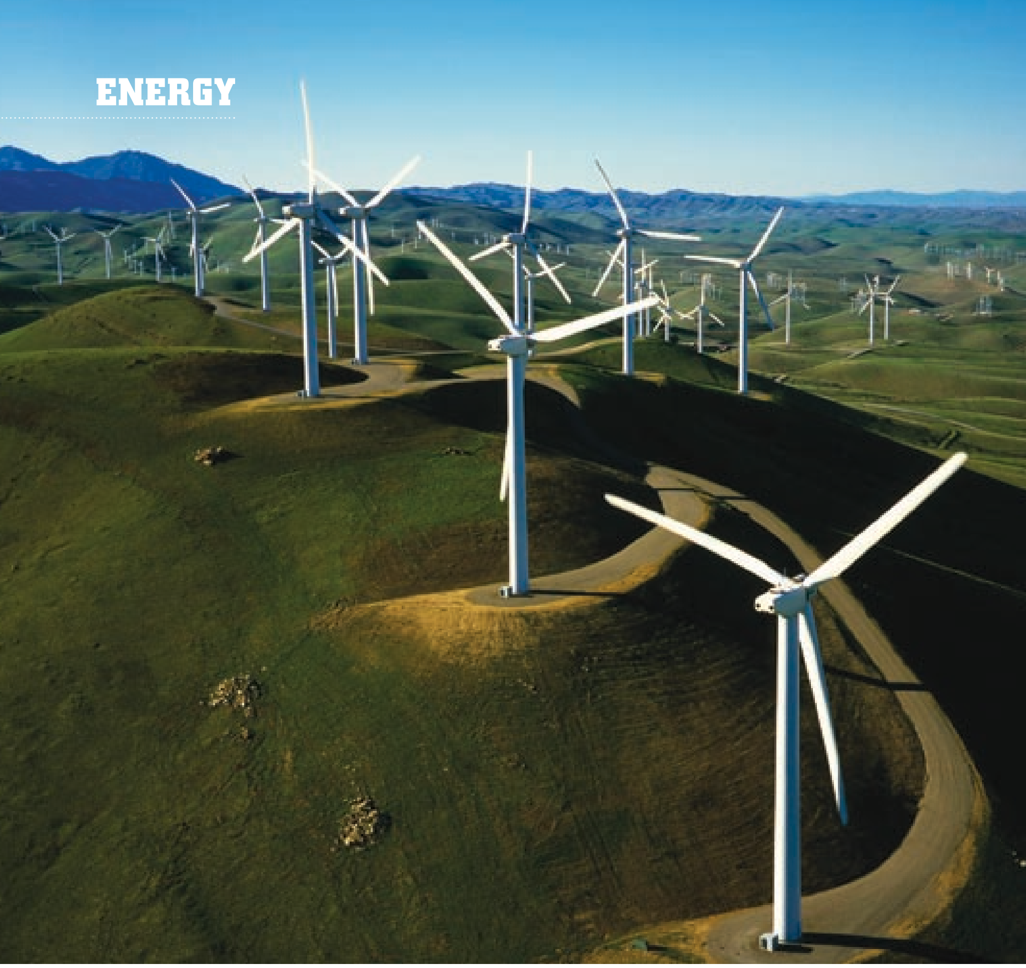
➡ MORE TO EXPLORE

Could Chronic Pain and Spread of Pain Sensation Be Induced and Maintained by Glial Activation? Elisabeth Hansson in *Acta Physiologica*, Vol. 187, No. 1–2, pages 321–327; published online May 22, 2006.

Do Glial Cells Control Pain? Marc R. Suter et al. in *Neuron Glia Biology*, Vol. 3, No. 3, pages 255–268; August 2007.

Proinflammatory Cytokines Oppose Opioid-Induced Acute and Chronic Analgesia. Mark R. Hutchinson et al. in *Brain, Behavior, and Immunity*, Vol. 22, No. 8, pages 1178–1189; published online July 2, 2008.

Pathological and Protective Roles of Glia in Chronic Pain. Erin D. Milligan and Linda R. Watkins in *Nature Reviews Neuroscience*, Vol. 10, pages 23–36; January 2009.



A PATH TO SUSTAINABLE ENERGY BY 2030

Wind, water and solar technologies can provide 100 percent of the world's energy, eliminating all fossil fuels. HERE'S HOW

By Mark Z. Jacobson and Mark A. Delucchi

In December leaders from around the world will meet in Copenhagen to try to agree on cutting back greenhouse gas emissions for decades to come. The most effective step to implement that goal would be a massive shift away from fossil fuels to clean, renewable energy sources. If leaders can have confidence that such a transformation is possible, they might commit to an historic agreement. We think they can.

A year ago former vice president Al Gore threw down a gauntlet: to repower America with 100 percent carbon-free electricity within 10 years. As the two of us started to evaluate the feasibility of such a change, we took on an even larger challenge: to determine how 100 percent of the world's energy, for *all* purposes, could be supplied by wind, water and solar resources, by as early as 2030. Our plan is presented here.

Scientists have been building to this moment for at least a decade, analyzing various pieces of the challenge. Most recently, a 2009 Stanford University study ranked energy systems according to their impacts on global warming, pollution, water supply, land use, wildlife and other concerns. The very best options were wind, solar, geothermal, tidal and hydroelectric power—all of which are driven by wind, water or sunlight (referred to as WWS). Nuclear power, coal with carbon capture, and ethanol were all poorer options, as were oil and natural gas. The study also found that battery-electric vehicles and hydrogen fuel-cell vehicles recharged by WWS options would largely eliminate pollution from the transportation sector.

Our plan calls for millions of wind turbines, water machines and solar installations. The numbers are large, but the scale is not an insurmountable hurdle; society has achieved massive

JOHN LEE *Aurora Photos (wind farm)*; BILL HEINSOHN *Aurora Photos (dam)*

HO/REUTERS/CORBIS (*solar panels*)

transformations before. During World War II, the U.S. retooled automobile factories to produce 300,000 aircraft, and other countries produced 486,000 more. In 1956 the U.S. began building the Interstate Highway System, which after 35 years extended for 47,000 miles, changing commerce and society.

Is it feasible to transform the world's energy systems? Could it be accomplished in two decades? The answers depend on the technologies chosen, the availability of critical materials, and economic and political factors.

Clean Technologies Only

Renewable energy comes from enticing sources: wind, which also produces waves; water, which includes hydroelectric, tidal and geothermal energy (water heated by hot underground rock); and sun, which includes photovoltaics and solar power plants that focus sunlight to heat a fluid that drives a turbine to generate electricity. Our plan includes only technologies that work or are close to working today on a large scale, rather than those that may exist 20 or 30 years from now.

To ensure that our system remains clean, we consider only technologies that have near-zero emissions of greenhouse gases and air pollutants over their entire life cycle, including construction, operation and decommissioning. For example, when burned in vehicles, even the most ecologically acceptable sources of ethanol create air pollution that will cause the same mortality level as when gasoline is burned. Nuclear power results in up to 25 times more carbon emissions than wind energy, when reactor construction and uranium refining and transport are considered. Carbon capture and sequestration technology can reduce carbon dioxide emissions from coal-fired power plants but will *increase* air pollutants and will extend all the other deleterious effects of coal mining, transport and processing, because more coal must be burned to power the capture and storage steps. Similarly, we consider only technologies that do not present significant waste disposal or terrorism risks.

In our plan, WWS will supply electric power for heating and transportation—industries that will have to revamp if the world has any hope of slowing climate change. We have assumed that most fossil-fuel heating (as well as ovens and stoves) can be replaced by electric systems and that most fossil-fuel transportation can be replaced by battery and fuel-cell vehicles. Hydrogen, produced by using WWS electricity to split water (electrolysis), would power fuel cells and be burned in airplanes and by industry.

KEY CONCEPTS

- Supplies of wind and solar energy on accessible land dwarf the energy consumed by people around the globe.
- The authors' plan calls for 3.8 million large wind turbines, 90,000 solar plants, and numerous geothermal, tidal and rooftop photovoltaic installations worldwide.
- The cost of generating and transmitting power would be less than the projected cost per kilowatt-hour for fossil-fuel and nuclear power.
- Shortages of a few specialty materials, along with lack of political will, loom as the greatest obstacles.

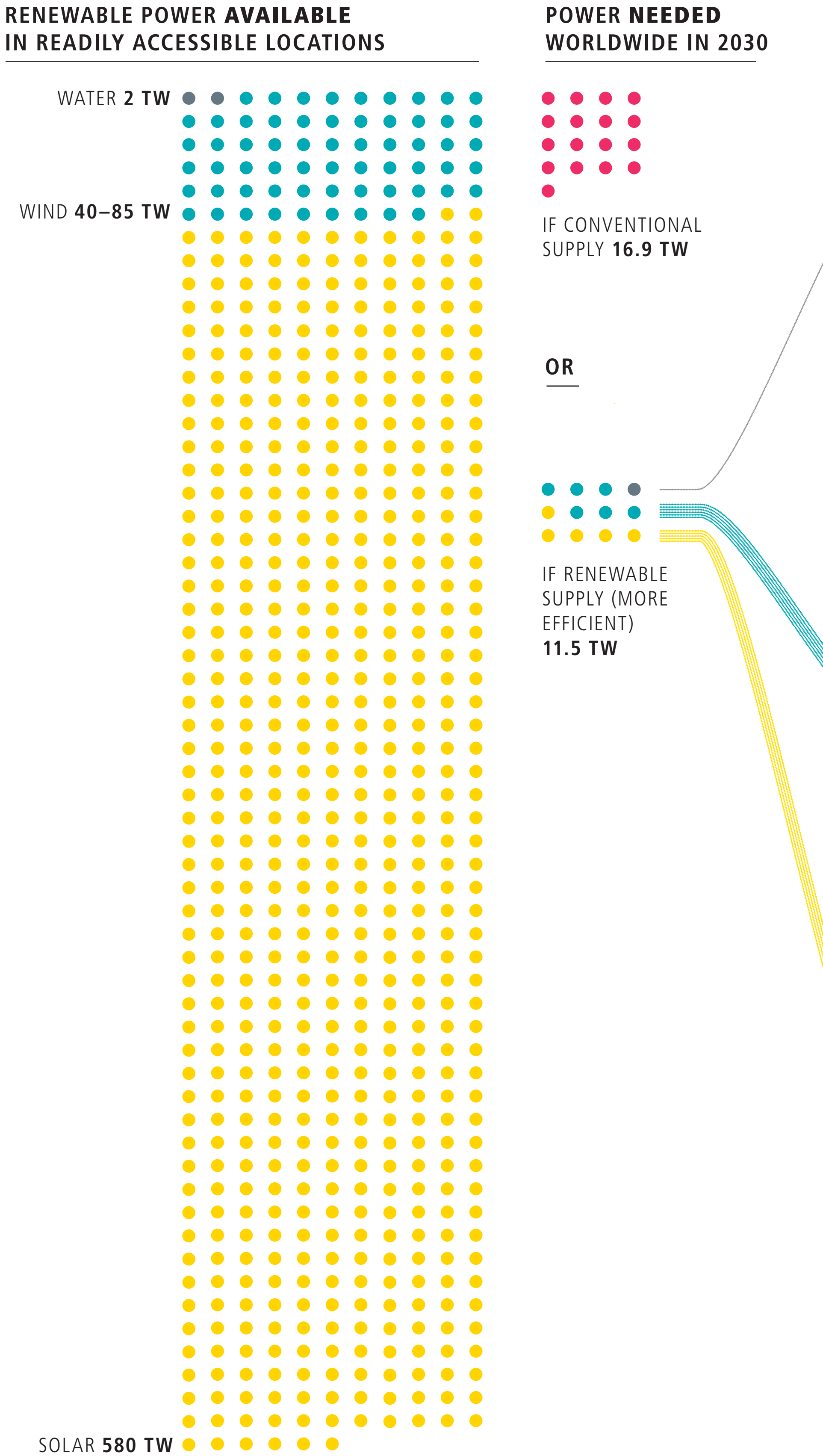
—The Editors

Plenty of Supply

Today the maximum power consumed worldwide at any given moment is about 12.5 trillion watts (terawatts, or TW), according to the U.S. Energy Information Administration. The agency projects that in 2030 the world will require 16.9 TW of power as global population and living standards rise, with about 2.8 TW in the U.S. The mix of sources is similar to today's, heavily dependent on fossil fuels. If, however, the planet were powered entirely by WWS, with no fossil-fuel or biomass combustion, an intriguing savings would occur. Global power demand would be only 11.5 TW, and U.S. demand would be 1.8 TW. That decline occurs because, in most cases, electrification is a more efficient way to use energy. For example, only 17 to 20 percent of the energy in gasoline is used to move a vehicle (the rest is wasted as heat), whereas 75 to 86 percent of the electricity delivered to an electric vehicle goes into motion.

Even if demand did rise to 16.9 TW, WWS sources could provide far more power. Detailed studies by us and others indicate that energy from the wind, worldwide, is about 1,700 TW. Solar, alone, offers 6,500 TW. Of course, wind and sun out in the open seas, over high mountains and across protected regions would not be available. If we subtract these and low-wind areas not likely to be developed, we are still left with 40 to 85 TW for wind and 580 TW for solar, each far beyond future human demand. Yet currently we generate only 0.02 TW of wind power and 0.008 TW of solar. These sources hold an incredible amount of untapped potential.

The other WWS technologies will help create a flexible range of options. Although all the sources can expand greatly, for practical reasons, wave power can be extracted only near coastal areas. Many geothermal sources are too deep to be tapped economically. And even though hydroelectric power now exceeds all other WWS sources, most of the suitable large reservoirs are already in use.



MW – MEGAWATT = 1 MILLION WATTS
GW – GIGAWATT = 1 BILLION WATTS
TW – TERAWATT = 1 TRILLION WATTS

The Editors welcome responses to this article. To comment and to see more detailed calculations, go to **www.ScientificAmerican.com/sustainable-energy**

RENEWABLE INSTALLATIONS REQUIRED WORLDWIDE

WATER **1.1 TW** (9% OF SUPPLY)

490,000
TIDAL TURBINES – 1 MW* – <1% IN PLACE
*size of unit

5,350
GEOTHERMAL PLANTS – 100 MW – 2% IN PLACE

900
HYDROELECTRIC PLANTS – 1,300 MW – 70% IN PLACE

WIND **5.8 TW** (51% OF SUPPLY)

3,800,000
WIND TURBINES – 5 MW – 1% IN PLACE

720,000
WAVE CONVERTERS* – 0.75 MW – <1% IN PLACE
*wind drives waves

SOLAR **4.6 TW** (40% OF SUPPLY)

1,700,000,000
ROOFTOP PHOTOVOLTAIC SYSTEMS* – 0.003 MW – <1% IN PLACE
*sized for a modest house; a commercial roof might have dozens of systems

49,000
CONCENTRATED SOLAR POWER PLANTS – 300 MW – <1% IN PLACE

40,000
PHOTOVOLTAIC POWER PLANTS – 300 MW – <1% IN PLACE

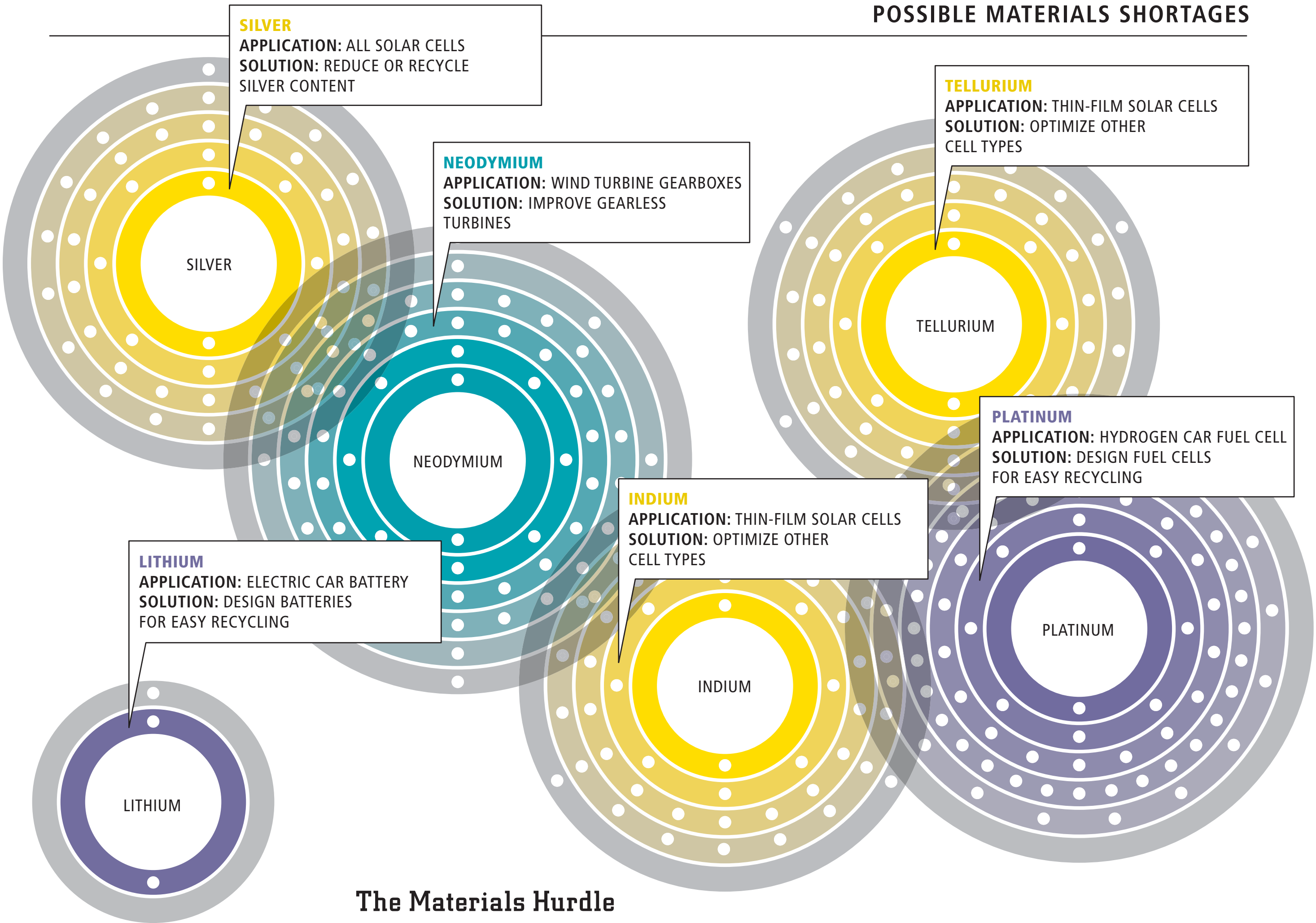
The Plan: Power Plants Required

Clearly, enough renewable energy exists. How, then, would we transition to a new infrastructure to provide the world with 11.5 TW? We have chosen a mix of technologies emphasizing wind and solar, with about 9 percent of demand met by mature water-related methods. (Other combinations of wind and solar could be as successful.)

Wind supplies 51 percent of the demand, provided by 3.8 million large wind turbines (each rated at five megawatts) worldwide. Although that quantity may sound enormous, it is interesting to note that the world manufactures 73 million cars and light trucks *every year.* Another 40 percent of the power comes from photovoltaics and concentrated solar plants, with about 30 percent of the photovoltaic output from rooftop panels on homes and commercial buildings. About 89,000 photovoltaic and concentrated solar power plants, averaging 300 megawatts apiece, would be needed. Our mix also includes 900 hydroelectric stations worldwide, 70 percent of which are already in place.

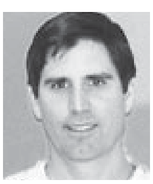
Only about 0.8 percent of the wind base is installed today. The worldwide footprint of the 3.8 million turbines would be less than 50 square kilometers (smaller than Manhattan). When the needed spacing between them is figured, they would occupy about 1 percent of the earth's land, but the empty space among turbines could be used for agriculture or ranching or as open land or ocean. The nonrooftop photovoltaics and concentrated solar plants would occupy about 0.33 percent of the planet's land. Building such an extensive infrastructure will take time. But so did the current power plant network. And remember that if we stick with fossil fuels, demand by 2030 will rise to 16.9 TW, requiring about 13,000 large new coal plants, which themselves would occupy a lot more land, as would the mining to supply them.

CATALOGTREE (*illustrations*); NICHOLAS EVELEIGH *Getty Images* (*plug*)



[THE AUTHORS]

Mark Z. Jacobson is professor of civil and environmental engineering at Stanford University and director of the Atmosphere/Energy Program there. He develops computer models to study the effects of energy technologies and their emissions on climate and air pollution. **Mark A. Delucchi** is a research scientist at the Institute of Transportation Studies at the University of California, Davis. He focuses on energy, environmental and economic analyses of advanced, sustainable transportation fuels, vehicles and systems.




The Materials Hurdle

The scale of the WWS infrastructure is not a barrier. But a few materials needed to build it could be scarce or subject to price manipulation.

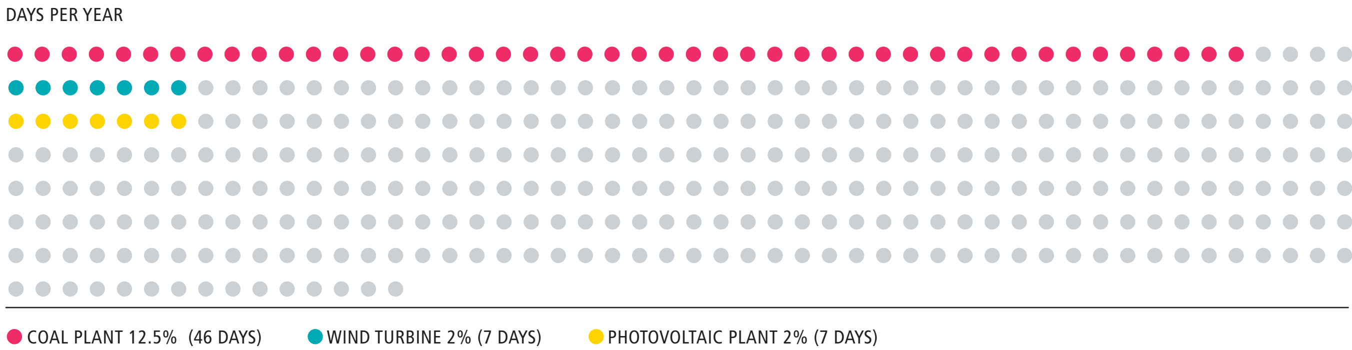
Enough concrete and steel exist for the millions of wind turbines, and both those commodities are fully recyclable. The most problematic materials may be rare-earth metals such as neodymium used in turbine gearboxes. Although the metals are not in short supply, the low-cost sources are concentrated in China, so countries such as the U.S. could be trading dependence on Middle Eastern oil for dependence on Far Eastern metals. Manufacturers are moving toward gearless turbines, however, so that limitation may become moot.

Photovoltaic cells rely on amorphous or crystalline silicon, cadmium telluride, or copper indium selenide and sulfide. Limited supplies of tellurium and indium could reduce the prospects for some types of thin-film solar cells, though not for all; the other types might be able to take up the slack. Large-scale production could be restricted by the silver that cells require, but finding ways to reduce the silver content could tackle that hurdle. Recycling parts from old cells could ameliorate material difficulties as well.

Three components could pose challenges for building millions of electric vehicles: rare-earth metals for electric motors, lithium for lithium-ion batteries and platinum for fuel cells. More than half the world's lithium reserves lie in Bolivia and Chile. That concentration, combined with rapidly growing demand, could raise prices significantly. More problematic is the claim by Meridian International Research that not enough economically recoverable lithium exists to build anywhere near the number of batteries needed in a global electric-vehicle economy. Recycling could change the equation, but the economics of recycling depend in part on whether batteries are made with easy recyclability in mind, an issue the industry is aware of. The long-term use of platinum also depends on recycling; current available reserves would sustain annual production of 20 million fuel-cell vehicles, along with existing industrial uses, for fewer than 100 years.

CATALOGTREE (*illustration*); COURTESY OF MARK Z. JACOBSON (*Jacobson*); COURTESY OF KAREN DELUCCHI (*Delucchi*)

AVERAGE DOWNTIME FOR ANNUAL MAINTENANCE



Smart Mix for Reliability

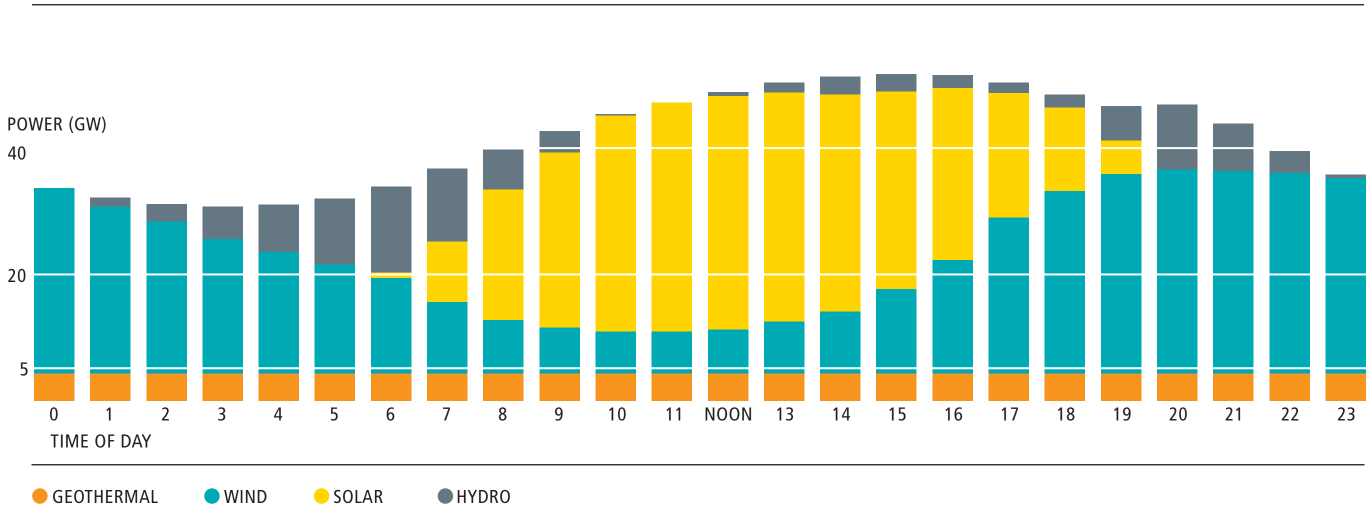
A new infrastructure must provide energy on demand at least as reliably as the existing infrastructure. WWS technologies generally suffer less downtime than traditional sources. The average U.S. coal plant is offline 12.5 percent of the year for scheduled and unscheduled maintenance. Modern wind turbines have a down time of less than 2 percent on land and less than 5 percent at sea. Photovoltaic systems are also at less than 2 percent. Moreover, when an individual wind, solar or wave device is down, only a small fraction of production is affected; when a coal, nuclear or natural gas plant goes offline, a large chunk of generation is lost.

The main WWS challenge is that the wind does not always blow and the sun does not always shine in a given location. Intermittency problems can be mitigated by a smart balance of sources, such as generating a base supply from steady geothermal or tidal power, relying on wind at night when it is often plentiful, using solar by day and turning to a reliable source such as hydroelectric that can be turned on and off quickly to smooth out supply or meet peak demand. For example, interconnecting wind farms that are only 100 to 200 miles apart can compensate for hours of zero power at any one farm should the wind not be blowing there. Also helpful is interconnecting geographically dispersed sources so they can back up one another, installing smart electric meters in homes that automatically recharge electric vehicles when demand is low and building facilities that store power for later use.

Because the wind often blows during stormy conditions when the sun does not shine and the sun often shines on calm days with little wind, combining wind and solar can go a long way toward meeting demand, especially when geothermal provides a steady base and hydroelectric can be called on to fill in the gaps.

▼ **CALIFORNIA CASE STUDY: To show the power of combining resources, Graeme Hoste of Stanford University recently calculated how a mix of four renewable sources, in 2020, could generate 100 percent of California's electricity around the clock, on a typical July day. The hydroelectric capacity needed is already in place.**

CLEAN ELECTRICITY 24/7



CATALOGTREE

As Cheap as Coal

The mix of WWS sources in our plan can reliably supply the residential, commercial, industrial and transportation sectors. The logical next question is whether the power would be affordable. For each technology, we calculated how much it would cost a producer to generate power and transmit it across the grid. We included the annualized cost of capital, land, operations, maintenance, energy storage to help offset intermittent supply, and transmission. Today the cost of wind, geothermal and hydroelectric are all less than seven cents a kilowatt-hour (¢/kWh); wave and solar are higher. But by 2020 and beyond wind, wave and hydro are expected to be 4¢/kWh or less.

For comparison, the average cost in the U.S. in 2007 of conventional power generation and transmission was about 7¢/kWh, and it is projected to be 8¢/kWh in 2020. Power from wind turbines, for example, already costs about the same or less than it does from a new coal or natural gas plant, and in the future wind power is expected to be the least costly of all options. The competitive cost of wind has made it the second-largest source of new electric power generation in the U.S. for the past three years, behind natural gas and ahead of coal.

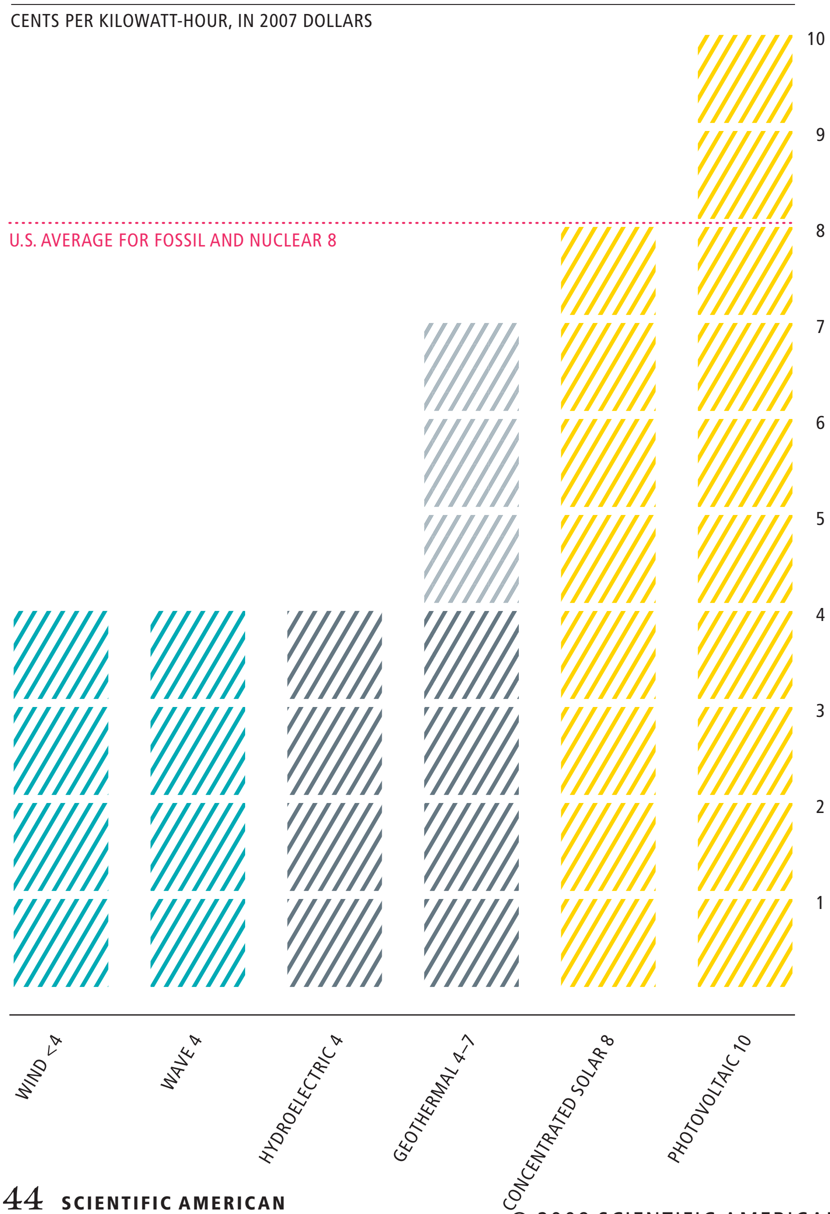
Solar power is relatively expensive now but should be competitive as early as 2020. A careful analysis by Vasilis Fthenakis of Brookhaven National Laboratory indicates that within 10 years, photovoltaic system costs could drop to about 10¢/kWh, including long-distance transmission and the cost of compressed-air storage of power for use at night. The same analysis estimates that concentrated solar power systems with enough thermal storage to generate electricity 24 hours a day in spring, summer and fall could deliver electricity at 10¢/kWh or less.

Transportation in a WWS world will be driven by batteries or fuel cells, so we should compare the economics of these electric vehicles with that of internal-combustion-engine vehicles. Detailed analyses by one of us (Delucchi) and Tim Lipman of the University of California, Berkeley, have indicated that mass-produced electric vehicles with advanced lithium-ion or nickel metal-hydride batteries could have a full lifetime cost per mile (including battery replacements) that is comparable with that of a gasoline vehicle, when gasoline sells for more than $2 a gallon.

When the so-called externality costs (the monetary value of damages to human health, the environment and climate) of fossil-fuel generation are taken into account, WWS technologies become even more cost-competitive.

Overall construction cost for a WWS system might be on the order of $100 trillion worldwide, over 20 years, not including transmission. But this is not money handed out by governments or consumers. It is investment that is paid back through the sale of electricity and energy. And again, relying on traditional sources would raise output from 12.5 to 16.9 TW, requiring thousands more of those plants, costing roughly $10 trillion, not to mention tens of trillions of dollars more in health, environmental and security costs. The WWS plan gives the world a new, clean, efficient energy system rather than an old, dirty, inefficient one.

COST TO GENERATE AND TRANSMIT POWER IN 2020



CATALOGTREE

▲ **COAL MINERS and other fossil-fuel workers, unions and lobbyists are likely to resist a transformation to clean energy; political leaders will have to champion the cause.**

Political Will

Our analyses strongly suggest that the costs of WWS will become competitive with traditional sources. In the interim, however, certain forms of WWS power will be significantly more costly than fossil power. Some combination of WWS subsidies and carbon taxes would thus be needed for a time. A feed-in tariff (FIT) program to cover the difference between generation cost and wholesale electricity prices is especially effective at scaling-up new technologies. Combining FITs with a so-called declining clock auction, in which the right to sell power to the grid goes to the lowest bidders, provides continuing incentive for WWS developers to lower costs. As that happens, FITs can be phased out. FITs have been implemented in a number of European countries and a few U.S. states and have been quite successful in stimulating solar power in Germany.

Taxing fossil fuels or their use to reflect their environmental damages also makes sense. But at a minimum, existing subsidies for fossil energy, such as tax benefits for exploration and extraction, should be eliminated to level the playing field. Misguided promotion of alternatives that are less desirable than WWS power, such as farm and production subsidies for biofuels, should also be ended, because it delays deployment of cleaner systems. For their part, legislators crafting policy must find ways to resist lobbying by the entrenched energy industries.

Finally, each nation needs to be willing to invest in a robust, long-distance transmission system that can carry large quantities of WWS power from remote

JEFF GENTNER *AP Photo* (protesters); DON FARRALL *Getty Images* (coal)

➥ MORE TO EXPLORE

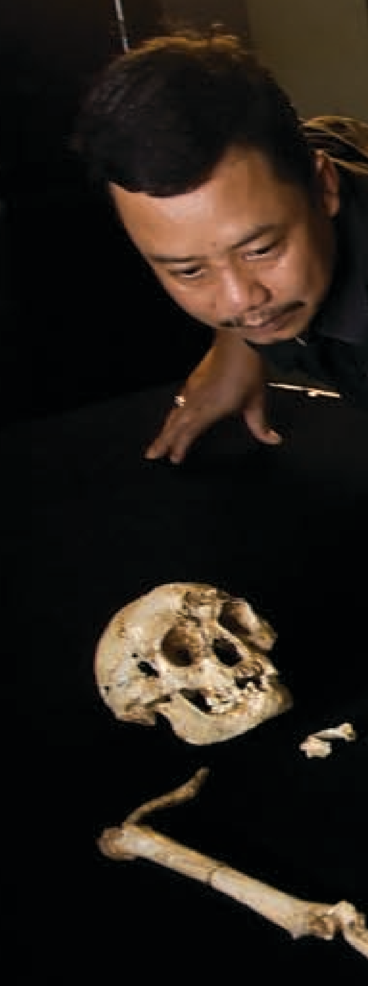
Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. S. Pacala and R. Socolow in *Science*, Vol. 305, pages 968–972; 2004.

Evaluation of Global Wind Power. Cristina L. Archer and Mark Z. Jacobson in *Journal of Geophysical Research—Atmospheres,* Vol. 110, D12110; June 30, 2005.

Going Completely Renewable: Is It Possible (Let Alone Desirable)? B. K. Sovacool and C. Watts in *The Electricity Journal,* Vol. 22, No. 4, pages 95–111; 2009.

Review of Solutions to Global Warming, Air Pollution, and Energy Security. M. Z. Jacobson in *Energy and Environmental Science,* Vol. 2, pages 148–173; 2009.

The Technical, Geographical, and Economic Feasibility for Solar Energy to Supply the Energy Needs of the U.S. V. Fthenakis, J. E. Mason and K. Zweibel in *Energy Policy,* Vol. 37, pages 387–399; 2009.



Rethinking the Hobbits of Indonesia

New analyses reveal the mini human species to be even stranger than previously thought and hint that major tenets of human evolution need revision

BY KATE WONG

PHOTOGRAPHS BY DJUNA IVEREIGH

KEY CONCEPTS

- In 2004 researchers working on the island of Flores in Indonesia found bones of a miniature human species—formally named *Homo floresiensis* and nicknamed the hobbit—that lived as recently as 17,000 years ago.
- Scientists initially postulated that *H. floresiensis* descended from *H. erectus*, a human ancestor with body proportions similar to our own.
- New investigations show that the hobbits were more primitive than researchers thought, however—a finding that could overturn key assumptions about human evolution.

—The Editors

In 2004 a team of Australian and Indonesian scientists who had been excavating a cave called Liang Bua on the Indonesian island of Flores announced that they had unearthed something extraordinary: a partial skeleton of an adult human female who would have stood just over a meter tall and who had a brain a third as large as our own. The specimen, known to scientists as LB1, quickly received a fanciful nickname—the hobbit, after writer J.R.R. Tolkien's fictional creatures. The team proposed that LB1 and the other fragmentary remains they recovered represent a previously unknown human species, *Homo floresiensis*. Their best guess was that *H. floresiensis* was a descendant of *H. erectus*—the first species known to have colonized outside of Africa. The creature evolved its small size, they surmised, as a response to the limited resources available on its island home—a phenomenon that had previously been documented in other mammals, but never humans.

The finding jolted the paleoanthropological community. Not only was *H. floresiensis* being held up as the first example of a human following the so-called island rule, but it also seemed to reverse a trend toward ever larger brain size over the course of human evolution. Furthermore, the same deposits in which the small-bodied, small-brained individuals were found also yielded stone tools for hunting and butchering animals, as well as remainders of fires for cooking them—rather advanced behaviors for a creature with a brain the size of a chimpanzee's. And astonishingly, LB1 lived just 18,000 years ago—thousands of years after our other late-surviving relatives, the Neandertals and *H. erectus*, disappeared [see "The Littlest Human," by Kate Wong; Scientific American, February 2005].

Skeptics were quick to dismiss LB1 as nothing more than a modern human with a disease that

stunted her growth. And since the announcement of the discovery, they have proposed a number of possible conditions to explain the specimen's peculiar features, from cretinism to Laron syndrome, a genetic disease that causes insensitivity to growth hormone. Their arguments have failed to convince the hobbit proponents, however, who have countered each diagnosis with evidence to the contrary.

A Perplexing Pastiche

Nevertheless, new analyses are causing even the proponents to rethink important aspects of the original interpretation of the discovery. The recent findings are also forcing paleoanthropologists to reconsider established views of such watershed moments in human evolution as the initial migration out of Africa by hominins (the group that includes all the creatures in the human line since it branched away from chimps).

Perhaps the most startling realization to emerge from the latest studies is how very primitive LB1's body is in many respects. (To date, excavators have recovered the bones of an estimated 14 individuals from the site, but LB1 remains the most complete specimen by far.) From the outset, the specimen has invited comparisons to the 3.2-million-year-old Lucy—the best-known representative of a human ancestor called *Australopithecus afarensis*—because they were about the same height and had similarly small brains. But it turns out LB1 has much more than size in common with Lucy and other pre-*erectus* hominins. And a number of her features are downright apelike.

A particularly striking example of the bizarre morphology of the hobbits surfaced this past May, when researchers led by William L. Jungers of Stony Brook University published their analysis of LB1's foot. The foot has a few modern fea-

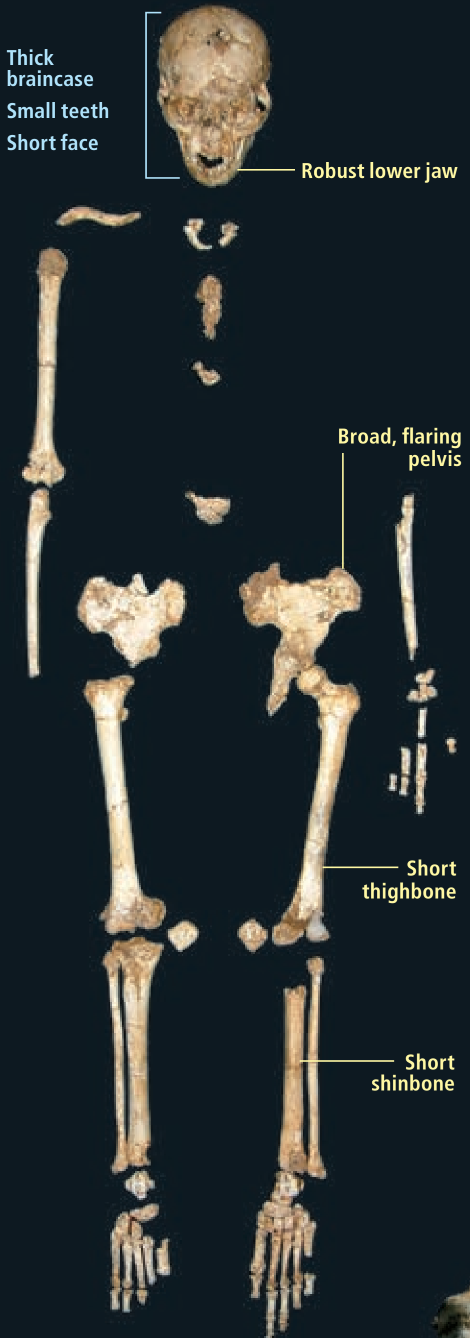
STRANGE SKELETON from Flores, Indonesia, calls into question which human ancestor was the first to leave Africa—and when. Archaeologist Thomas Sutikna (*left*) is one of the leaders of the excavation of the cave that yielded the skeleton.

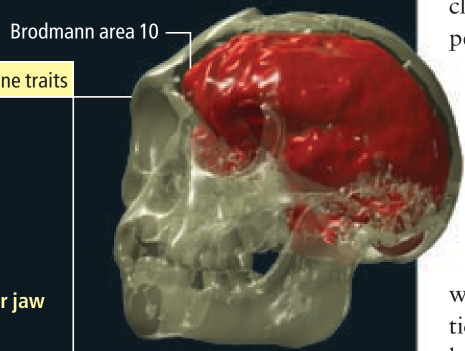
[THE EVIDENCE]

A Mysterious Mosaic

To date, excavators have recovered the remains of about 14 individuals from Liang Bua, a cave site on Flores. The most complete specimen is a nearly complete skeleton called LB1 that dates to 18,000 years ago. Some of its characteristics call to mind those of apes and of australopithecines such as the 3.2-million-year-old Lucy. Other traits, however, are in keeping with those of our own genus, *Homo.* This mélange of primitive features (*yellow*) and modern ones (*blue*) has made it difficult to figure out where on the human family tree the hobbits belong.

Homo traits | Ape and australopithecine traits





BRAIN is the size of a chimpanzee's. But a virtual reconstruction—generated from CT scans of the interior of the braincase—indicates that despite its small size, the organ had a number of advanced features, including an enlarged Broadmann area 10, a part of the brain that has been theorized to play a role in complex cognitive activities. Such features may help explain how a creature with a brain the size of a chimp's was able to make stone tools.

WRIST resembles that of an African ape. Of particular interest is a bone called the trapezoid (*shown*), which has a pyramidal form. Modern humans, in contrast, have a trapezoid shaped like a boot, which facilitates tool manufacture and use by better distributing forces across the hand.

FOOT is exceptionally long compared with the short leg. This relative foot length is comparable to that seen in bonobos, and it suggests the hobbits were inefficient runners. Other apelike traits include long, curved toes and the absence of an arch. Yet the big toe aligns with the rest of the toes, among other modern characteristics.

tures—for instance, the big toe is aligned with the other toes, as opposed to splaying out to the side as it does in apes and australopithecines. But by and large, it is old-fashioned. Measuring around 20 centimeters in length, LB1's foot is 70 percent as long as her short thighbone, a ratio unheard of for a member of the human family. The foot of a modern human, in contrast, is on average 55 percent as long as the femur. The closest match to LB1 in this regard, aside from, perhaps, the large-footed hobbits of Tolkien's imagination, is a bonobo. Furthermore, LB1's big toe is short, her other toes are long and slightly curved, and her foot lacks a proper arch—all primitive traits.

"A foot like this one has never been seen before in the human fossil record," Jungers declared in a statement released to the press. It would not have made running easy. Characteristics of the pelvis, leg and foot make clear that the hobbits walked upright. But with their short legs and relatively long feet, they would have had to use a high-stepping gait to avoid dragging their toes on the ground. Thus, although they could probably sprint short distances—say, to avoid becoming dinner for one of the Komodo dragons that patrolled Flores—they would not have won any marathons.

If the foot were the only part of the hobbit to exhibit such primitive traits, scientists might have an easier time upholding the idea that *H. floresiensis* is a dwarfed descendant of *H. erectus* and just chalking the foot morphology up to an evolutionary reversal that occurred as a consequence of dwarfing. But the fact is that archaic features are found throughout the entire skeleton of LB1. A bone in the wrist called the trapezoid, which in our own species is shaped like a boot, is instead shaped like a pyramid, as it is in apes; the clavicle is short and quite curved, in contrast to the longer, straighter clavicle that occurs in hominins of modern body form; the pelvis is basin-shaped, as in australopithecines, rather than funnel-shaped, as in *H. erectus* and other later *Homo* species. The list goes on.

Indeed, from the neck down LB1 looks more like Lucy and the other australopithecines than *Homo*. But then there is the complicated matter of her skull. Although it encased a grapefruit-size brain measuring just 417 cubic centimeters—a volume within the range of chimpanzees and australopithecines—other cranial features, such as the narrow nose and prominent brow arches over each eye socket, mark LB1 as a member of our genus, *Homo*.

WILLIAM L. JUNGERS *Stony Brook University (skeleton)*; COURTESY OF KIRK E. SMITH *Mallinckrodt Institute of Radiology, Washington University School of Medicine (skull)*

Primitive Roots

Fossils that combine *Homo*-like skull characteristics with primitive traits in the trunk and limbs are not unprecedented. The earliest members of our genus, such as *H. habilis,* also exhibit a hodgepodge of old and new. Thus, as details of the hobbits' postcranial skeletons have emerged, researchers have increasingly wondered whether the little Floresians might belong to a primitive *Homo* species, rather than having descended from *H. erectus,* which scientists believe had modern body proportions.

A new analysis conducted by doctoral candidate Debbie Argue of the Australian National University in Canberra and her colleagues bolsters this view. To tackle the problem of how the hobbits are related to other members of the human family, the team employed cladistics—a method that looks at shared, novel traits to work out relationships among organisms—comparing anatomical characteristics of LB1 to those of other members of the human family, as well as apes.

In a paper in press at the *Journal of Human Evolution,* Argue and her collaborators report that their results suggest two possible positions for the *H. floresiensis* branch of the hominin family tree. The first is that *H. floresiensis* evolved after a hominin called *H. rudolfensis,* which arose some 2.3 million years ago but before *H. habilis,* which appeared roughly two million years ago. The second is that it emerged after *H. habilis* but still well before *H. erectus,* which arose around 1.8 million years ago. More important, Argue's team found no support for a close relationship between *H. floresiensis* and *H. erectus,* thereby dealing a blow to the theory that the hobbits were the product of island dwarfing of *H. erectus.* (The study also rejected the hypothesis that hobbits belong to our own species.)

If the hobbits are a very early species of *Homo* that predates *H. erectus,* that positioning on the family tree would go a long way toward accounting for LB1's tiny brain, because the earliest members of our genus had significantly less gray matter than the average *H. erectus* possessed. But Argue's findings do not solve the brain problem entirely. LB1 aside, the smallest known noggin in the genus *Homo* is a *H. habilis* specimen with an estimated cranial capacity of 509 cubic centimeters. LB1's brain was some 20 percent smaller than that.

Could island dwarfing still have played a role in determining the size of the hobbit's brain? When the discovery team first attributed LB1's wee brain to this phenomenon, critics complained that her brain was far smaller than it should be for a hominin of her body size, based on known scaling relationships. Mammals that undergo dwarfing typically exhibit only moderate reduction in brain size. But study results released this past May suggest that dwarfing of mammals on islands may present a special case. Eleanor Weston and Adrian Lister of the Natural History Museum in London found that in several species of fossil hippopotamus that became dwarfed on the African island nation of Madagascar, brain size shrank significantly more than predicted by standard scaling models. Based on their hippo model, the study authors contend, even an ancestor the size of *H. erectus* could conceivably attain the brain and body proportions of LB1 through island dwarfing.

The work on hippos has impressed researchers such as Harvard University's Daniel Lieberman. In a commentary accompanying Weston and Lister's report in *Nature,* Lieberman wrote that their findings "come to the rescue" in terms of explaining how *H. floresiensis* got such a small brain.

Although some specialists favor the original interpretation of the hobbits, Mike Morwood of the University of Wollongong in Australia, who helps to coordinate the Liang Bua project, now thinks the ancestors of LB1 and the gang were early members of *Homo* who were already small—much smaller than even the tiniest known *H. erectus* individuals—when they arrived on Flores and then "maybe underwent a little insular dwarfing" once they got there.

Did *Homo sapiens* Copy Hobbits?

Analysis of hobbit implements spanning the time from 95,000 to 17,000 years ago indicates that the tiny toolmakers used the same so-called Oldowan techniques that human ancestors in Africa employed nearly two million years ago. The hobbits combined these techniques in distinctive ways, however—a tradition that the modern humans who inhabited Liang Bua starting 11,000 years ago followed, too. This finding raises the intriguing possibility that the two species made contact and that *H. sapiens* copied the hobbits' style of tool manufacture, rather than the other way around.

HOBBIT KNIFE

SICK HUMAN HYPOTHESES

Scientists who doubt that LB1 belongs to a new human species argue that she is simply a modern human with a disease resulting in a small body and small brain. Those who think LB1 does represent a new species, however, have presented anatomical evidence against each of the proposed diagnoses, several of which are listed below.

Laron syndrome, a genetic disease that causes insensitivity to growth hormone.

Myxoedematous endemic cretinism, a condition that arises from prenatal nutritional deficiencies that hinder the thyroid.

Microcephalic osteodysplastic primordial dwarfism type II, a genetic disorder whose victims have small bodies and small brains but nearly normal intelligence.

[FIELD NOTES]

Digging for Hobbits

Liang Bua (*right*) is a large limestone cave located in the lush highlands of western Flores. Beyond the remains of some 14 hobbits, excavations there have yielded thousands of stone tools, as well as the bones of Komodo dragons, elephantlike stegodonts, giant rats and a carnivorous bird that stood some three meters high. The hobbits seem to have occupied the cave from around 100,000 to 17,000 years ago, They may have been drawn to Liang Bua because of its proximity to the Wae Racang River, which would have attracted thirsty prey animals. Researchers are now looking for clues to why, after persisting for so long, the hobbits eventually vanished. They are also eager to recover a second small skull. Such a find would establish that LB1 and the other specimens do indeed represent a new species and are not just the remains of diseased modern humans. Bones and teeth containing DNA suitable for analysis would be likewise informative. —***K.W.***

▲ The hobbit occupation levels at Liang Bua extend deep into the moist ground. To keep the walls of the trenches from collapsing, which could kill workers, the team employs a sophisticated shoring system.

▶ Inside the pit team members carefully scrape away dirt layer by layer, exposing bones and artifacts as they go. They record the position of each item of interest before placing it into a plastic bag. Meanwhile the dirt itself is loaded into buckets that are sent up to the surface for closer inspection.

▼ An excavator examines a *Stegodon* rib. The concentration of stone tools in this spot indicates that the hobbits butchered the creature here.

▲ The sediment removed from the excavation pit is thoroughly examined for bone and artifact fragments that might have gone unnoticed in the pit. The local Manggarai villagers who work at the site sort through the sediment in three stages: first with their hands (*shown*), then by sieving the dry sediment through screens, and last by taking the sediment bucket by bucket out to a station set up in the rice paddy outside the cave and wetting the contents before sieving them again, in hopes of recovering even the tiniest teeth and shards of bone.

Artifacts left behind by the hobbits support the claim that *H. floresiensis* is a very primitive hominin. Early reports on the initial discovery focused on the few stone tools found in the hobbit levels at Liang Bua that were surprisingly sophisticated for a such a small-brained creature—an observation that skeptics highlighted to support their contention that the hobbits were modern humans, not a new species. But subsequent analyses led by Mark W. Moore of the University of New England in Australia and Adam R. Brumm of the University of Cambridge have revealed the hobbit toolkit to be overall quite basic and in line with the implements produced by other small-brained hominins. The advanced appearance of a handful of the hobbit tools at Liang Bua, Moore and Brumm concluded, was produced by chance, which is not unexpected considering that the hobbits manufactured thousands of implements.

To make their tools, the hobbits removed large flakes from rocks outside the cave and then struck smaller flakes off the large flakes inside the cave, employing the same simple stone-working techniques favored by humans at another site on Flores 50 kilometers east of Liang Bua called Mata Menge 880,000 years ago—long before modern humans showed up on the island. (The identity of the Mata Menge toolmakers is unknown, because no human remains have turned up there yet, but they conceivably could be the ancestors of the diminutive residents of Liang Bua.) Furthermore, the Liang Bua and Mata Menge tools bear a striking resemblance to artifacts from Olduvai Gorge in Tanzania that date to between 1.2 million and 1.9 million years ago and were probably manufactured by *H. habilis*.

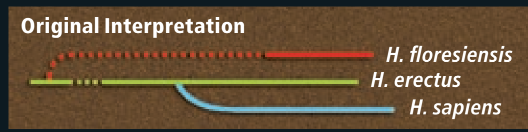
Tiny Trailblazer

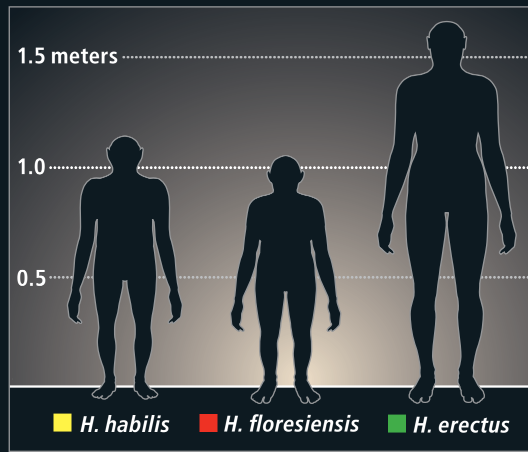
In some ways, the latest theory about the enigmatic Flores bones is even more revolutionary that the original claim. "The possibility that a very primitive member of the genus *Homo* left Africa, perhaps roughly two million years ago, and that a descendant population persisted until only several thousand years ago, is one of the more provocative hypotheses to have emerged in paleoanthropology during the past few years," reflects David S. Strait of the University at Albany. Scientists have long believed that *H. erectus* was the first member of the human family to march out of the natal continent and colonize new lands, because that is the hominin whose remains appear outside of Africa earliest in the fossil record. In explanation, it was pro-

[FINDINGS]

The Hobbits' Roots

Researchers originally believed that LB1 (*left*) and the other hobbits, formally known as *Homo floresiensis,* were descendants of a human ancestor with essentially modern body proportions known as *H. erectus* that shrank dramatically in response to the limited resources available on their island home. But a new analysis suggests *H. floresiensis* is significantly more primitive than *H. erectus* and evolved either right after one of the earliest known members of our genus, *H. habilis* (*right tree*) or right before it (*far right tree*). Either way, the study implies that *H. floresiensis* evolved in Africa, along with the other early *Homo* species, and was already fairly small when the species reached Flores, although it may have undergone some dwarfing when it got there.





posed that humans needed to evolve large brains and long striding limbs and to invent sophisticated technology before they could finally leave their homeland.

Today the oldest unequivocal evidence of humans outside of Africa comes from the Republic of Georgia, where researchers have recovered *H. erectus* remains dating to 1.78 million years ago [see "Stranger in a New Land," by Kate Wong; Scientific American, November 2003]. The discovery of the Georgian remains dispelled that notion of a brawny trailblazer with a tricked-out toolkit, because they were on the small side for *H. erectus*, and they made Oldowan tools, rather than the advanced, so-called Acheulean implements experts expected the first pioneers to make. Nevertheless, they were *H. erectus*.

But if proponents of the new view of hobbits are right, the first intercontinental migrations were undertaken hundreds of thousands of years earlier than that—and by a fundamentally different kind of human, one that arguably had more in common with primitive little Lucy than the colonizer paleoanthropologists had envisioned. This scenario implies that scientists could conceivably locate a long-lost chapter of human prehistory in the form of a two-million-year record of this primitive pioneer stretching between Africa and Southeast Asia if they look in the right places.

This suggestion does not sit well with some researchers. "The further back we try to push the divergence of the Flores [hominin], the more difficult it becomes to explain why a [hominin] lineage that must have originated in Africa has left only one trace on the tiny island of Flores," comments primate evolution expert Robert Martin of the Field Museum in Chicago. Martin remains unconvinced that *H. floresiensis* is a legitimate new species. In his view, the possibility that LB1—the only hobbit whose brain size is known—was a modern human with an as yet unidentified disorder that gave rise to a small brain has not been ruled out. The question, he

[IMPLICATIONS]

➥ MORE TO EXPLORE

The Primitive Wrist of *Homo floresiensis* and Its Implications for Hominin Evolution. Matthew W. Tocheri et al. in *Science,* Vol. 317, pages 1743–1745; September 21, 2007.

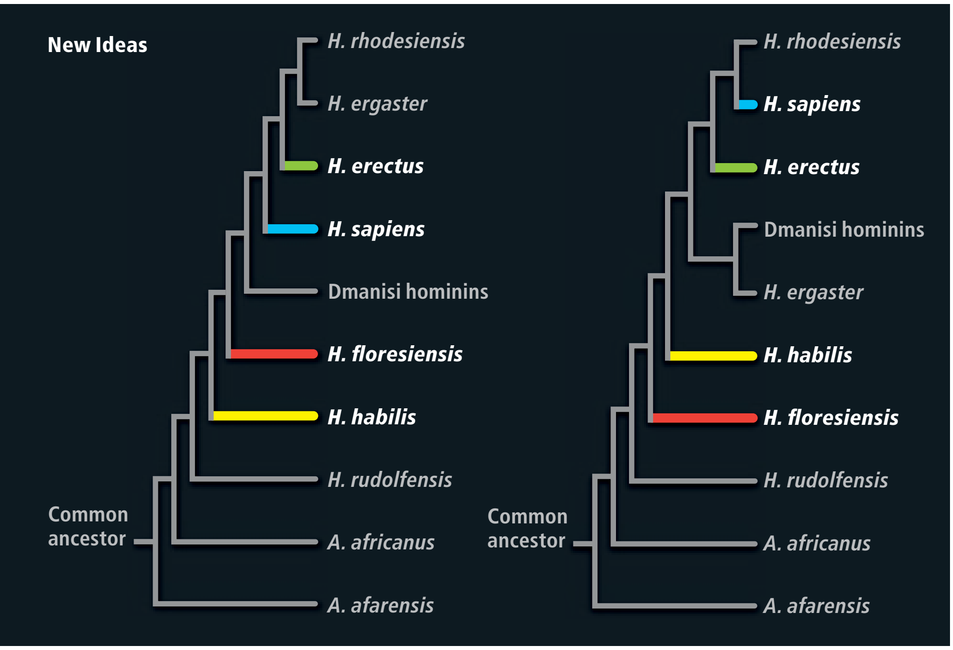
A New Human: The Startling Discovery and Strange Story of the "Hobbits" of Flores, Indonesia. Mike Morwood and Penny van Oosterzee. Smithsonian, 2007.

The Foot of *Homo floresiensis.* W. L. Jungers et al. in *Nature,* Vol. 459, pages 81–84; May 7, 2009.

***Homo floresiensis* and the African Oldowan.** Mark W. Moore and Adam R. Brumm in *Interdisciplinary Approaches to the Oldowan.* Edited by Erella Hovers and David R. Braun. Springer, 2009.

***Homo floresiensis:* A Cladistic Analysis.** Debbie Argue et al. in *Journal of Human Evolution* (in press).

LB1's Virtual Endocast, Microcephaly and Hominin Brain Evolution. Dean Falk et al. in *Journal of Human Evolution* (in press).



BASED ON "*HOMO FLORESIENSIS*: A CLADISTIC ANALYSIS," DEBBIE ARGUE ET AL. IN *JOURNAL OF HUMAN EVOLUTION* (IN PRESS) (*trees*)

says, is whether such a condition can also explain the australopithecinelike body of LB1.

In the meantime, many scientists are welcoming the shake-up. LB1 is "a hominin that no one would be saying anything about if we found it in Africa two million years ago," asserts Matthew W. Tocheri of the Smithsonian Institution, who has analyzed the wrist bones of the hobbits. "The problem is that we're finding it in Indonesia in essentially modern times." The good news, he adds, is that it suggests more such finds remain to be recovered.

"Given how little we know about the Asian hominin record, there is plenty of room for surprises," observes Robin W. Dennell of the University of Sheffield in England. Dennell has postulated that even the australopithecines might have left Africa, because the grasslands they had colonized in Africa by three million years ago extended into Asia. "What we need, of course, are more discoveries—from Flores, neighboring islands such as Sulawesi, mainland Southeast Asia or anywhere else in Asia," he says.

Morwood, for his part, is attempting to do just that. In addition to the work at Liang Bua and Mata Menge, he is helping to coordinate two projects on Sulawesi. And he is eyeing Borneo, too. Searching the mainland for the ancestors of the Liang Bua hobbits will be difficult, however, because rocks of the right age are rarely exposed in this part of the world. But with stakes this high, such challenges are unlikely to prevent intrepid fossil hunters from trying. "If we don't find something in the next 15 years or so in that part of the world, I might start wondering whether we got this wrong," Tocheri reflects. "The predictions are that we should find a whole bunch more." ■

Kate Wong is a staff editor and writer at Scientific American.

Blazing a Trail

The textbook account of human origins holds that *H. erectus* was the first human ancestor to wander out of Africa and colonize distant lands around 1.8 million years ago. But the evidence from Flores suggests that an older, more primitive forebear was the original pioneer, one who ventured away from the natal continent perhaps around two million years ago. If so, then paleoanthropologists may have missed a significant chunk of the human fossil record spanning nearly two million years and stretching from Africa to Southeast Asia.

Already hobbit hunter Mike Morwood (*right*) is looking for more remains of *H. floresiensis* and its ancestors at two sites on Sulawesi. And he thinks further excavation at Niah cave in north Borneo could produce evidence of hominins much older than the ones at Liang Bua. The mainland will be harder to comb, because rocks of the right age are rarely exposed there.

The Everything TV

The Internet stands ready to upend the television-viewing experience, but exactly how is a matter of considerable dispute

BY MICHAEL MOYER

KEY CONCEPTS

- High-quality video is migrating online, but forces in the cable and entertainment industries are trying to slow down and control the process.
- The structure of broadband access in the U.S. subordinates Internet content to cable television delivery.
- Viewing Internet content on your television requires a user interface that is powerful enough to find and organize the near-infinite content available online but easy enough to use with a simple remote control.

—The Editors

It should not be so difficult. In an age when nearly all forms of media are digital, where broadband signals course through the industrial world as surely (and as critically) as electricity and freshwater, it should be possible to sit on one's couch, push a button or two, and call up to your television any form of video-related entertainment you desire. New-release movies. Last week's *Lost*. The first season of *Cosmos*. Setup should not require an electrical engineering degree, and you should not be forced to sift through 10 incompatible search functions to find the shows you desire.

Yet it is not easy to watch what you want when you want to. The reasons are not easily parsed and depend as much on technological circumstance as they do on the well-placed fears of entrenched industry powers. Digital distribution threatens their business models like nothing in the history of media, but as the music industry so dramatically illustrated, fighting the consumer's desire for limitless content is a loser's game. "I guarantee that five years from now TV as we know it is gone," says Doc Searls, a fellow at the Berkman Center for Internet and Society at Harvard University. "It will have been a 60-year-old experiment that will be followed by something else." The major film studios are beginning to upload onto the Web their most precious material, and a plethora of devices are emerging that promise to help the confused consumer pull the richness of the Internet into his or her television. Behind the digital scenes, battles are now taking place that will shape the future of video for decades to come.

The Third Era

The Internet's invasion of the living room marks what might be called the third era of television. The first era arrived in the middle of the last century via bunny ears and national broadcast networks such as NBC and ABC that still command most television viewers. In the 1980s cable television ushered in the second era by using a new transmission technology—copper wires bundled into coaxial cables—to transmit hundreds more channels into the home.

Although cable greatly expanded the menu of

SPLASHLIGHT; COURTESY OF BROADWAY VIDEO ENTERPRISES AND NBC STUDIOS, INC. (*SNL* icon)

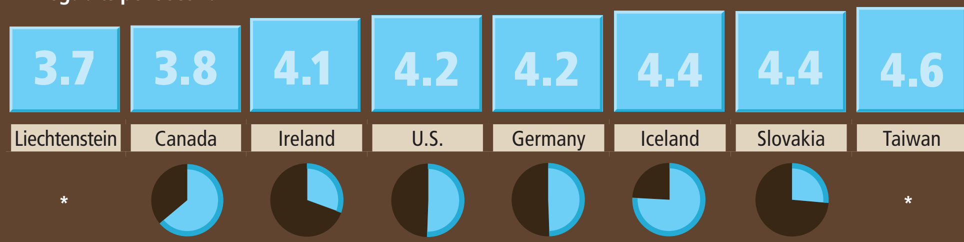

Search
Live
News
Sports
Streaming
Sitcoms
Favorites
Matt Damon
SNL
User-generated
Photos
Videos
Options
Recents

[DATA RATES]

The Fastest Internet

Network-heavy applications such as high-definition streaming video require fast Internet connections. Yet only 50.8 percent of U.S. households are served by broadband, and those that are access a relatively pokey signal compared with the offerings in Asia and in northern and eastern Europe.

FAST, FASTER, FASTEST
Average broadband connection speed in megabits per second

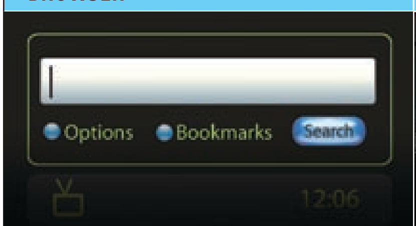
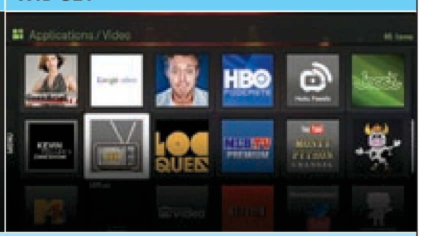


Percentage of households with broadband (*blue*)

available content, it came at a price: what was once literally free to pluck from the air now had a serious monthly bill attached. Network TV was financed exclusively by commercials; cable networks such as MTV and the Food Network collect a fee—on average about $0.25 per customer per month—that comes out of your cable bill. (This average excludes ESPN, which demands about $3 per customer per month from the cable companies.)

THE REMOTE PROBLEM

At a computer, navigating Internet content is simple: just use the keyboard and mouse. Once the Internet comes to the television screen, viewers require a system that allows for easy on-screen navigation from the couch—what is known as a "10-foot user interface." The two major contenders are browser- and widget-based systems, each with its own pros and cons.

BROWSER	WIDGET
	
WHAT IT IS	
Much like on a typical computer desktop, an Internet browser allows you to access anything on the Web by clicking on its bookmark or typing in its Web address.	The television screen displays only a select number of icons, or widgets. Each widget accesses a separate service, such as YouTube or Hulu.
HARDWARE	
Typing in Web addresses and following links requires a wireless keyboard and mouse, unwieldy additions to the living room.	The simplicity of moving to and clicking on an icon requires only a typical remote control.
LIMITATIONS	
Anything on the Web you want, you can get. This solution essentially turns your television into a large computer monitor.	Only approved widgets appear on the television, putting your choice of content in someone else's hands. Hulu, for instance, has blocked its content from Yahoo! widgets.

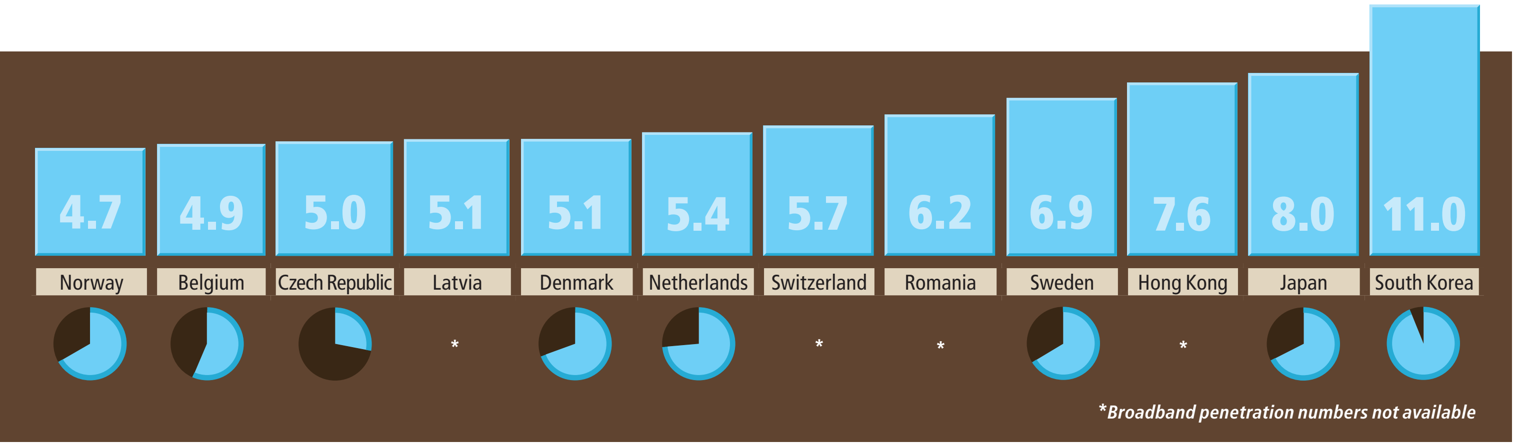
In the late 1990s engineers working with the @Home startup figured out a way to deliver digital data on top of cable television signals. This meant that cable customers could get broadband Internet without additional infrastructure. Today about 36.5 million households nationwide use cable modems to get online, making it the most popular way to access the Internet in the U.S. Yet ironically, the relative ubiquity of cable broadband is one of the primary forces holding back third-generation television.

Cable companies grew into corporate giants by delivering the second generation of television. They are television distributors that also happen to deliver the Internet, not the other way around. Thus, despite the engineering workarounds that allow them to pipe the Internet via their copper wires, their systems are still optimized for television. On cable systems, the Web comes through the bandwidth reserved for a channel or a set of channels. It receives as much in the way of resources as does, say, ESPN and its four siblings. "There is a standing engineering set of specifications that almost requires the Internet be subordinated to television," Searls says.

Almost as many U.S. households receive broadband through a telephone company's digital subscriber line (DSL) service, but the story here is much the same: existing infrastructure—in this case, copper telephone lines—have been repurposed for high-speed Internet signals. The Internet is a secondary concern in this electronic ecosystem as well.

This setup makes it nearly impossible to get a true televisionlike experience over existing infrastructure, which shows in the quality of broadband available: the U.S. ranks just 18th in average broadband download speeds, slower than Romania, Iceland and the Czech Republic. Average download speeds in South Korea, the world's leader, are nearly three times as fast as in the U.S. According to Phil McKinney, vice pres-

JEN CHRISTIANSEN; SOURCE: *AKAMAI REPORT: THE STATE OF THE INTERNET*, Q1, 2009, AND OECD BROADBAND STATISTICS, 2008; COURTESY OF BOXEE (*screen shot*)



ident and chief technology officer of HP's Personal Systems Group, the network in the U.S. is the "fundamentally constrained resource."

There is hope, however. Although telecom companies such as Verizon and AT&T also deliver cable television through their telephone lines, they are not as closely wedded to the TV-first model as the cable companies are. Their core business is delivering telephone service. As Americans stop subscribing to dedicated landlines—at last count, one in five American households rely purely on mobile phones—these companies have begun to build the next generation of data lines feeding into the home: fiber-optic cables. The bandwidth of these services reaches up to 30 megabits per second for both uploads and downloads—about 10 times that of the typical broadband customer. That leaves plenty of room for full high-definition video streams and quick uploads of YouTube videos. It is the first neighborhood infrastructure designed and constructed explicitly for the Internet.

Strangled by Cable

Before your TV screen pulls in video via the Internet, those videos must first go up online. Copyright holders deeply fear this prospect. Movie studios fret about piracy. Over-the-air broadcasters such as NBC fear ending up like the newspaper industry, with viewership, though not advertising dollars, shifting to the Web. And cable broadcasters know that when Internet offerings grow strong enough for customers to drop their cable subscriptions—marketing surveys show cash-strapped customers will sooner drop cable than broadband Internet—their 25-cents-per-subscriber-per-month fees will evaporate as well. "The copyright holders are trying to orchestrate it so that content will only move if you pay for it," says Philip Leigh, founder of consulting firm Inside Digital Media.

Thus, content providers are gingerly experimenting with ways to deliver their wares over the Internet. The first major salvo in this experiment is the Web site Hulu.com, which NBC and Fox launched as a joint venture in 2008 (Disney, the parent company of ABC, has since signed on as well). The site is the online home to most of the popular shows that air on those broadcast networks. It streams video in such a way that the end users can neither record the shows for posterity nor skip the advertisements. By any measure, it has been a tremendous success. At this writing, it is the second most popular video site on the Internet (after YouTube); according to the ratings service Nielsen, the ratings for programs such as *Lost* on ABC would jump by as much as 25 percent if online views were included.

Free video poses an explicit threat to the cable industry, however, which is built on the premise that customers will pay $50 a month or more for programming variety. As such, you will not find shows from the Discovery Channel or MTV on any exclusively ad-supported site. Rather the cable industry is beginning to experiment with Web sites that require a proof of registration. That is, you can watch these programs on the Web, but only if you also already subscribe to cable TV. Time Warner and Comcast are introducing the "TV Everywhere" system this year, which will at first include content from six networks, including CBS, AMC and TNT. If the companies are able to recruit other channels into the project, then "TV Everywhere will surpass user-generated content and will be the biggest thing in Internet video," according to Comcast CEO Brian Roberts.

The allure for the cable companies is obvious: there is no risk of Internet video cannibalizing cable subscriptions if Internet video *requires* a cable subscription. "The carriers are also in the content business," Searls says, "and so in order to protect the business models of the primary form of content they're carrying—

GLOSSARY

BROADBAND

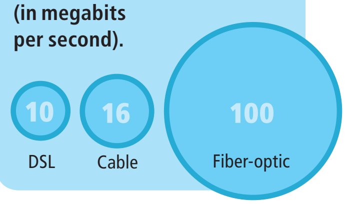
A diverse set of wired and wireless technologies that transmit information at high speeds—although just how fast a technology must be to qualify as "broadband" is a matter of contention [*see box on page 59*].

INTERNET

A global information network built on a system of software protocols that specify how information must be structured and processed. The Internet is often carried to customers through broadband connections, but the Internet must often share space on broadband with other data streams such as television and telephone signals.

BROADBAND BREAKDOWN

All broadband is not the same. Newer technology such as fiber-optic cable allows for much faster Internet connections, as measured here by the total average speed (upload plus download) of advertised Internet service across the Internet world (in megabits per second).



OECD BROADBAND STATISTICS, 2008

How to Get the Everything TV Now

In bits and pieces, Internet-based video is coming into your living room. Although no one device yet allows you to access all the content you could desire, a well-designed system will open most of the available services. Here are the key components that you should know.

WIRELESS ROUTER

First, you'll need a home network. Look for a high-bandwidth wireless router that runs the 802.11 "G" or "N" standards—older routers may be too slow to handle streaming video. Alternatively, you can run an Ethernet cable to your entertainment center.

TELEVISION

At minimum, you'll want to upgrade to a high-definition flat-panel television with at least one high-definition media interface (HDMI) input. But the newest TVs are designed to directly access the Internet. Services vary, however: some may allow you to connect to Amazon Video-on-Demand and your streaming Netflix queue; others may allow only trinkets such as a stock-market ticker. The current state-of-the-art is the Sony Bravia KDL-W5100 series ($1,500 to $5,000), which allows full access to Amazon, YouTube and Netflix.

SET-TOP BOXES

Even without the latest TV, a variety of devices can pull Internet content into your living room. Services, price and ease of use will vary, though.

Laptop • The most powerful solution is to simply use your television as a giant monitor. Look for a laptop with an HDMI output for easy setup and buy a wireless keyboard and mouse to use as controllers from your couch. The HP Pavillion dv6 does all this for $650.

Streaming stations • The Roku player ($100) has no hard drive; it is designed to stream video from Netflix on demand, Amazon.com's video library and the MLB.TV service. It can't yet access Hulu, YouTube or other standard Internet video sites. Another service called ZillionTV aims to plug some of these holes; it is expected to launch this year.

TiVo HD • Early Tivos were pure digital video recorders—devices that let you record live television to watch later. The new TiVo HD boxes also connect to the Internet and access Netflix, Amazon and YouTube ($300 to $600, depending on size of hard drive).

Apple TV • The Apple TV allows you to access the movies and TV shows available in the Apple's iTunes store but little else ($230 to $330, depending on size of hard drive).

GEORGE RETSECK (*illustration*); COURTESY OF BOXEE (*screen shot*); COURTESY OF HEWLETT-PACKARD (*laptop*); COURTESY OF ROKU (*Roku player*); COURTESY OF TIVO (*TiVo HD box*); COURTESY OF APPLE (*Apple TV box*)

which is still television—they have an incentive to keep a heavier foot on the brakes than on the accelerator pedal."

This brake is nowhere more evident than in the download limitations cable companies have begun to place on their Internet customers. Under the guise of protecting against peer-to-peer networking, where users share music and videos on a distributed network, Comcast has instituted a cap of 250 gigabytes per month on the data their customers can download or stream. Time Warner is experimenting with caps as low as five gigabytes a month. The companies claim that few customers are affected by the limits, which may currently be true. But it also kills Internet video in the cradle—a single high-definition movie will often require more than the five gigabytes Time Warner budgets for a month's worth of Internet access.

Home Connections

As Hulu has shown, there is a rich appetite for television content over the more flexible medium of the Internet. Yet getting video to your computer is one thing. Getting it to your 60-inch high-definition TV—and in a way that is easy to set up and intuitive to use—is another.

The most straightforward option is to simply connect a computer to your TV set. A standard high-definition multimedia interface cable, more commonly known by its acronym HDMI, will

WEB SITES

A growing number of Web-based services help to exploit the power of Internet-based entertainment.

BOXEE.COM
This software allows you to access most Internet-based content in an easy-to-use widget-based interface.

HULU.COM
The granddaddy of television content online, Hulu carries advertising-supported programming from NBC, Fox and Disney.

VIDEOSURF.COM
Using computer vision and image-identification technologies, this search engine scans online videos to create an index of who and what appears in them. Type in an actor, for example, and it will find all instances of that actor's online videos and in what parts of the video he or she appears.

carry digital video and audio from a recent-vintage laptop to a flat-panel TV. "Computers have become such an everyday part of our life that when we look at the television monitor it is becoming obvious that there is no difference between it and a laptop screen," says Leigh of Inside Digital Media. "Contrary to the uninitiated, consumers are not confused by this."

Connecting one's laptop to the television still leaves open the question of what to do for a remote control. Leigh's answer—use a wireless keyboard and mouse—gives the user unconstrained power over content and, crucially, the ability to type in search terms. But we are now so accustomed to one-handed operation of a remote control that it is hard to imagine how bulky keyboards will replace them on the coffee table.

There is also the question of how to find content in a world without channels. Let's say I want to watch an episode of *30 Rock*. Was that on Hulu.com? Or TV Everywhere? Right now, McKinney says, "you need a secret decoder ring to figure out where the content is." Stand-alone programs such as the free and open-source Boxee are designed to collect all video on the Internet and display on your television a single "home page" directory of everything. Yet here we see another example where open accessibility sometimes conflicts with cable's business plans.

Although Hulu was originally featured as a channel on Boxee, this past February the content providers behind Hulu—NBC, Fox and Disney—blocked Boxee from accessing the Hulu Web site. When asked about it on-stage at the *Wall Street Journal*'s "D: All Things Digital" conference in May, NBC Universal CEO Jeff Zucker said that "right now we are committed to Hulu being an online experience." One way to interpret this statement is that Hulu is not a threat to the traditional cable business so long as the content on Hulu stays on a 15-inch laptop screen. Widespread use of Boxee (and other devices that make it easy to watch Internet video on the television) would cut into the revenue that studios make from cable television fees.

There are, of course, other devices that allow you to pull content down from the Internet into your television. Apple TV accesses the iTunes store. A startup named Roku makes a small device that pulls streaming video from Netflix, the Amazon.com digital library and Major League Baseball games. Other devices go by names like Vudu and ZillionTV. But they all share one common thread: all the content is prepaid. Free television does not exist on these Internet TV devices. So long as it is more profitable for both the cable companies and the content producers to sell you TV through your cable package, expect the limitations to remain in place.

The solution, of course, would be to detangle the Internet from cable companies. The new fiber-optic systems are a step in that direction. Because they are essentially "Internet-only" systems, disentangled from the legacy business models that constrain cable operators, they allow for a potentially transformative Internet experience. Consider South Korea, where the Internet is both fast and ubiquitous. Warner Brothers has begun to scale back its DVD operations there to concentrate exclusively on Internet-delivered movies, which are now available two weeks before the DVD appears in stores. Some independent movie studios in the U.S. have even begun to experiment with Internet delivery before the movie ever gets to a theater. It might take some time to move all our media to this kind of instant-on, Internet-based future. "But it's coming," Leigh says, "and you can't stop it." ■

Michael Moyer is a staff editor and writer at Scientific American.

➥ MORE TO EXPLORE

IPTV and Internet Video: Expanding the Reach of Television Broadcasting. Wes Simpson and Howard Greenfield. Focal Press, 2007.

Organization for Economic Co-operation and Development (OECD) Communications Outlook 2009. Available online at **www.oecd.org/sti/telecom/outlook**

Public Knowledge. A Washington, D.C.–based Internet advocacy group: **www.publicknowledge.org**

[ACCESS]

The Internet's New Rules

When President Barack Obama signed the $787-billion stimulus package earlier this year, he claimed that the government would be "remaking the American landscape with the largest new investment in our nation's infrastructure since Eisenhower built an Interstate Highway System." In the 21st century infrastructure includes the Internet. The law provides for $7.2 billion in grants to upgrade and expand broadband access in the U.S., primarily in underserved rural areas that require miles of cables to reach relatively small communities. At the same time, the law requires that the Federal Communications Commission draw up a national plan for broadband by February 2010. What that plan includes—and how the grant money gets allocated—will largely define the capabilities of and restrictions on the Internet for years to come.

The primary question is whether the FCC is going to require some kind of "Net neutrality" protections in the national broadband plan. These protections would require that Internet Service Providers (ISPs) not hinder certain kinds of Internet traffic, that they treat all traffic equally. The ISPs claim that they could better preserve the overall health of the network if they were able to slow, for instance, bandwidth-heavy peer-to-peer file sharing. Yet without Net neutrality protections, ISPs would be able to block any kind of file or applications they chose, giving them the power to decide the fate of all Internet-based services.

In addition, the FCC has to decide on what, exactly, "broadband" means. It currently defines it as an advertised download speed of at least 0.77 megabit per second, a mere fraction of the average speeds of 92 megabits per second advertised in Japan. (Advertised speeds are always higher than actual speeds, because they assume a perfect connection that is not shared with other users.) A lower requirement means that more homes can be wired for less money but without the ability to stream high-quality video. *—M.M.*

The RISE of VERTICAL FARMS

Growing crops in city skyscrapers would use less water and fossil fuel than outdoor farming, eliminate agricultural runoff and provide fresh food

By Dickson Despommier

KEY CONCEPTS

- Farming is ruining the environment, and not enough arable land remains to feed a projected 9.5 billion people by 2050.
- Growing food in glass high-rises could drastically reduce fossil-fuel emissions and recycle city wastewater that now pollutes waterways.
- A one-square-block farm 30 stories high could yield as much food as 2,400 outdoor acres, with less subsequent spoilage.
- Existing hydroponic greenhouses provide a basis for prototype vertical farms now being considered by urban planners in cities worldwide.

—The Editors

Together the world's 6.8 billion people use land equal in size to South America to grow food and raise livestock—an astounding agricultural footprint. And demographers predict the planet will host 9.5 billion people by 2050. Because each of us requires a minimum of 1,500 calories a day, civilization will have to cultivate another Brazil's worth of land—2.1 billion acres—if farming continues to be practiced as it is today. That much new, arable earth simply does not exist. To quote the great American humorist Mark Twain: "Buy land. They're not making it any more."

Agriculture also uses 70 percent of the world's available freshwater for irrigation, rendering it unusable for drinking as a result of contamination with fertilizers, pesticides, herbicides and silt. If current trends continue, safe drinking water will be impossible to come by in certain densely populated regions. Farming involves huge quantities of fossil fuels, too—20 percent of all the gasoline and diesel fuel consumed in the U.S. The resulting greenhouse gas emissions are of course a major concern, but so is the price of food as it becomes linked to the price of fuel, a mechanism that roughly doubled the cost of eating in most places worldwide between 2005 and 2008.

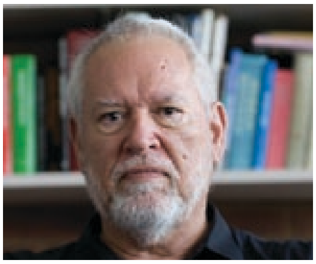
Some agronomists believe that the solution lies in even more intensive industrial farming, carried out by an ever decreasing number of highly mechanized farming consortia that grow crops having higher yields—a result of genetic modification and more powerful agrochemicals. Even if this solution were to be implemented, it is a short-term remedy at best, because the rapid shift in climate continues to rearrange the agricultural landscape, foiling even the most sophisticated strategies. Shortly after the Obama administration took office, Secretary of Energy Steven Chu warned the public that climate change could wipe out farming in California by the end of the century.

What is more, if we continue wholesale deforestation just to generate new farmland, global warming will accelerate at an even more catastrophic rate. And far greater volumes of agricultural runoff could well create enough aquatic "dead zones" to turn most estuaries and even parts of the oceans into barren wastelands.

As if all that were not enough to worry about, foodborne illnesses account for a significant

KENN BROWN *Mondolithic Studios*

[THE AUTHOR]



Dickson Despommier is professor of public health and microbiology at Columbia University and president of the Vertical Farm Project, which functions as a clearinghouse for development work (see www.verticalfarm.com). As a postdoctoral fellow at the Rockefeller University years ago, he became friends with René Dubos, a renowned agricultural sciences researcher who introduced him to the concept of human ecology.

number of deaths worldwide—salmonella, cholera, *Escherichia coli* and shigella, to name just a few. Even more of a problem are life-threatening parasitic infections, such as malaria and schistosomiasis. Furthermore, the common practice of using human feces as a fertilizer in most of Southeast Asia, many parts of Africa, and Central and South America (commercial fertilizers are too expensive) facilitates the spread of parasitic worm infections that afflict 2.5 billion people.

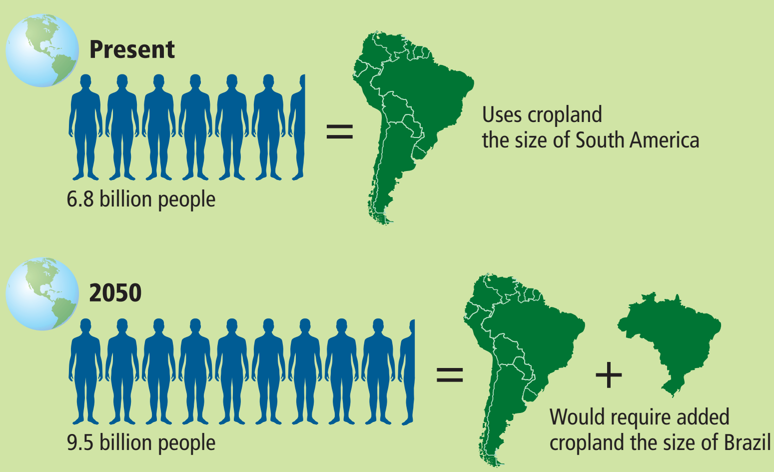
Clearly, radical change is needed. One strategic shift would do away with almost every ill just noted: grow crops indoors, under rigorously controlled conditions, in vertical farms. Plants grown in high-rise buildings erected on now vacant city lots and in large, multistory rooftop greenhouses could produce food year-round using significantly less water, producing little waste, with less risk of infectious diseases, and no need for fossil-fueled machinery or transport from distant rural farms. Vertical farming could revolutionize how we feed ourselves and the rising population to come. Our meals would taste better, too; "locally grown" would become the norm.

The working description I am about to explain might sound outrageous at first. But engineers, urban planners and agronomists who have scrutinized the necessary technologies are convinced that vertical farming is not only feasible but should be tried.

[PROBLEM]

Feeding the Future: Not Enough Land

Growing food and raising livestock for 6.8 billion people require land equal in size to South America. By 2050 another Brazil's worth of area will be needed, using traditional farming; that much arable land does not exist.



Do No Harm

Growing our food on land that used to be intact forests and prairies is killing the planet, setting up the processes of our own extinction. The minimum requirement should be a variation of the physician's credo: "Do no harm." In this case, do no further harm to the earth. Humans have risen to conquer impossible odds before. From Charles Darwin's time in the mid-1800s and forward, with each Malthusian prediction of the end of the world because of a growing population came a series of technological breakthroughs that bailed us out. Farming machines of all kinds, improved fertilizers and pesticides, plants artificially bred for greater productivity and disease resistance, plus vaccines and drugs for common animal diseases all resulted in more food than the rising population needed to stay alive.

That is until the 1980s, when it became obvious that in many places farming was stressing the land well beyond its capacity to support viable crops. Agrochemicals had destroyed the natural cycles of nutrient renewal that intact ecosystems use to maintain themselves. We must switch to agricultural technologies that are more ecologically sustainable.

As the noted ecologist Howard Odum reportedly observed: "Nature has all the answers, so what is your question?" Mine is: How can we all live well and at the same time allow for ecological repair of the world's ecosystems? Many climate experts—from officials at the United Nations Food and Agriculture Organization to sustainable environmentalist and 2004 Nobel Peace Prize winner Wangari Maathai—agree that allowing farmland to revert to its natural grassy or wooded states is the easiest and most direct way to slow climate change. These landscapes naturally absorb carbon dioxide, the most abundant greenhouse gas, from the ambient air. Leave the land alone and allow it to heal our planet.

Examples abound. The demilitarized zone between South and North Korea, created in 1953 after the Korean War, began as a 2.5-mile-wide strip of severely scarred land but today is lush and vibrant, fully recovered. The once bare corridor separating former East and West Germany is now verdant. The American dust bowl of the 1930s, left barren by overfarming and drought, is once again a highly productive part of the nation's breadbasket. And all of New England, which was clear-cut at least three times since the 1700s, is home to large tracts of healthy hardwood and boreal forests.

COURTESY OF STEVEN CHEN (*Despommier*); LAURIE GRACE (*illustration*)

FARMING EXACTS a heavy toll on the environment: fertilizer runoff feeds large algae blooms that create ocean dead zones (*left; blue and green swirls*); irrigation and vehicles waste massive quantities of water and fossil fuels (*top right*); and pesticides contaminate food, land and groundwater (*bottom right*).

JACQUES DESCLOITRES *Modis Land Rapid Response Team/NASA/GSFC/Visible Earth (phytoplankton bloom);* DAVID R. FRAZIER *Getty Images (irrigation);* PAUL GREBLIUNAS *Getty Images (spraying pesticide)*

The Vision

For many reasons, then, an increasingly crowded civilization needs an alternative farming method. But are enclosed city skyscrapers a practical option?

Yes, in part because growing food indoors is already becoming commonplace. Three techniques—drip irrigation, aeroponics and hydroponics—have been used successfully around the world. In drip irrigation, plants root in troughs of lightweight, inert material, such as vermiculite, that can be used for years, and small tubes running from plant to plant drip nutrient-laden water precisely at each stem's base, eliminating the vast amount of water wasted in traditional irrigation. In aeroponics, developed in 1982 by K. T. Hubick, then later improved by NASA scientists, plants dangle in air that is infused with water vapor and nutrients, eliminating the need for soil, too.

Agronomist William F. Gericke is credited with developing modern hydroponics in 1929. Plants are held in place so their roots lie in soilless troughs, and water with dissolved nutrients is circulated over them. During World War II, more than eight million pounds of vegetables were produced hydroponically on South Pacific islands for Allied forces there. Today hydroponic greenhouses provide proof of principles for indoor farming: crops can be produced year-round, droughts and floods that often ruin entire harvests are avoided, yields are maximized because of ideal growing and ripening conditions, and human pathogens are minimized.

Most important, hydroponics allows the grower to select where to locate the business, without concern for outdoor environmental conditions such as soil, precipitation or temperature profiles. Indoor farming can take place anywhere that adequate water and energy can be supplied. Sizable hydroponic facilities can be found in the U.K., the Netherlands, Denmark, Germany, New Zealand and other countries. One leading example is the 318-acre Eurofresh Farms in the Arizona desert, which produces large quantities of high-quality tomatoes, cucumbers and peppers 12 months a year.

Most of these operations sit in semirural areas, however, where reasonably priced land can be found. Transporting the food for many miles adds cost, consumes fossil fuels, emits carbon dioxide and causes significant spoilage. Moving

greenhouse farming into taller structures within city limits can solve these remaining problems. I envision buildings perhaps 30 stories high covering an entire city block. At this scale, vertical farms offer the promise of a truly sustainable urban life: municipal wastewater would be recycled to provide irrigation water, and the remaining solid waste, along with inedible plant matter, would be incinerated to create steam that turns turbines that generate electricity for the farm. With current technology, a wide variety of edible plants can be grown indoors [*see illustration on opposite page*]. An adjacent aquaculture center could also raise fish, shrimp and mollusks.

Start-up grants and government-sponsored research centers would be one way to jump-start vertical farming. University partnerships with companies such as Cargill, Monsanto, Archer Daniels Midland and IBM could also fill the bill. Either approach would exploit the enormous talent pool within many agriculture, engineering and architecture schools and lead to prototype farms perhaps five stories tall and one acre in footprint. These facilities could be the "playground" for graduate students, research scientists and engineers to carry out the necessary trial-and-error tests before a fully functional farm emerged. More modest, rooftop operations on apartment complexes, hospitals and schools could be test beds, too. Research installations already exist at many schools, including the University of California, Davis, Pennsylvania State University, Rutgers University, Michigan State University, and schools in Europe and Asia. One of the best known is the University of Arizona's Controlled Environment Agriculture Center, run by Gene Giacomelli.

Integrating food production into city living is a giant step toward making urban life sustainable. New industries will grow, as will urban jobs never before imagined—nursery attendants, growers and harvesters. And nature will be able to rebound from our insults; traditional farmers would be encouraged to grow grasses and trees, getting paid to sequester carbon. Eventually selective logging would be the norm for an enormous lumber industry, at least throughout the eastern half of the U.S.

GROWING TECHNIQUES

Three technologies would be exploited in vertical farms.

AEROPONICS

Plants are held in place so their roots dangle in air that is infused with water vapor and nutrients. Good for root crops (potatoes, carrots).

HYDROPONICS

Plants are held in place so their roots lie in open troughs; water with dissolved nutrients is continually circulated over them. Good for many vegetables (tomatoes, spinach) and berries.

DRIP IRRIGATION

Plants grow in troughs of lightweight, inert material, such as vermiculite, reused for years. Small tubing on the surface drips nutrient-laden water precisely at each stem's base. Good for grains (wheat, corn).

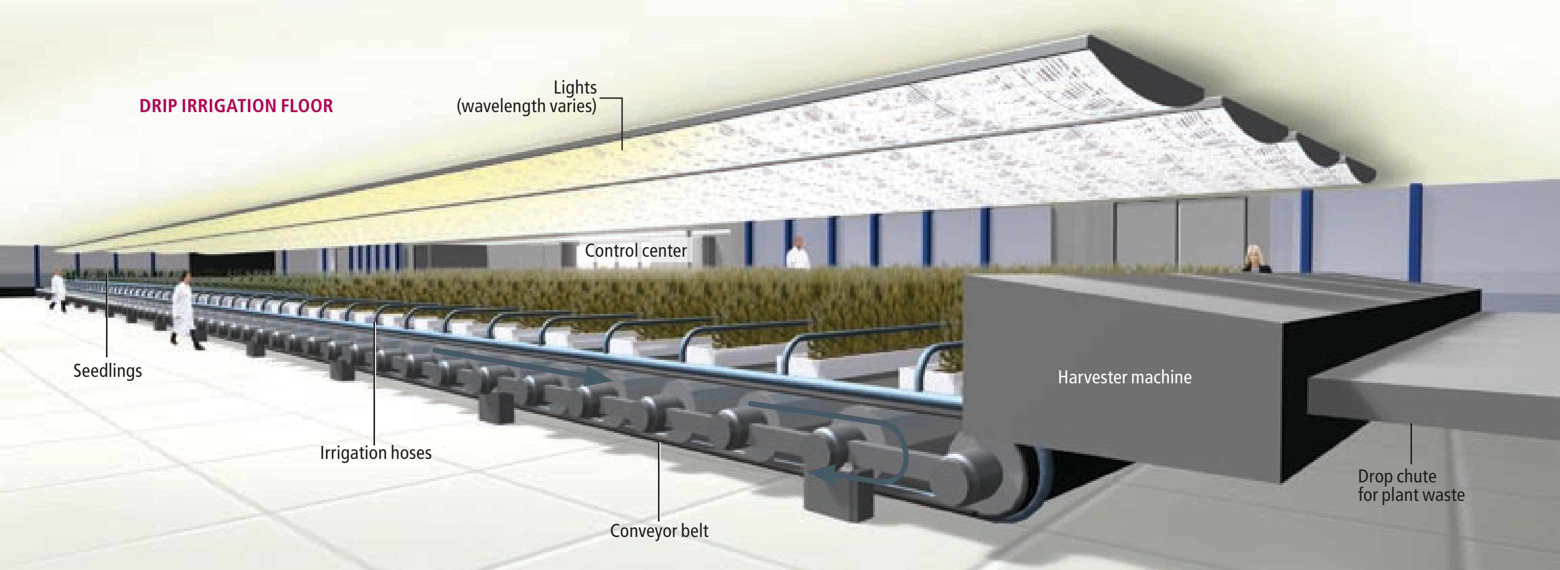
Practical Concerns

In recent years I have been speaking regularly about vertical farms, and in most cases, people raise two main practical questions. First, skeptics wonder how the concept can be economically viable, given the often inflated value of properties in cities such as Chicago, London and Paris. Downtown commercial zones might not be affordable, yet every large city has plenty of less desirable sites that often go begging for projects that would bring in much needed revenue.

In New York City, for example, the former Floyd Bennett Field naval base lies fallow. Abandoned in 1972, the 2.1 square miles scream out for use. Another large tract is Governors Island,

Maximum Yield

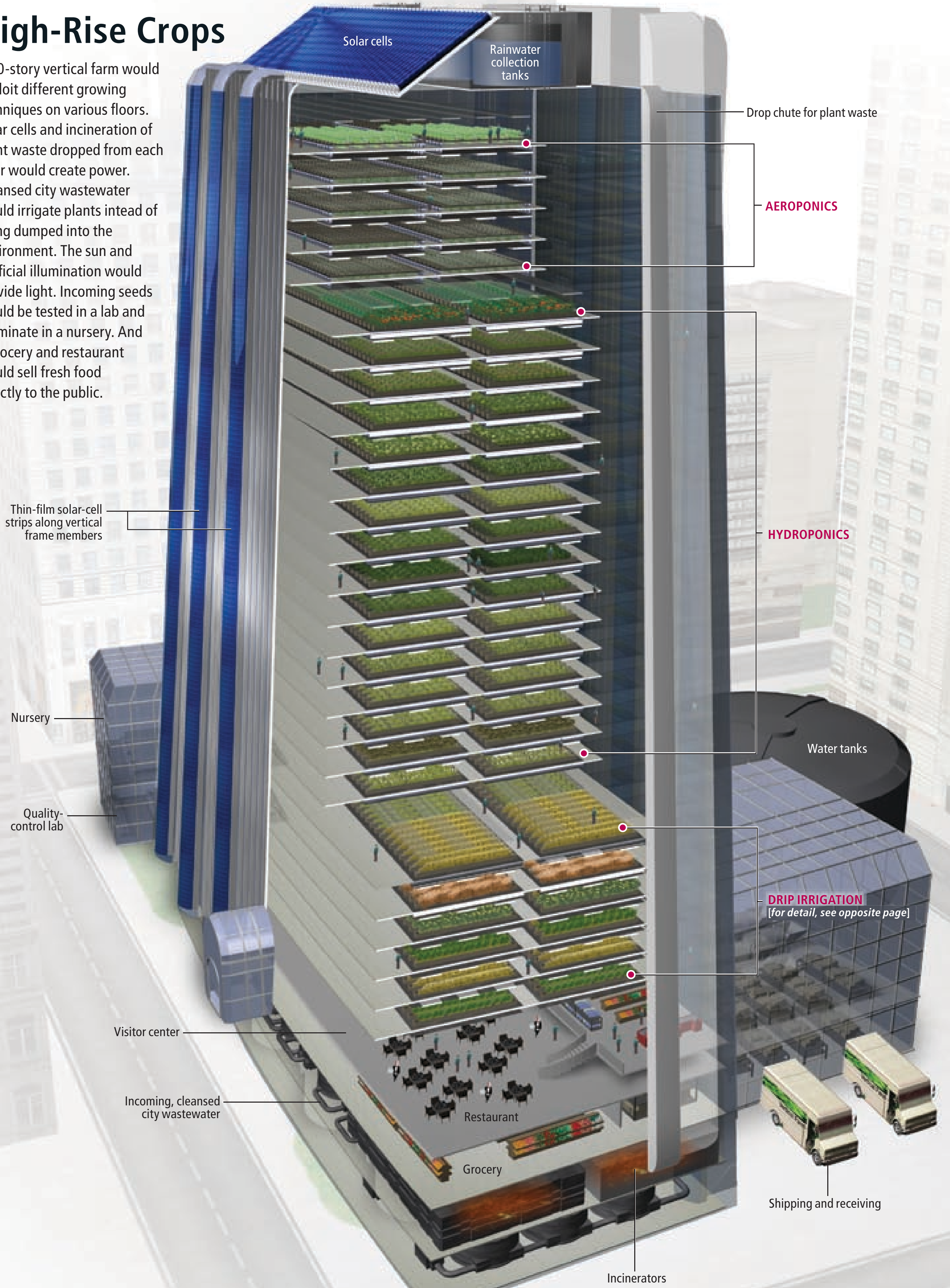
On most floors of a vertical farm [*see opposite page*], an automated conveyor would move seedlings from one end to the other, so that the plants would mature along the way and be at the height of producing grain or vegetables when they reached a harvester. Water and lighting would be tailored to optimize growth at each stage. Inedible plant material would drop down a chute to electricity-generating incinerators in the basement.



KEVIN HAND

High-Rise Crops

A 30-story vertical farm would exploit different growing techniques on various floors. Solar cells and incineration of plant waste dropped from each floor would create power. Cleansed city wastewater would irrigate plants intead of being dumped into the environment. The sun and artificial illumination would provide light. Incoming seeds would be tested in a lab and germinate in a nursery. And a grocery and restaurant would sell fresh food directly to the public.



EUROFRESH FARMS, enclosing 318 acres in Willcox, Ariz., has grown tomatoes, cucumbers and peppers hydroponically for more than a decade, proving that the technology—and indoor farming—can be efficient on a massive scale.

COURTESY OF HOLLIS GRAPHICS (*greenhouse*); COURTESY OF EUROFRESH FARMS (*aerial view*)

a 172-acre parcel in New York Harbor that the U.S. government recently returned to the city. An underutilized location smack in the heart of Manhattan is the 33rd Street rail yard. In addition, there are the usual empty lots and condemned buildings scattered throughout the city. Several years ago my graduate students surveyed New York City's five boroughs; they found no fewer than 120 abandoned sites waiting for change, and many would bring a vertical farm to the people who need it most, namely, the underserved inhabitants of the inner city. Countless similar sites exist in cities around the world. And again, rooftops are everywhere.

Simple math sometimes used against the vertical farm concept actually helps to prove its viability. A typical Manhattan block covers about five acres. Critics say a 30-story building would therefore provide only 150 acres, not much compared with large outdoor farms. Yet growing occurs year-round. Lettuce, for example, can be harvested every six weeks, and even a crop as slow to grow as corn or wheat (three to four months from planting to picking) could be harvested three to four times annually. In addition, dwarf corn plants, developed for NASA, take up far less room than ordinary corn and grow to a height of just two or three feet. Dwarf wheat is also small in stature but high in nutritional value. So plants could be packed tighter, doubling yield per acre, and multiple layers of dwarf crops could be grown per floor. "Stacker" plant holders are already used for certain hydroponic crops.

Combining these factors in a rough calculation, let us say that each floor of a vertical farm offers four growing seasons, double the plant density, and two layers per floor—a multiplying factor of 16 ($4 \times 2 \times 2$). A 30-story building covering one city block could therefore produce 2,400 acres of food (30 stories $\times$ 5 acres $\times$ 16) a year. Similarly, a one-acre roof atop a hospital or school, planted at only one story, could yield 16 acres of victuals for the commissary inside. Of course, growing could be further accelerated with 24-hour lighting, but do not count on that for now.

Other factors amplify this number. Every year droughts and floods ruin entire counties of crops, particularly in the American Midwest. Furthermore, studies show that 30 percent of what is harvested is lost to spoilage and infestation during storage and transport, most of which would be eliminated in city farms because food would be sold virtually in real time and on location as a consequence of plentiful demand. And do not forget that we will have largely eliminated the mega insults of outdoor farming: fertilizer runoff, fossil-fuel emissions, and loss of trees and grasslands.

The second question I often receive involves

the economics of supplying energy and water to a large vertical farm. In this regard, location is everything (surprise, surprise). Vertical farms in Iceland, Italy, New Zealand, southern California and some parts of East Africa would take advantage of abundant geothermal energy. Sun-filled desert environments (the American Southwest, the Middle East, many parts of Central Asia) would actually use two- or three-story structures perhaps 50 to 100 yards wide but miles long, to maximize natural sunlight for growing and photovoltaics for power. Regions gifted with steady winds (most coastal zones, the Midwest) would capture that energy. In all places, the plant waste from harvested crops would be incinerated to create electricity or be converted to biofuel.

One resource that routinely gets overlooked is very valuable as well; in fact, communities spend enormous amounts of energy and money just trying to get rid of it safely. I am referring to liquid municipal waste, commonly known as blackwater. New York City occupants produce one billion gallons of wastewater every day. The city spends enormous sums to cleanse it and then dumps the resulting "gray water" into the Hudson River. Instead that water could irrigate vertical farms. Meanwhile the solid by-products, rich in energy, could be incinerated as well. One typical half-pound bowel movement contains 300 kilocalories of energy when incinerated in a bomb calorimeter. Extrapolating to New York's eight million people, it is theoretically possible to derive as much as 100 million kilowatt-hours of electricity a year from bodily wastes alone, enough to run four, 30-story farms. If this material can be converted into useful water and energy, city living can become much more efficient.

Upfront investment costs will be high, as experimenters learn how to best integrate the various systems needed. That expense is why smaller prototypes must be built first, as they are for any new application of technologies. Onsite renewable energy production should not prove more costly than the use of expensive fossil fuel for big rigs that plow, plant and harvest crops (and emit volumes of pollutants and greenhouse gases). Until we gain operational experience, it will be difficult to predict how profitable a vertical farm could be. The other goal, of course, is for the produce to be less expensive than current supermarket prices, which should be attainable largely because locally grown food does not need to be shipped very far.

HURDLES

Several roadblocks could stifle the spread of urban farms, but all can be solved.

Reclaim enough abandoned city lots and open rooftops as sites for indoor agriculture.

Convert municipal wastewater into usable irrigation water.

Supply inexpensive energy to circulate water and air.

Convince city planners, investors, developers, scientists and engineers to build prototype farms where practical issues could be resolved.

Desire

It has been five years since I first posted some rough thoughts and sketches about vertical farms on a Web site I cobbled together (www.verticalfarm.com). Since then, architects, engineers, designers and mainstream organizations have increasingly taken note. Today many developers, investors, mayors and city planners have become advocates and have indicated a strong desire to actually build a prototype high-rise farm. I have been approached by planners in New York City, Portland, Ore., Los Angeles, Las Vegas, Seattle, Surrey, B.C., Toronto, Paris, Bangalore, Dubai, Abu Dhabi, Incheon, Shanghai and Beijing. The Illinois Institute of Technology is now crafting a detailed plan for Chicago.

All these people realize that something must be done soon if we are to establish a reliable food supply for the next generation. They ask tough questions regarding cost, return on investment, energy and water use, and potential crop yields. They worry about structural girders corroding over time from humidity, power to pump water and air everywhere, and economies of scale. Detailed answers will require a huge input from engineers, architects, indoor agronomists and businesspeople. Perhaps budding engineers and economists would like to get these estimations started.

Because of the Web site, the vertical farm initiative is now in the hands of the public. Its success or failure is a function only of those who build the prototype farms and how much time and effort they apply. The infamous Biosphere 2 closed-ecosystem project outside Tucson, Ariz., first inhabited by eight people in 1991, is the best example of an approach not to take. It was too large of a building, with no validated pilot projects and a total unawareness about how much oxygen the curing cement of the massive foundation would absorb. (The University of Arizona now has the rights to reexamine the structure's potential.)

If vertical farming is to succeed, planners must avoid the mistakes of this and other nonscientific misadventures. The news is promising. According to leading experts in ecoengineering such as Peter Head, who is director of global planning at Arup, an international design and engineering firm based in London, no new technologies are needed to build a large, efficient urban vertical farm. Many enthusiasts have asked: "What are we waiting for?" I have no good answer for them. ■

MORE TO EXPLORE

Our Ecological Footprint: Reducing Human Impact on the Earth. Mathis Wackernagel and William Rees. New Society Publishers, 1996.

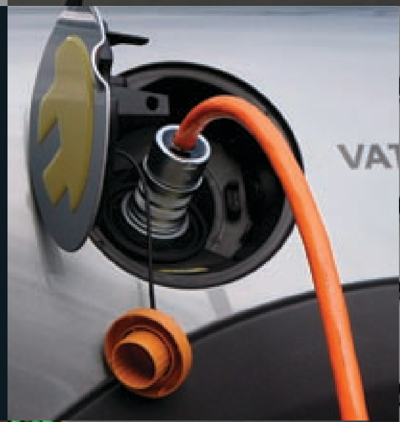
Cradle to Cradle: Remaking the Way We Make Things. William McDonough and Michael Braungart. North Point Press, 2002.

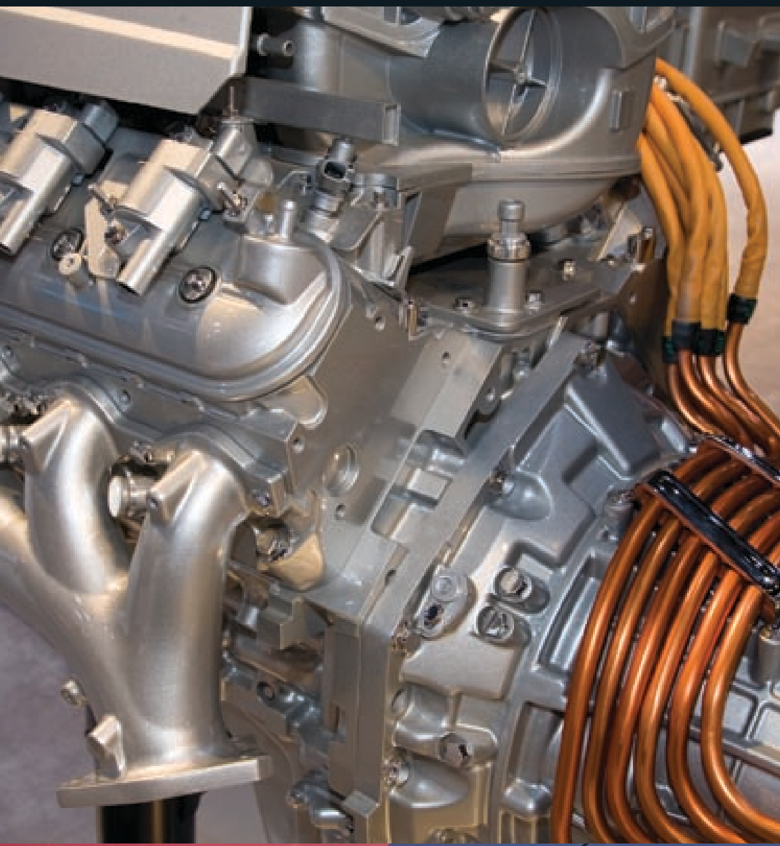
Growing Vertical. Mark Fischetti in *Scientific American Earth 3.0,* Vol. 18, No. 4, pages 74–79; 2008.

University of Arizona Controlled Environment Agricultural Center: **http://ag.arizona.edu/ceac**

Vertical Farm: The Big Idea That Could Solve the World's Food, Water and Energy Crises. Dickson Despommier. Thomas Dunne Books/ St. Martin's Press (in press).

THE FUTURE OF CARS





INDUSTRY LEADERS LOOK WAY DOWN THE ROAD

For a glimpse into what automobiles will be like 20 years from now, contributing editor Stuart F. Brown conducted a group interview with executives at General Motors, Tesla Motors and Toyota and also spoke separately with a program manager at the Electric Power Research Institute. The interviewees, whose comments have been edited for length, foresee increased communication among cars and a combination of vehicle types. Some, like Tesla's current sports cars, will draw their energy from a battery pack. Others, in common with today's Toyota's Prius and the 2010 Chevy Volt, will be hybrid designs, relying on both electric motors and small internal-combustion engines. Many forthcoming hybrids will charge batteries by plugging into the electric grid, and hydrogen fuel cells might be a reality. But that is not all that the participants see. Read on. *—The Editors*

PARTICIPANTS

Larry D. Burns
Vice President, Research and Development and Strategic Planning, General Motors*

Bill Reinert
National Manager, Advanced Technology Vehicles, Toyota Motor Sales USA

Mark S. Duvall
Director, Electric Transportation and Energy Storage, Electric Power Research Institute

JB Straubel
Chief Technical Officer, Tesla Motors

**Burns retired in October, after participating in the interview recorded here.*

SCIENTIFIC AMERICAN: Let's start by talking about the transportation fuels we can expect to see in the years leading up to 2030.

REINERT: Through the middle of the next decade, gasoline prices should remain fairly low. I think for at least the next five years and probably the next 10 the predominant number of cars will have internal-combustion engines. You will see six- to eight-speed automatic transmissions, continuously variable transmissions, low-loss lubricants and maybe even new ceramic bearings to reduce friction. And we've got a lot of stuff in near to midterm development to really make major improvements in how the internal-combustion engine functions.

Yet if we look out to 2020–2025, you'll see the gasoline engine and the diesel engine starting to grow together, becoming very similar to each other. You're going to see ethanol die out, as I think it should. But it will be replaced by biogasoline and second- and third-generation biofuels that are compatible with older cars. Biomass, probably from algae, maybe from municipal solid waste, will be used to produce synthetic gasoline and synthetic diesel.

By this time we may see a developed battery, a replacement for lithium technology that allows full, no-compromise electric cars. But they would still be a niche. And I think that you'll probably start to see low-carbon hydrogen [*Editor's note: not derived from natural gas*] that has been developed to supply fuel cells. So you will see niche battery electric vehicles coming and that market starting to mature more in the later years. Plug-in hybrids and major range-extended hybrids will be a subset of the market. There will be a lot of internal-combustion-type hybrids and then fuel cells starting to come onto the market.

At 2030 we still have an internal-combustion-type component, strong hybrids, probably range-extended electric vehicles and small electric vehicles, and fuel cells are starting to make bigger inroads.

SA: Wireless communication is exploding all around us. How will it affect vehicles?

BURNS: Connected vehicles is another important transformational technology. The fact is that we are now beginning to have vehicles that can communicate with each other. We have the opportunity to have more and more of the driving task be done autonomously by the vehicle. Our road maps for all of the enabling technology for autonomously driven vehicles, and for vehicles that don't crash, will be coming together in the next five to 10 years.

REINERT: I'd like to talk about how vehicle communication might affect urban vehicles. I think that not only is peer-to-peer vehicle communication critical as we start to platoon cars for congestion mitigation, but it also is important from a social-networking angle as you start to get the millennium generation coming in, people who have always been networked. And you start to have computational clouds that follow the people around. You aren't attached to a computer anymore, and your car becomes part of a computing platform.

BURNS: I have an 18-year-old daughter. When I grew up, my rite of passage was my first car. For my daughter, I think it was her first cell phone. Today she has an iPhone, and she has a Saturn Vue. If I asked her which one she would give up if she had to, I think she would give up

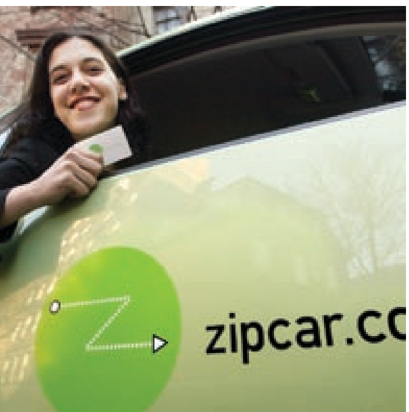
KEY CONCEPTS

- The car fleet of 2030 will use a patchwork quilt of different fuels and power trains, with some cars meant for short hops and city driving.
- As the years go by, vehicles will become increasingly connected to one another electronically, for crash prevention and social networking. Driver distraction will be an ongoing concern.
- Whether cars that run on hydrogen fuel cells will be common in 20 years remains an open question.

—The Editors

OPPOSITE PAGE: RYAN McVAY *Getty Images* (*door handle*); RICHARD B. LEVINE *Newscom* (*GM fuel cell*); ALINA NOVOPASHINA *Corbis* (*recharging plug*); ROGER T. SCHMIDT *Getty Images* (*tire*); PETER DAZELEY *Getty Images* (*fuel gauge*); GETTY IMAGES (*hybrid engine*); FRANK MUCKENHEIM *Corbis* (*start button*); JAMES LEYNSE *Corbis* (*no gas symbol*); BRUCE BENEDICT *Corbis* (*headlight*); CORBIS (*hybrid engine*); THIS PAGE: COURTESY OF GM CORP. (*Burns*); COURTESY OF TOYOTA (*Reinert*); COURTESY OF ELECTRIC POWER RESEARCH INSTITUTE (*Duvall*); COURTESY OF TESLA MOTORS (*Straubel*)

If car owners want to hit a button that says, “charge now,” they would just pay more when doing that. But the default will be charging off peak.




CHEVROLET VOLT

the car before she would give up the social networking associated with that iPhone. This social-networking point that you raise is enormously important. It’s such a powerful behavioral force. And when you have this convergence of an inexperienced driver who wants to text-message, that’s a formula for real concern. I think that as technologists, we have solutions within our grasp so that these young drivers can have both.

REINERT: Absolutely. If we can’t make these cars a social-networking tool just like the iPhone, we’ll lose the customers younger than Larry’s daughter. They just won’t want to get into the cars if they lose their social-networking cloud. I would guess that the automobile companies sooner or later will have connectivity partners to help us through. I would guess that partnerships will be the new thing that will start to emerge out of all of this.

SA: Batteries are essential to many of the advanced vehicles now under development. Are they good enough yet?

DUVALL: In the near term we’re absolutely right in trying to deliver as long a battery life a possible. Carmakers are going to baby the batteries at the beginning at the expense of slightly higher cost. Later, costs will come down and batteries will get worked harder. We have seen this in hybrids already, which enables them to get better miles per gallon.

BURNS: The Chevy Volt will have a 16- kilowatt-hour battery, and we’ll use only half of that energy to run the car. We will learn and discover, and we will improve for sure, but we’ve got to get out there and start doing it.

Our industry in normal times builds 70 million cars and trucks per year. So for any battery-based solution to matter, you’re going to have to get into tens of millions of units per year, and I think we’ve got a ways to go before [durability and cost issues are solved enough to allow that kind of scale].

As a manufacturer, if you have to replace the battery one or two times in a vehicle with a 150,000-mile lifetime you are in trouble. I do believe there will be continuous improvement with lithium-ion batteries, but I think we’re going to need some invention and breakthrough to get the cost per kilowatt-hour down to where we need it to be.

We’ve got to have some breakthroughs here on chemistry. There’s a big difference between using these batteries in your recording devices and cell phones and in an automobile in terms of the temperature extremes and [changing demands for power] and the need to cool the cells uniformly and manage their state of charge uniformly. We’re going to be discovering a whole lot of that as we get out with these early-generation applications of lithium-ion.

REINERT: To a certain extent, the battery longevity is going to shape the applications for a while. So Toyota, and I assume other manufacturers, is going to be very cautious about how we cycle the batteries, about the charge-sustaining and charge-depleting modes we operate them in, and about the actual size of the battery, with an eye toward warranty costs. Lithium-ion batteries still are not available with the 150,000-mile durability you have with an internal-combustion engine. So that’s going to limit the penetration of the battery-powered cars to either niche markets, urban cars, plug-in hybrids with very small batteries, or range-extended cars with moderate-size batteries.

STRAUBEL: I would suggest maybe another way to look at this is to think about the cost per mile. We can talk about a minimum durability required, but it’s a little bit different with the case of a replaceable battery pack. You have to consider the cost of operating the vehicle per mile, along with the associated replacement cost, if there is one, of changing the battery pack. On those metrics, we’re close, possibly over a threshold in some cases, where it’s actually cheaper to operate and own an electric vehicle than a gasoline car. That’s not the case necessarily with $2 per gallon gasoline, but it absolutely is the case with $3.50 or $4 gasoline in most parts of Europe. And especially if there are any political incentives or tax credits involved.

DUVALL: Many utilities might be willing to help with the costs of your home infrastructure because they are really interested in off-peak charging. And in turn you would enroll in a rate program that would cause your vehicle to charge predominantly off peak. Which really means that your vehicle wouldn’t charge during the six hottest months of the year from, say, 2 P.M. to 9 P.M.

SA: Is it practical to use plugged-in electric vehicles to fill in low-demand times on the grid?

MARIO TAMA *Getty Images (Zipcar)*; COURTESY OF GM CORP. *(Chevrolet Volt)*; JEFFREY COOLIDGE *Getty Images (bumper sticker)*

DUVALL: That's where the utilities' interests lie. In the short run, we agree with the automakers that we need to reach certain objectives with the vehicles, including lifetime batteries. Then we can start talking about doing other stuff. To us, smart charging [where electric cars and the grid can schedule lowest-cost battery recharging] is a daunting enough task for the present.

I think you will probably see the utilities go to what's called time-of-use pricing for most of their customers—meaning you will pay more for the loads on your house at the peak hours and less at night. So vehicle chargers or clothes dryers that turn on automatically at 3 A.M. would cost less than running at the peak time. And occasionally if car owners want to hit a button that says, "charge now," they will just pay more when they're doing that. But their default behavior will be charging off peak.

SA: We have heard a lot about fuel cells during the past decade. How do their prospects look today?

DUVALL: I would say the biggest challenges with fuel cells may not be the vehicles themselves but the infrastructure to provide the hydrogen. And when it comes down to it, we can either make hydrogen from re-forming fossil fuels or make it from electricity by electrolyzing water. If we are making the hydrogen with electricity, electric vehicles are a more efficient use of that energy. And the infrastructure is much less costly.

So I think if you were designing the U.S. energy network from the ground up today, you would have an easier time creating a role for hydrogen. You could put in place a hydrogen infrastructure such as advanced electrolysis. But right now unless hydrogen vehicles can provide an absolute sea change in efficiencies, electricity as a transportation fuel is pretty tough to beat on efficiency. And it will come from the same sources as hydrogen.

STRAUBEL: I definitely think that fuel cells are going to have a struggle to make sense in any time frame. I think the physics around the energy efficiency of that fuel cycle is going to be one of the thorniest issues to solve. I don't see fuel cells as the Holy Grail in the long term.

REINERT: But right now Daimler, GM, Honda and Toyota have very well developed fuel cells, mostly waiting on fuel-cell infrastructure, which should come into play some time around the year 2025. I think that you're going to see a more segmented usage pattern, and the idea that we're going to have a 400-mile range for every car in the fleet may not be as important in 10 years as it is to customers today. It may be enough to have an adequate range to get yourself through your day plus [another half day], for example, and that you have services such as Zipcars that allow you to buy the exact car usage you need and no more.

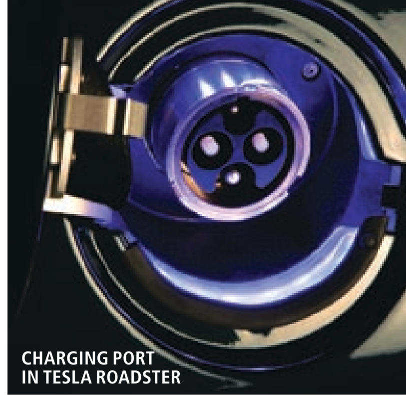
SA: The fuel efficiency, exhaust emissions and safety of vehicles all have to meet standards. What are your thoughts about future regulation?

STRAUBEL: We really need to focus these policy decisions on things that can be economic in order to scale up. If we put policy in place to implement something that won't be economic for two decades, it's useless. It's not going to affect any issues related to CO_2 reduction or energy security or anything else.

BURNS: The reason I get worried about trying to pick the winner [for future transportation] is that it can induce policy makers to take options out of play, and it's way too early to take some of those options out of play, in my judgment. We've been doing some really interesting work where we looked at this not as an "or" question: that it's either batteries or fuel cells or biofuels, but we've looked at it as an "and" question. What if we had all of them in play? Whether it's electricity or renewables or whether it's hydrogen, none of them by themselves can displace the amount of petroleum and CO_2 that we're talking about. Don't dismiss any of these, put them all in play together and see where the world heads with that.

All this technology will matter only if we can get it to high volume. Because you're not going to have impacts on energy, environment, safety and congestion if you only sell specialized niche products. I just find so many regulators and politicians and other people weighing in on this debate who don't have a clue about what's required to get to high-volume commercialization of a technology.

DUVALL: Let's be very careful before we adopt very expensive alternatives that try to create a one-size-fits-all technology. We need to avoid the silver bullet approach—it's always proved to be generally more expensive and have less of a chance of success. ■



CHARGING PORT IN TESLA ROADSTER

FUEL CELL AND RELATED COMPONENTS

COURTESY OF TESLA MOTORS (*charging port*); COURTESY OF HONDA (*fuel cell*)

MORE TO EXPLORE

Hybrid Vehicles Gain Traction. Joseph J. Romm and Andrew A. Frank in *Scientific American,* Vol. 294, No. 4, pages 56–63; April 2006.

High Hopes for Hydrogen. Joan Ogden in *Scientific American,* Vol. 295, No. 3, pages 70–77; September 2006.

Driving toward Crashless Cars. Steven Ashley in *Scientific American,* Vol. 299, No. 6, pages 58–65; December 2008.

Electric Transportation 2009 Overview. Electric Power Research Institute (EPRI). Available online at **http://mydocs.epri.com/docs/Portfolio/PDF/2009_P018.pdf**

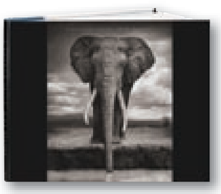
For a discussion of the GREET computer model that realistically compares different fuels and propulsion systems, see the Argonne National Laboratory Transportation Technology R&D Center: **www.transportation.anl.gov/modeling_simulation/GREET**

African Wildlife ▪ Nuclear Proliferation ▪ Ancient Alcohol

BY KATE WONG

➔ A SHADOW FALLS

by Nick Brandt. Abrams, 2009 ($50)



Wildlife photographer Nick Brandt's stunning images of African animals reveal such familiar creatures as lions, zebras, giraffes and elephants in a remarkable new light. Here a lion faces an oncoming storm in Kenya's Masai Mara National Reserve.

EXCERPT

➔ RED CLOUD AT DAWN: TRUMAN, STALIN, AND THE END OF THE ATOMIC MONOPOLY

by Michael D. Gordin. Farrar, Straus and Giroux, 2009 ($27)

Science historian Michael D. Gordin recounts the events leading up to August 29, 1949, when the Soviets detonated an atomic bomb in the deserts of Kazakhstan—a test explosion that brought the U.S. monopoly on nuclear weapons to a close. Here he describes how, four years earlier, the U.S. prepared to test the first atomic bomb in Alamogordo, N.M.

"The world's first nuclear explosion, the Trinity test, was actually the second test conducted by Los Alamos scientists. Since none of the participants in the [Manhattan Project] had ever experienced an explosion of the anticipated size of Trinity (radically underestimated in advance as the equivalent of four thousand to five thousand tons of TNT), Kenneth Bainbridge, to whom [J. Robert] Oppenheimer had delegated the testing procedure, opted to conduct a scale model of the forthcoming atomic test by detonating one hundred tons of TNT off a thirty-eight-foot-high tower.... The test, which also served as a dry run of the wiring and instrumentation, was conducted on May 7, 1945. Some fission products were placed in the explosive so that radioactive traces could be measured. This was as close to a practice run as the Americans had.

"In retrospect, many American scientists understandably considered the Trinity test of July 16, 1945, as the watershed of their involvement in weapons design. Yet during the preceding months, it was by no means clear that the explosion would work, and [General Leslie] Groves authorized the construction of a twenty-five-by-ten-foot, two hundred-ton vessel (code-named 'Jumbo') to contain the explosion in case of a misfire, so as to recover the valuable plutonium. It was eventually decided to proceed without Jumbo, but the very consideration of it reveals how uncertain the Manhattan Project seemed even at that late date."

ALSO NOTABLE

BOOKS

- **Uncorking the Past: The Quest for Wine, Beer, and Other Alcoholic Beverages**
  by Patrick McGovern. University of California Press, 2009 ($29.95)
- **Hybrid: The History and Science of Plant Breeding**
  by Noel Kingsbury. University of Chicago Press, 2009 ($35)
- **Strange Bedfellows: The Surprising Connection between Sex, Evolution and Monogamy**
  by David P. Barash and Judith Eve Lipton. Bellevue Literary Press, 2009 ($25)
- **The Rising Sea**
  by Orrin Pilkey and Rob Young. Island Press, 2009 ($25.96)
- **Heaven's Touch: From Killer Stars to the Seeds of Life, How We Are Connected to the Universe**
  by James B. Kaler. Princeton University Press, 2009 ($24.95)
- **The Gates of Hell: Sir John Franklin's Tragic Quest for the North West Passage**
  by Andrew Lambert. Yale University Press, 2009 ($32.50)
- **When You Were a Tadpole and I Was a Fish: And Other Speculations about This and That**
  by Martin Gardner. Hill and Wang, 2009 ($26)
- **Chasing Molecules: Poisonous Products, Human Health, and the Promise of Green Chemistry**
  by Elizabeth Grossman. Island Press, 2009 ($26.95)
- **The Bird: A Natural History of Who Birds Are, Where They Came From, and How They Live**
  by Colin Tudge. Crown, 2009 ($30)

FOLKS WE FOLLOW ON TWITTER

- **Neil deGrasse Tyson, director, Hayden Planetarium at the American Museum of Natural History (@neiltyson)**
- **Richard Wiseman, magician and professor of psychology, University of Hertfordshire in England (@RichardWiseman)**
- **Shawn Carlson, physicist and executive director, Society for Amateur Scientists (@DrShawn1)**
- **Charles Seife, science writer and professor of journalism, New York University (@cgseife)**

LION BEFORE STORM II—SITTING PROFILE, MASAI MARA, 2006, BY NICK BRANDT

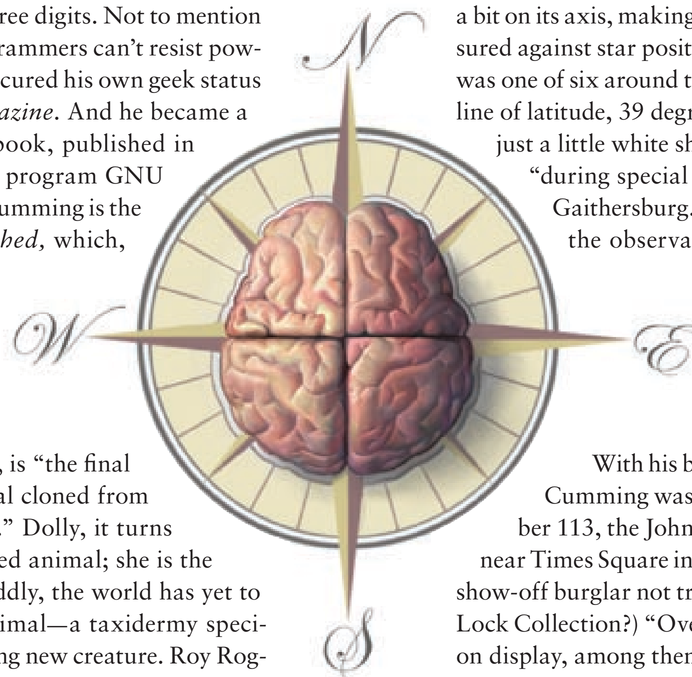
You Nerd a Vacation

Sightseeing on the shoulders of giants

BY STEVE MIRSKY

After five years of gallivanting across the globe, Charles Darwin settled down at Down House in Downe, England. Other than day trips to London, he hardly left his neighborhood for the remaining 45 years of his life. After three days at a conference in London this past summer, I took a day trip to Downe to see Darwin's house, which is now a small museum. What I did not know at the time was that I was visiting site number 043 in *The Geek Atlas: 128 Places Where Science & Technology Come Alive* (O'Reilly Media, 2009).

Author John Graham-Cumming holds a doctorate in computer security and is described in the book as "a wandering programmer." (That background probably explains the zeroes that give all his site numbers three digits. Not to mention the choice of 128 places—programmers can't resist powers of 2.) Graham-Cumming secured his own geek status by contributing to *Linux Magazine*. And he became a supergeek with his previous book, published in 2008, a guide to the software program GNU Make. That's right, Graham-Cumming is the author of *GNU Make Unleashed,* which, he notes, "saturated its target market of 100 readers."



The "come alive" in the title of the new book may be a bit of an overstatement. For example, site number 059, the National Museum of Scotland, is "the final resting place of the first animal cloned from an adult cell: Dolly the Sheep." Dolly, it turns out, was not just the first cloned animal; she is the first stuffed cloned animal. Oddly, the world has yet to see the first cloned stuffed animal—a taxidermy specimen sampled to make a spanking new creature. Roy Rogers's horse, Trigger, is just sitting there, or rather standing there, waiting for further immortality. (Technically and fittingly, Trigger is mounted, not stuffed.)

Or some enterprising researcher could double-down and attempt to make a sheep from Dolly in her current state, thereby creating a clone from a stuffed animal and a clone from a stuffed cloned animal.

Site number 029 is the Escher Museum, in the Hague, in the Netherlands, in the Europe. It houses the vast majority of M. C. Escher's optically illusory prints of impossible shapes. Rumor has it that admission is free to anyone who actually finishes climbing the front steps.

A descendant of the apple tree that allegedly filled Newton with gravitas is site number 069, located outside Newton's dorm at the University of Cambridge. Visitors might also see faculty member Stephen Hawking, whom the geniuses at *Investor's Business Daily* editorialized would not be alive if he were British and had to depend on England's National Health Service. Hawking issued a statement revealing that he is in fact British, even though his voice synthesizer sounds nothing like Benny Hill.

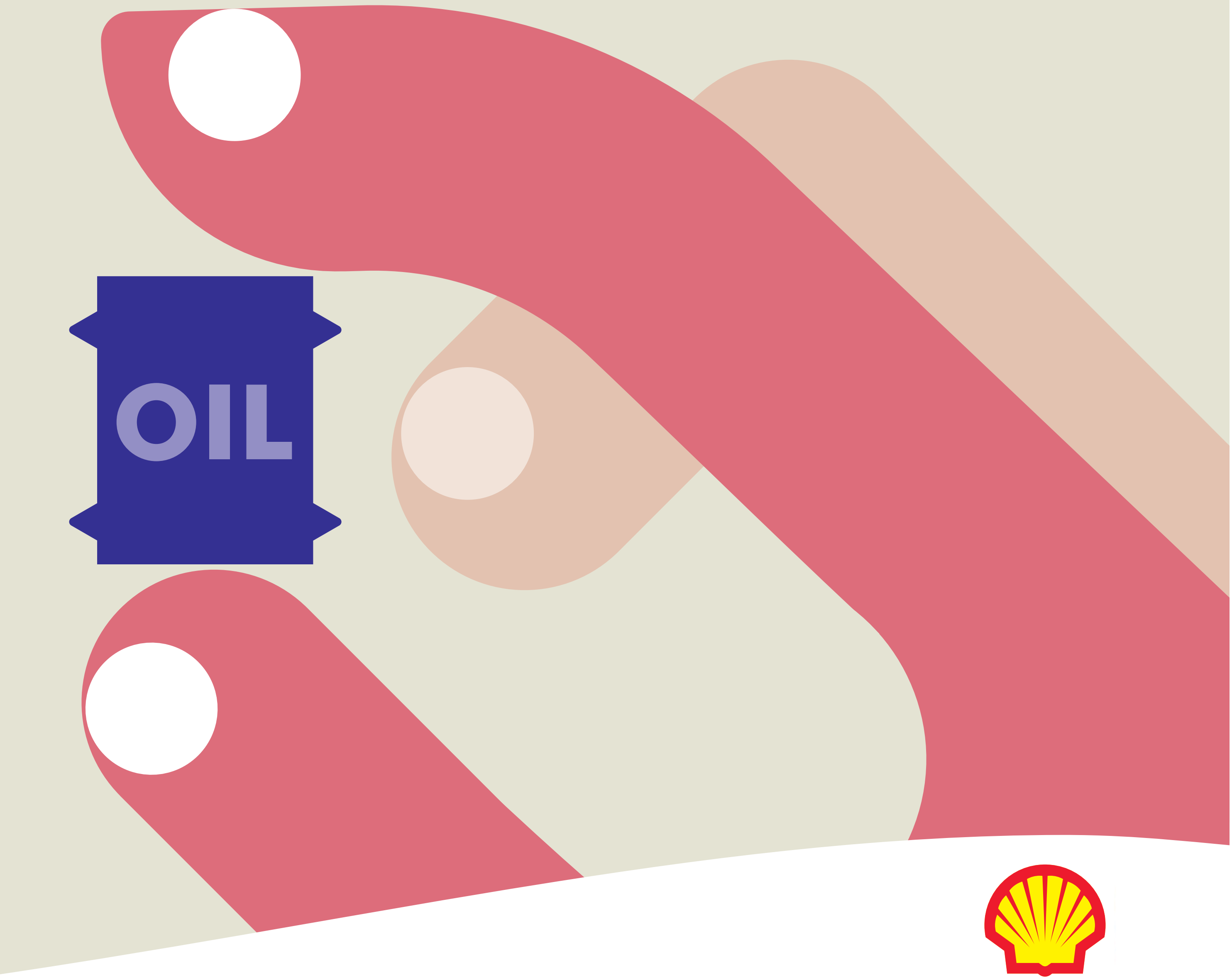
The Gaithersburg International Latitude Observatory in Maryland claims the honor of being site 099. This landmark is where they used to keep track of how the earth wobbles a bit on its axis, making the latitude variable when measured against star positions. The Gaithersburg location was one of six around the world all on exactly the same line of latitude, 39 degrees, 8 minutes north. Today it's just a little white shack. Oh, and it's closed, except "during special events organized by the city of Gaithersburg." Nevertheless, you can include the observatory in a three-site, single-day Maryland tour that also hits the National Electronics Museum (100) and the National Cryptological Museum (101). Good luck figuring out the latter's address.

With his background in security, Graham-Cumming was naturally attracted to site number 113, the John M. Mossman Lock Collection, near Times Square in New York City. (How has some show-off burglar not tried to knock over the Mossman Lock Collection?) "Over 370 bank and vault locks" are on display, among them ancient Egyptian wooden-pin locks that once may have kept mummies under wraps.

The atlas includes well-crafted explanations of the science related to the sites, so that an armchair traveler can still enjoy a virtual visit, aka a geek sneak peek. Which can sometimes be preferable. The Chernobyl Exclusion Zone (080), the region left virtually uninhabited by the world's greatest nuclear reactor disaster, has a notable lack of really fine hotels.

Graham-Cumming should consider a second volume of nerdy spots. Because there are lots of us for whom repeated stress leading to irreparable metal fatigue to a spiral coil is spring break. ■

PHOTOGRAPH BY FLYNN LARSEN; ILLUSTRATION BY MATT COLLINS


OIL