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Fierce Storms, Methane Seas:
TITAN REVEALED
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The Brain's Dark Energy

Mysterious brain activity holds clues to disorders and maybe even to **consciousness**

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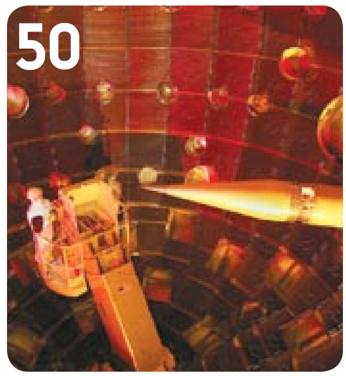
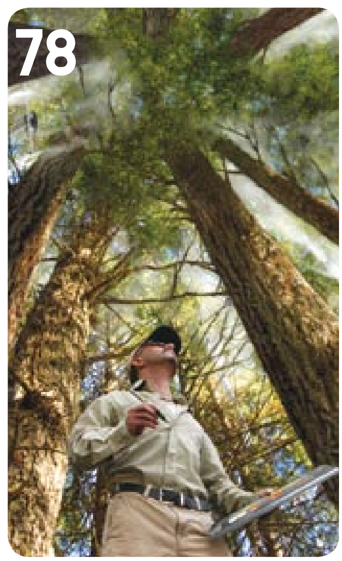
SCIENTIFIC AMERICAN March 2010 ▪ Volume 302 Number 3





ON THE COVER

Remarkably, the brain carries out a great deal of meaningful activity all the time, even when a person is sitting back and doing nothing at all. Image by Aaron Goodman.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toyota.com/beyondcars
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WE SEE WAYS TO ENRICH THE COMMUNITY. At Toyota, building great partnerships is as important to us as building great cars. It's why we value being a part of the places where we work and live. We employ locally, partner with area vendors and suppliers, and collaborate with local organizations to better the community. Can a car company work in harmony with a community? Why not? To us, it's all part of the big picture.
Pictured: Antonio Spagnoli & Janai Grayson, Toyota Team Members
Toyota Highlander, built in Princeton, Indiana*

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The Stimulus Package and Science

It's been a year since President Barack Obama signed the American Recovery and Reinvestment Act of 2009 into law. So what has the stimulus money done for the science community?

GETTY IMAGES

More at **www.ScientificAmerican.com/mar2010**

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Limits of Perception

"Every man takes the limits of his own field of vision for the limits of the world."
—Arthur Schopenhauer, *Studies in Pessimism*

Riding in a Manhattan subway car the other morning, I read that quote by 19th-century German philosopher Arthur Schopenhauer on one of the transit authority's "Train of Thought" posters. It amused me that I had actually gone underground to see the light. That is, Schopenhauer's words captured clearly what I had been only vaguely mulling about some of this issue's major features and what they represent: the utility of looking at an area of science anew by coming at it from a different perspective. In this, I realize, I am hardly the first person to notice that when attempting to solve a problem, changing your physical vantage point or mental framework can loft you past perceived limits. In some cases, it can be difficult to recognize evidence that may be right before your eyes because you fail to appreciate it for what it is.

And so it was with the subject of this month's cover story. What scientists once thought was unremarkable cellular "noise" in neuron signaling has come to be viewed as important to overall system-wide functioning in the brain. It's common, and completely understandable, for researchers to strip noise from any signals they are trying to measure. But neuroscientist Marcus E. Raichle, author of "The Brain's Dark Energy," starting on page 44, was one of the first to wonder whether the noise itself had meaning. As he later said at a conference on brain network dynamics, "It turns out that this is yet one more signal in the biological world whose 'noise' is highly important and is very information rich."

Raichle, a pioneer in the use of brain imaging, and his colleagues have observed that in brains at "rest"—when you are not thinking of anything in particular or even when you are asleep—dispersed areas are still buzzing with communication. This intrinsic activity he calls the brain's default mode. Determining the exact role of this previously unappreciated "dark energy" is an ongoing area of study, but it appears to be involved in how the brain prepares for future events that involve conscious processing. Disruptions of such activity may underlie certain brain disorders as well.

In another feature article, geochemist Robert M. Hazen also proposes a new view—one applied to our understanding of how Earth's deep geohistory shaped its mineral riches. Once there were mere dozens of minerals in the universe, but today our planet has more than 4,400 known mineral species. How did that diversification happen?

In "Evolution of Minerals," beginning on page 58, Hazen suggests we reconsider mineralogy, which does not traditionally look beyond minerals' timeless properties. He and his colleagues use "Earth's history as a frame for understanding minerals and the processes that created them." With this long-range lens, it becomes clear that the rise of life and its metabolic activities dramatically directed our planet's uniquely diverse mineral kingdom. Up to two thirds of the mineral species co-evolved with life through a series of epochs. The "rock of ages" takes on a whole new meaning. ■

MARIETTE DiCHRISTINA
editor in chief

ETHAN HILL (*DiChristina*); AARON GOODMAN (*energized brain*)

Letters to the Editor

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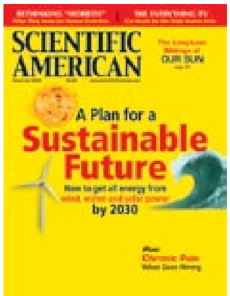
Letters may be edited for length and clarity. We regret that we cannot answer each one. Post a comment on any article instantly at www.ScientificAmerican.com/sciammag

Renewables ■ Vertical Farms ■ Educated Women



NOVEMBER 2009

"Could we all not come closer to a more peaceful society by rediscovering the wisdom of educating the women of our planet?"

— *Sohail Husain* YALE UNIVERSITY SCHOOL OF MEDICINE

■ Winds of Change

I found it surprising that in "A Path to Sustainable Energy by 2030," Mark Z. Jacobson and Mark A. Delucchi do not mention the effects of the suggested energy sources on climate. The authors propose to absorb about six terawatts of energy from about 60 terawatts available in the wind, or about 10 percent of its total energy. Because the winds, at least near the U.S., usually flow around highs or lows, where the speed and related Coriolis force tend to maintain the pressure difference, I can easily envision that absorbing the energy will change the rate at which the pressure centers collapse. How this would change the weather, I do not know, but it must make a change to give us some of the energy. Possibly, the weather change would be an improvement, but as a believer in Murphy's Law, I would be surprised. About 100 years ago dumping garbage into the ocean was justified because the oceans were infinite compared to the effect, so no one calculated how much was allowable. Let's be smarter this time! Why not do the calculations before we cause more problems?

Paul Roetling
Grand Island, N.Y.

Jacobson and Delucchi have a bold vision and a generally balanced account of the opportunities and difficulties. Three matters of concern should be explored further, however. First, vast solar arrays in deserts would suffer from serious loss of efficiency in sandstorms. Second, extensive studies were published in the 1970s on the design of liquid-hydrogen-powered aircraft, the massive energy systems needed at major airports and the difficulties of servicing aircraft whose systems are at three kelvins. Although these problems might eventually be solved, it is very optimistic to think this could be done by 2030. Third, and probably the biggest worry of all, is the rate of construction of these new energy systems that the plan would require. All new global energy systems have grown over a century or so at an average of 1 to 2 percent a year; the article implies a rate of 5 percent a year. Admittedly, the authors compare previous novel construction rates to their proposals, but these were not on the global scale. New technologies that do not reach about 2 to 3 percent of the market lose momentum, fall into the "snake pit" and are forgotten.

John E. Allen
Kingston University
London

THE AUTHORS REPLY: *Sandstorms are limited primarily to the Sahara, Persian Gulf states and Gobi Desert but hardly contribute to reduced solar radiation in North or South America or Australia in comparison. During severe events, solar power is reduced in sandstorm regions, but the solar radiation reaching the ground in the annual average in such regions is still large because the events occur periodically. With respect to the second point, we propose that most transportation modes use electricity. Only in cases where electricity cannot be used do we propose hydrogen or hydrogen-electric hybrid vehi-*

HO/REUTERS/CORBIS

SOLAR, wind and water power can potentially satisfy the world's energy demand.

cles. Air transport is probably the most difficult sector to address; however, a recent European Commission report suggests that there are "no critical barriers to implementation" of a liquid-hydrogen aircraft fleet (http://ec.europa.eu/research/transport/news/article_786_en.html). Although liquid hydrogen requires more than four times the volume of jet fuel, it is about one-third the weight of jet fuel for the same energy, which more than makes up for the additional weight of the fuel tank. As a result, a fully fueled liquid-hydrogen plane will produce more drag but weigh less than a jet-fueled plane. With respect to the third point, our plan is for governments to mobilize infrastructure changes at a rapid pace. The examples given in the letter are based on typical market penetrations, not on aggressive efforts.

Vertical vs. Horizontal

Aspects of the system described in Dickson Despommier's "The Rise of Vertical Farms" seem problematic to me. I did like the concept of recycling nutrients and the use of multispecies agriculture. I have done some experiments with organic hydroponics, but I grew the plants outside using natural light. With a 30-story building, 300 feet on each side, you cannot collect enough natural light to grow plants in the entire building. During June, at the peak of the growing season, the amount of sunlight incident on the south, west and east walls of the building will be about a thirtieth of the sunlight incident on a farm with 30 300-by-300-foot plots. In addition, there is no reasonably priced technology to distribute light to the inner parts of the building.

If the deficit in light were to be made up by photovoltaic-powered lights, each square foot of growing area would require about 20 square feet of panels. This difference in area is a result of the inefficiency of the panels and electrical lights. And if the light deficit in the central part of the building were to be made up by electrical lights, the heat load in the building would be enormous. There would also be an enormous moisture load from the respirating plants, creating the need for a huge ventilation system. If high-quality agricultural land is not available, a more feasible approach may be to use recycled nutrients to grow food at ground level on poor-quality land.

Larry Schlussler
Sun Frost
Arcata, Calif.

Save the Planet

Among several reasons cited in favor of educating women in "How Women Can Save the Planet," Lawrence M. Krauss correctly states that educated women "are less likely to accept fundamentalist extremism." I believe that it is especially important for Muslim groups such as the Taliban to know that the founder of Islam, the Prophet Muhammad, 1,400 years ago told his followers that they could earn paradise by educating their daughters. Could we all not come closer to a more peaceful society, a paradise on earth, by rediscovering the wisdom of educating the women of our planet?

Sohail Husain
Yale University School of Medicine

ERRATUM In "Putting Madness in Its Place" [News Scan], JR Minkel referred to residents of Oakland County, Calif. The subjects of the study were residents of the city of Oakland, which is in Alameda County.

CLARIFICATIONS In "A Path to Sustainable Energy by 2030," Mark Z. Jacobson and Mark A. Delucchi write about the use of neodymium in wind turbine gearboxes; however, its use is limited to certain permanent magnets in turbine generators.

In "You Nerd a Vacation" [Anti Gravity], Steve Mirsky writes that Dolly the sheep was the first animal cloned from an adult cell. Dolly was the first case of a cloned mammal, but the feat has been achieved in amphibians and fish since at least the 1960s.

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National Science and Technology Development Agency

Research Inspired Business in Thailand: Science, Technology and Innovation Hub at Thailand Science Park

A science, technology and innovation – based economy is now a top national priority for Thailand's social and economic advancement and sustainable growth. The vision that research and technology transfer are key boosters for national wealth and well being is being deployed across all state agencies. With a mission to build Thailand's scientific capacity and competitiveness, the National Science and Technology Development Agency (NSTDA) acts as research and development hub for highly qualified human resources as well as first rate science and technology infrastructure. Bridging the gap between research and the marketplace, NSTDA builds alliances of universities, industry and government to successfully link science and business. A focus is placed on Thailand's national missions and directed to the agriculture, industry and services sectors targeting the automobile, information, computer and electronics, as well as, foods, medicals, energy, and textiles industries.

The Place Where Innovation Begins

NSTDA and its four National Research Centers: National Center for Genetic Engineering and Biotechnology (BIOTEC), National Metal and Materials Technology Center (MTEC), National Electronics and Computer Technology Center (NECTEC) and National Nanotechnology Center (NANOTEC) are all located in the "Thailand Science Park". Run by NSTDA's Technology Management Center (TMC), Thailand Science Park has been designed from its inception to inspire and stimulate the formation and growth of research-based businesses and innovative companies. The co-location of research and industry and working amongst a like-minded community with advanced infrastructure are key contributing factors to the many successful collaborative ventures initiated by NSTDA.

NSTDA engages with the private sector through joint R&D, knowledge and technology transfer, and S&T related services in an effort to stimulate the growth of knowledge-based businesses. In Thailand Science Park, access to NSTDA's four National Research Centers (BIOTEC, MTEC, NECTEC and NANOTEC) – laboratories and equipment, pilot plants, and testing units – is provided for all of NSTDA's partners and collaborators.

With such a critical S&T mass located right in Thailand Science Park, NSTDA and all Centers are proving to be unstoppable force in moving the wheels of research and innovation forward. As collaborations gain momentum, technology-driven private companies are being drawn to Thailand Science Park, recognizing the benefits of operating closer to scientists and having access to the most advanced research infrastructure within the site.

Today, Thailand Science Park houses NSTDA, BIOTEC, NECTEC, MTEC, NANOTEC, TMC and 60 private companies ranging from small, medium and large-sized businesses.

Shiseido Southeast Asia Research Center
"Before the establishment of the Shiseido Southeast Asia Research Center in Thailand, Shiseido Company was very well supported by BIOTEC both in terms of technology and other cooperation. Researchers at BIOTEC are the focal points in our making the decision of setting up our research center in Thailand."
– Shigeyuki Ogawa, General Manager, Shiseido Southeast Asia Research Center

Shiseido is Japan's largest cosmetics company, having 11 research centers around the world and holds more than 1,500 patents. All centers do research and development in 7 fields of technology – basic research, life sciences, pharmacology, product technology, pharmacy, advanced dermatology, and product safety and functionality. There are more than 1,000 Shiseido researchers all over the world.

Betagro Science Center
"We chose Thailand Science Park as the location for Betagro Science Center as we see great value in potential collaboration between our science center and the 4 National Research Centers. Having access to expertise and a great number of researchers in addition to advanced lab equipment will propel our R&D forward at a faster pace. And we truly believe that the 'scientific' and 'learning-driven' atmosphere will help induce our researchers to be more creative in their innovations."
– Vanus Taepaisitpongse, CEO of Betagro Group

Betagro Group is one of Thailand's largest groups of companies in the agro-industrial and food business sector. Betagro Group exports products to many major markets including Japan and EU. With 20,000 staff in 26 locations, the operations of Betagro cover animal feed production, livestock, animal health products, and premium quality food products.

Green Nanomaterials Research Center
"Innovation is a key strategy at SCG. However, innovation must be built on a strong base of science and technology. With ever-changing and fierce competition, we can no longer afford to do research alone. S&T related support from NSTDA will accelerate our innovative path to new products and services. The establishment of the Green Nanomaterials Research Center in Thailand Science Park encourages our researchers to work closely with top scientists at NSTDA's affiliated Centers, as well as with researchers at the nearby Sirindhorn International Institute of Technology, and the Asian Institute of Technology,." – Pramote Techasupatkul, President of SCG

SCG is one of Thailand's largest enterprises. With extensive industry knowledge, advanced production technology and product design capability, SCG is now recognized as a leading manufacturer of a diverse range of products in a wide variety of construction related applications in Thailand and the ASEAN region. By focusing on innovation in products and services, SCG can continuously offer new products and services which extend well beyond the original cement business. This means more value for our customers.

Moving Forward to Accelerate Innovation

Today, Thailand Science Park, Phase I is fully occupied with more than 60 corporate tenants (>25 % foreign owned) and whose economic impact is worth USD 100 millions per annum. There is a skilled workforce of 500, 60 percent of whom are R&D personnel.

To meet rapidly growing demand, NSTDA has started construction of Thailand Science Park, Phase II, whose designated name is Innovation Cluster II (or INC II). It is expected to be finished and in operation by 2011. INC II comprises four inter-connected towers, and is built around a concept of "Work-Life Integration" with a highly conducive environment for research. It will be a place to live and to work, and will meet the ever-changing needs of today's knowledge workers.

NSTDA embraces the expansion of Thailand Science Park which will continue to foster home-grown innovation and technology development. Collaboration with the public and private sectors, as well as with research institutions is being strengthened to ensure business competitiveness to create new markets, and to drive economic growth.

For more information, please contact:

www.sciencepark.or.th

Soil Progress ▪ Madame Curie ▪ Provident Vaccination

Compiled by Daniel C. Schlenoff

MARCH 1960

MODERN AGRICULTURE—"The 20th-century Israelites came to a land of encroaching sand dunes along a once-verdant coast, of malarial swamps and naked limestone hills from which an estimated three feet of topsoil have been scoured, sorted and spread as sterile overwash upon the plains or swept out to sea in flood waters. The land of Israel had shared the fate of land throughout the Middle East. A decline in productivity and in population had set in with the fading of the Byzantine Empire some 1,300 years ago. Today most of the people of the world live in the lands where mankind has lived longest in organized societies. There, with few exceptions, the soil is in the worst condition. The example of Israel shows that the land can be reclaimed and that increase in the food supply can overtake the increase that will double the 2,800 million world population before the end of this century."

The entire article is at www.ScientificAmerican.com/mar2010

MARCH 1910

CURIE, DEBIERNE—"According to the theory of radio-active transformations, the quantity of polonium present in radio-active minerals must be very small. According to this theory, polonium is looked upon as a descendant of radium, and the relative proportion of these substances in radio-active equilibriums is equal to the ratio of their mean lives. The mean life of radium being about 5,300 times greater than that of polonium, and radium being found in pitchblende in about the proportion of 0.2 gramme per ton, it is seen that the same mineral cannot contain more than about 0.04 milligramme of polonium per ton. We have undertaken recently a chemical research with a view of preparing polonium in a concentrated state. This was performed on several tons of residues from the uranium mineral which were at our disposal for this purpose. —Mdme. P. Curie and A. Debierne"

MEDICAL MONITOR— "It is of the highest importance that the physician be kept informed of the variable temperature of the blood. According to present practice, temperature readings are taken at regular intervals, say, three or four times a day, by a sensitive thermometer. This practice obviously gives no information as to those oscillations in temperature which may have occurred in the meantime, and which, in some cases, it would be desirable to know. A firm of Berlin constructors have recently perfected an apparatus allowing this important factor to be recorded continually and automatically [*see illustration*]."

BODY TEMPERATURE: Continuous electric monitoring, 1910

SCIENTIFIC AMERICAN, VOL. II, NO. 11; MARCH 12, 1910

MARCH 1860

BURNING GLASS— "Important to cotton shippers: beware of bulls' eyes! It has been observed (says the *New York Tribune*) that the fires which have occurred so frequently in vessels laden with cotton, have been confined principally to American ships, in which the convex side-lights called bulls' eyes, are a peculiarity. Foreign vessels rarely use these for lights, and not a single fire has occurred in them at our cotton ports. The theory is that the bull's eye acts as a burning lens, whenever the sun chances to shine through it, and will ignite any combustible article lying in its focus."

GET VACCINATED—" 'Gas [for interior illumination], it is supposed, is a powerful disinfectant, and hence there is no contagion within the circle of its influence.' We copy the above sentence for the purpose of disputing the inference that gas will protect people from the small-pox. Small-pox is doubtless uncommon among that class of people who burn gas for light in our cities, because they generally have sufficient intelligence and forethought to attend to the vaccination of their families, and its ravages are almost wholly confined to that improvident class who make no provision against the small-pox, or anything else in the future, and who live by the light of burning fluid."

Energy & Environment

The Deadliest Catch

A proposed trade ban could take bluefin tuna off the menu BY MICHAEL MOYER

END OF THE LINE: At Tokyo's Tsukiji fish market, around 1,000 bluefin tuna are auctioned off every day.

THIS JANUARY A 511-POUND MONSTER OF A BLUEFIN TUNA SOLD at Tokyo's Tsukiji fish market for $175,000—by far the highest price paid for a fish in nine years. By that afternoon, customers at Kyubey, a Michelin-starred restaurant a stone's throw from the market, were dining on the tuna's fatty belly, or *toro,* the most opulent and rich cut from the most valuable fish in the world.

Japanese diners could soon face much higher bills for bluefin. This month a meeting of the Convention on International Trade in Endangered Species (CITES) in Doha, Qatar, is slated to consider a proposal to ban all commercial trade of the Northern bluefin, *Thunnus thynnus,* grouping it with megafauna superstars such as the white rhino and the Asian elephant. Japan imports about 80 percent of the total bluefin catch in the Atlantic and Mediterranean, even as those stocks have plummeted to such paltry levels that many scientists speculate that the fish could be headed for extinction.

Never before has such a commercially important animal been subject to an international trade ban, and proponents have braced for furious opposition. To qualify for a complete trade ban, CITES requires that the population of a species must have declined to less than about 20 percent of its historic population size or have suffered from an extremely high recent rate of decline. And although it is no simple task to measure the total size of a population that wanders from the Mediterranean to the Gulf of Mexico over its decades-long life span, recent scientific committees organized by the United Nations Food and Agriculture Organization and the International Commission for the Conservation of Atlantic Tunas (ICCAT) agree that the Northern bluefin meets the criteria.

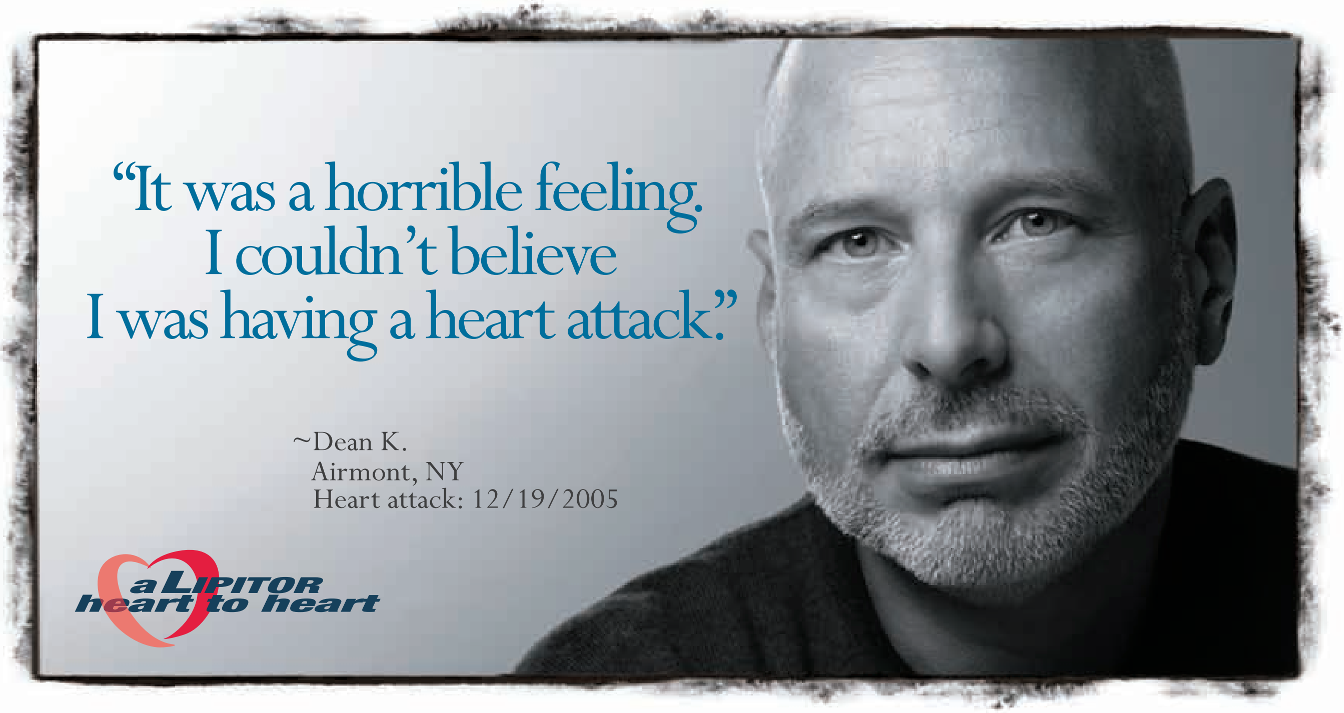
Another condition of a CITES listing is that enforcement inspectors must be able to identify the tuna—a task that turns out to be almost as difficult as measuring the population. There are three species of bluefin tuna—Northern, Pacific and Southern—and even trained taxonomists have trouble distinguishing Northern bluefin from its Pacific cousin.

The problem extends all the way to the plate. Late last year a team of researchers from Columbia University and the American Museum of Natural History examined 68 samples of tuna smuggled out of sushi restaurants in New York City and Denver. They found that 19 of 31 restaurants either could not identify or misidentified the species of tuna they were serving—for example, replacing bluefin with bigeye (or vice versa). Of the nine samples of fish advertised as "white tuna," they discovered that five were not tuna at all but rather escolar, a fish banned as a health hazard in Italy and Japan because it contains indigestible wax esters that can cause diarrhea.

Traditional DNA analysis techniques could not identify the various species of tuna; the fish are too genetically similar. Instead the researchers introduced a new approach. Conventional DNA "barcoding" techniques break apart DNA sequences into a jumbled bag of base pairs, then compare how similar the bag is to a reference bag. The new approach looks at the order of nucleotides in a DNA sequence at a specific location on the genome. The approach enables positive identification of any tuna sample—even one that is sitting on a bed of rice.

"Some sort of DNA-based identification will be a critical component for making CITES an effective regulation," says Jacob Lowenstein, one of the co-authors of the research. "This will probably in the short term become the standard tool for regulatory bodies." And even if the CITES proposal fails, there will still be much to enforce. ICCAT is charged with setting bluefin catch quotas in the Atlantic and Mediterranean, and by most accounts it has done a terrible job of it. "ICCAT was convened and estab-

JERRY DRIENDL *Getty Images*



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tablets

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Call 1-888-LIPITOR (1-888-547-4867) or visit www.lipitor.com/dean

*You are encouraged to report negative side effects of prescription drugs to the FDA.
Visit www.fda.gov/medwatch or call 1-800-FDA-1088.*

IMPORTANT FACTS

LIPITOR atorvastatin calcium tablets (LIP-ih-tore)

LOWERING YOUR HIGH CHOLESTEROL

High cholesterol is more than just a number, it's a risk factor that should not be ignored. If your doctor said you have high cholesterol, you may be at an increased risk for heart attack and stroke. But the good news is, you can take steps to lower your cholesterol.

With the help of your doctor and a cholesterol-lowering medicine like LIPITOR, along with diet and exercise, you could be on your way to lowering your cholesterol.

Ready to start eating right and exercising more? Talk to your doctor and visit the American Heart Association at www.americanheart.org.

WHO IS LIPITOR FOR?

Who can take LIPITOR:

- People who cannot lower their cholesterol enough with diet and exercise
- Adults and children over 10

Who should NOT take LIPITOR:

- Women who are pregnant, may be pregnant, or may become pregnant. LIPITOR may harm your unborn baby. If you become pregnant, stop LIPITOR and call your doctor right away.
- Women who are breast-feeding. LIPITOR can pass into your breast milk and may harm your baby.
- People with liver problems
- People allergic to anything in LIPITOR

BEFORE YOU START LIPITOR

Tell your doctor:

- About all medications you take, including prescriptions, over-the-counter medications, vitamins, and herbal supplements
- If you have muscle aches or weakness
- If you drink more than 2 alcoholic drinks a day
- If you have diabetes or kidney problems
- If you have a thyroid problem

ABOUT LIPITOR

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

LIPITOR can lower the risk of heart attack, stroke, certain types of heart surgery, and chest pain in patients who have heart disease or risk factors for heart disease such as:

- age, smoking, high blood pressure, low HDL-C, family history of early heart disease

LIPITOR can lower the risk of heart attack or stroke in patients with diabetes and risk factors such as diabetic eye or kidney problems, smoking, or high blood pressure.

POSSIBLE SIDE EFFECTS OF LIPITOR

Serious side effects in a small number of people:

- **Muscle problems** that can lead to kidney problems, including kidney failure. Your chance for muscle problems is higher if you take certain other medicines with LIPITOR.
- **Liver problems**. Your doctor may do blood tests to check your liver before you start LIPITOR and while you are taking it.

Call your doctor right away if you have:

- Unexplained muscle weakness or pain, especially if you have a fever or feel very tired
- Allergic reactions including swelling of the face, lips, tongue, and/or throat that may cause difficulty in breathing or swallowing which may require treatment right away
- Nausea, vomiting, or stomach pain
- Brown or dark-colored urine
- Feeling more tired than usual
- Your skin and the whites of your eyes turn yellow
- Allergic skin reactions

Common side effects of LIPITOR are:

- Diarrhea
- Upset stomach
- Muscle and joint pain
- Changes in some blood tests

HOW TO TAKE LIPITOR

Do:

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

Don't:

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

NEED MORE INFORMATION?

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

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Rx only

lished in the 1960s because of widespread concern by tuna fishermen over the decline of bluefin tuna," says Carl Safina, president of the Blue Ocean Institute. "Since its inception the bluefin population has done nothing but go down."

Even though ICCAT sets catch quotas far higher than the recommendations of its own scientific advisory board, poaching and smuggling are still rampant. In 2007, for instance, ICCAT had set the quota for the Eastern Atlantic and Mediterranean at 29,500 metric tons of bluefin, even though scientists had recommended that ICCAT shut down the Mediterranean fisheries for two months during spawning season and limit total catch to less than 15,000 metric tons. Fishermen caught an estimated 61,000 tons, most of it in the Mediterranean spawning grounds. Says Safina, "It's an all-out war on the fish at the moment."

Carbon Rock Lock: Storing CO_2 on the East Coast

Sucking carbon dioxide and other greenhouse gases from smokestacks and burying them underneath the ground is a key technology cited by politicians and scientists as a way to help combat climate change. One open question is where best to store the CO_2. A recent analysis points to the volcanic rock off the East Coast of the U.S.

Such rock, known as basalt, might be better than other sites, such as deep saline aquifers or nearly empty oil wells, because the rock not only stores CO_2 but also over a relatively short period of years forms carbonate minerals out of it—in other words, limestone. And coastal basalt has the added benefit of having an overlying ocean, which acts as a second barrier of protection against the gas leaking out.

Research led by geophysicist David S. Goldberg of Columbia University's Lamont-Doherty Earth Observatory had previously shown that basalt lies off the West Coast of California, Oregon and Washington. His group's latest search has turned up vast deposits in the East off the coast of Georgia, Massachusetts, New Jersey, New York and South Carolina. One formation off of New Jersey could hold as much as one billion metric tons of CO_2, report Goldberg and his team in the online January 4 *Proceedings of the National Academy of Sciences USA.* Of course, the world's nations emit over 30 billion metric tons of CO_2 a year.

If scientists can show that CO_2 stays put underground—experiments are under way off the coast of Oregon and in Iceland—then basalt could become important considering how widespread it is, points out Klaus S. Lackner, director of the Lenfest Center for Sustainable Energy at the Earth Institute. "The Siberian basalt traps, the Deccan flats in India—there are enormous amounts of basalt" around the world, he notes.

—David Biello

GREENHOUSE SPONGE: Volcanic rock known as basalt converts CO_2 to carbonate minerals, making the widely distributed substance ideal for carbon sequestration.

Medicine & Health

Stem Cell Vitamin Boost

Vitamin C increases the production of induced stem cells BY CARINA STORRS

SOON AFTER THE EXCITING DISCOVERY OF A method to turn human adult cells into stem cells in 2007 came the frustration of actually trying to make that transformation efficient. In creating induced pluripotent stem (iPS) cells, scientists typically only get 0.01 percent of a sample of human fibroblast (skin) cells to change.

A group led by Duanqing Pei of the Guangzhou Institutes of Biomedicine and Health in China has found that a simple chemical can boost the efficiency by 100-fold—namely, vitamin C.

The researchers can trigger the conversion to iPS cells by introducing genes or proteins to adult cells, typically with a virus. Once the cells become pluripotent, they have the ability to become any cell in the body, thereby offering the promise of repairing damaged organs and treating disease. But scientists have yet to come up with the ideal recipe. "It's a worldwide effort to boost efficiency and make this more practical for much wider participation from the scientific community," Pei says.

In their effort, Pei and his group started with the realization that the factors that induce cells to become pluripotent were causing the cells to make the free radicals known as reactive oxygen species (ROS). "A high level of ROS is definitely very bad for the fibroblasts," Pei notes, because it speeds cell death. To fight off the ROS, Pei's team tested a variety of antioxidant chemicals in the cells' growing medium. Experimenting with mouse cells, the group

JUICED UP: The antioxidant properties of vitamin C are not only good for health but also good for making lots of induced pluripotent stem cells.

GETTY IMAGES (*basalt and orange juice*) found that the petri dish containing vitamin C had 30 percent more mouse cells than the dish that did not, suggesting that the antioxidant helped to ward off the effects of aging.

Surprisingly, vitamin C not only helped cells survive, but it also enhanced their progression to pluripotency. After 14 days, when cells start to become fully pluripotent, 10 to 20 percent of the mouse cells that were grown with vitamin C expressed genes associated with pluripotency, compared with only 0.1 to 0.2 percent of the colonies grown without vitamin C. The group saw a similar improvement in human fibroblast reprogramming, in which ascorbic acid boosted the conversion rate from 0.01 to 1 percent.

The researchers, who published their findings in the December 24 *Cell Stem Cell,* also tested other antioxidants, but none boosted the development of pluripotency the way vitamin C did. That has lead Pei to believe that, in addition to ascorbic acid's antioxidant property, an as yet unknown mechanism plays a role. And although more detailed analysis is needed, having vitamin C around does not seem to introduce negative cellular changes.

"Overall, I think this is quite impressive progress," remarks Kwang-Soo Kim, director of the Molecular Neurobiology Lab at Harvard Medical School. Although 1 percent may not seem all that efficient, it could be enough to push the field significantly. "We don't need to generate 50 percent of the cells," Kim says, "as long as we can reproducibly generate a sufficient number of iPS lines."

URSULA MARKUS *Photo Researchers, Inc.*

Mutant Cholesterol Fends Off Dementia

Cholesterol may conjure up associations of cardiovascular disease, but growing evidence shows that the lipid has great importance in the health of the brain, where one quarter of the body's cholesterol resides. A new study has found that a common alteration to a gene that controls the size of cholesterol particles slows a person's rate of dementia and protects against Alzheimer's disease.

Individuals with the mutation—a swap of one amino acid (isoleucine) for another (valine) in the gene for cholesterol ester transfer protein (CETP)—had "significantly slower memory decline," report researchers in a paper published online January 12 in the *Journal of the American Medical Association.* In fact, those who harbored two valine alleles experienced cognitive decline 51 percent more slowly than those with isoleucine—and had a 70 percent reduction in their risk for developing Alzheimer's.

The results are preliminary, and the precise dynamic behind this cognitively protective phenomenon remains unknown. But the gene has previously been linked to longevity, and work is already under way to design drugs that alter CETP function in the interest of helping those with heart disease, notes senior author Richard B. Lipton of the Albert Einstein College of Medicine. Those therapies, Lipton hopes, might also provide some of the cognitive benefits revealed in this study. *—Katherine Harmon*

Research & Discovery

Heavy Brows, High Art

Were Neandertals our mental equals? BY CHARLES Q. CHOI

Newly discovered painted scallops and cockleshells in Spain are the first hard evidence that Neandertals made jewelry. These findings suggest humanity's closest extinct relatives might have been capable of symbolism after all.

Body ornaments made of painted and pierced seashells dating back 70,000 to 120,000 years have been found in Africa and the Near East for decades, and they serve as signs of symbolic thought among the earliest modern humans. The absence of similar finds in Europe at that time, when it was Neandertal territory, has supported the notion that our early relatives lacked symbolism, a potential sign of mental inferiority that might help explain why *Homo sapiens* eventually replaced them. Although hints of Neandertal art and jewelry have cropped up, such as pierced and grooved animal-tooth pendants, they have often been shrugged off as artifacts mixed in from modern humans or as imitation without understanding.

Now archaeologist João Zilhão of the University of Bristol in England and his colleagues have found 50,000-year-old jewelry at two caves in southeastern Spain, 10,000 years before modern humans entered Europe. Cueva (Cave) Antón contained a pierced king scallop shell painted with orange pigment made of yellow goethite and red hematite collected some five kilometers from the site. Among material unearthed at Cueva de los Aviones, alongside quartz and flint artifacts, were two pierced cockleshells that were painted with traces of red hematite. No dyes were found on food shells or stone tools, suggesting the jewelry was not just painted at random.

These discoveries, in combination with earlier artifacts, indicate that "Neandertals had the same capabilities for symbolism, imagination and creativity as modern humans," Zilhão says. Anthropologist Erik Trinkaus of Washington University in St. Louis, who did not take part in this study, hopes that the finds "will start to bury the idea that's been around for 100 years—that Neandertals died out because they were stupid." The jewelry also implies that Neandertals might have taught our ancestors how to paint—or vice versa. Zilhão and his team offered details online January 11 in the *Proceedings of the National Academy of Sciences USA*.

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

COURTESY OF JOÃO ZILHÃO *University of Bristol*

NEANDERTAL PAINT JOB appears on this composite image of a king scallop shell. The external side (*right*) shows remnant flecks of orange paint. The coloration was perhaps an attempt to regain the original appearance or to match the shell's naturally red internal side (*left*).

Numbers War

School battles heat up again in the traditional vs. reform-math debate

BY LINDA BAKER

Over the past 20 years educators have fought over the best way to teach numbers to kids. Advocates of traditional math tout the practice of algorithms and teacher-centered learning, whereas reform-math proponents focus on underlying concepts and student inquiry. In the face of continued declining scores in the U.S., these so-called math wars have heated up recently with the circulation of petitions, the release of contested curriculum guidelines and, in one case, the filing of a lawsuit. At stake is the ability of American high school graduates to perform everyday math tasks and compete in a global economy.

The war began in 1989, when the National Council of Teachers of Mathematics (NCTM) released a set of standards that reshaped a generation of instruction. Instead of having students memorize formulas and compute problems such as adding fractions, advocates of reform math encouraged students to develop their own visual representations of math concepts and use calculators to solve numerical tasks.

In recent years a détente between the two camps formed, one that emphasized a middle ground. But if there is a truce, it is an uneasy one—new volleys from both sides continue to appear. Last October, for example, the NCTM released yet another document, "Focus in High School Mathematics: Reasoning and Sense Making," which calls for a new approach revolving around applications. "Our 15-year-olds cannot use math to address simple real-life situations," explains Gary Martin, a professor of math education at Auburn University and chair of the committee that wrote the document. Martin says that the new guidelines teach students how to "apply mathematical reasoning in a variety of contexts" instead of simply "carrying out procedures in a rote way." He cited as an example a problem that asks students to compare the relative fuel-efficiency gains in two pairs of vehicles. The answer varies depending on whether one considers relative fuel efficiency or the total number of gallons of gasoline saved.

Although many educators have praised the report, critics say the document's vague approach to mathematical analysis is reminiscent of the NCTM's 1989 guidelines. "The sense is that all reasoning students attempt is valuable and should be celebrated," says Stanford University mathematician Jim Milgram, who prefers a more traditional approach. "The trouble with this approach is that it is exactly status quo; we seem to have a mindset that, 'Gee, Johnny reasoned'; it doesn't matter that his actual reasoning is flawed."

Vern Williams, a math teacher in Falls Church, Va., who has participated in several national math panels, says the high school guidelines downplay the link between reasoning and traditional procedures such as factoring polynomials. "Some of the most elegant math

GETTY IMAGES

GREATER THAN OR EQUAL TO? Debate continues on the merits of teaching equation solving, geometry proofs and other old-school approaches in math education versus reform methods, which stress visual representations and real-world applications.

problems are deemed useless because they don't involve real-world applications," he says. Williams adds that many courses in geometry, "the one high school class that demands formal reasoning," have already been "gutted" and are no longer proof-based. Instead students use algebraic tools to analyze geometric shapes, build three-dimensional models, and solve actual construction and design problems.

For his part, Martin says the document was not intended to define specific content; rather it shows how reasoning and sense making can be incorporated throughout the curriculum. But detractors of reform math do not seem to be ready to agree. In one notable example, a group of parents and educators in Seattle have filed a brief appealing the school board's decision last May to adopt the Discovering Mathematics series, a reform-math high school text that uses student investigations as a means of discovering math principles—such as using toothpick models to derive recursive sequences. Citing declining test scores after a three-year pilot of the text, the suit claims the Discovering series is associated with a widening achievement gap between white students and minority and low-income students.

"A good textbook is very important," says Cliff Mass, a professor of atmospheric sciences at the University of Washington and one of three plaintiffs in the suit. He argues that the absence of "real math" in the Discovery series makes it very difficult for disadvantaged students to work through problems on their own.

Math experts have expressed other concerns about diluted instruction, including the decision by many school districts to require algebra I in eighth grade instead of the traditional ninth. Being younger, students tend to get a watered-down version of algebra I, but "then they are expected to continue on the trajectory of geometry and algebra II without a firm footing," points out William McCallum, a math professor at the University of Arizona.

McCallum is working on Common Core, a 48-state initiative that aims to resolve some of the debates by producing standardized, nationwide guidelines. The effort, which is sponsored by the Council of Chief State School Officers and the National Governors Association, was scheduled to have been completed in February.

One sentiment unites almost all math professionals—after decades of wrangling, the system still isn't working. According to the National Center for Education Statistics, U.S. high school students ranked in the bottom quarter in math performance, as compared with students of nations belonging to the Organization for Economic Cooperation and Development. In a future expected to depend even more on science, health and technology, that is bad news indeed.

Linda Baker, based in Portland, Ore., described ideas to boost urban bicycling in the October 2009 issue.

Dark Side of Black Holes

Dark matter could explain the early universe's giant black holes BY CHARLES Q. CHOI

Black holes one billion times the sun's mass or more lie at the heart of many galaxies, driving their spin and development. Common today, some 14 billion years after the big bang, such supermassive black holes were rare in the early universe—or at least they were supposed to be. Evidence of supermassive black holes existing when the universe was less than one billion years old has stumped scientists, because current theories of stellar evolution suggest that such giants should take much longer to grow. Now it seems this enigma could be solved by a mystery substance—dark matter.

The puzzle of early supermassive holes took shape in 2003, when the Sloan Digital Sky Survey detected roughly half a dozen of them. According to conventional thinking, the first regular stars were born when the universe was about 200 million years old, but given the state of the universe at the time, they could have formed black holes at most only about 100 times the sun's mass. It would simply take too long to merge and make the billion-year-old, billion-solar-mass monsters seen by the Sloan survey.

Dark matter could solve the conundrum, say theoretical physicist Katherine Freese of the University of Michigan at Ann Arbor and her colleagues. Unseen but demonstrating its existence via gravity, the substance makes up at least 80 percent of the universe's matter (and about one quarter of the entire universe). But scientists are unsure exactly what dark matter is made of. Among the leading hypothetical candidates are weakly interacting massive particles called neutralinos. They can annihilate one another when they meet, generating heat, gamma rays, neutrinos, and antimatter particles such as positrons and antiprotons.

Freese and her co-workers calculate that when the universe was just 80 million to 100 million years old, as protostellar clouds of gas tried to cool and shrink, their gravity would have drawn in neutralinos that annihilated one another, unleashing energy that would have created the first stars. They dub these objects "dark stars," fueled by dark matter rather than nuclear energy as in normal stars.

Their initial findings hinted that dark stars would have dwarfed regular stars. Because dark stars do not need the high densities seen in regular stars, which depend on atomic nuclei getting forced together for fusion, they would be much fluffier, with the largest ones reaching up to approximately 200,000 times the sun's width. Scientists have also estimated that the cooler surface temperatures of dark stars would have allowed them to grow up to 1,000 times the mass of the sun, as compared with the roughly 150-solar-mass size limit of current stars.

Freese and her colleagues, who plan to submit their analysis to the *Astrophysical Journal,* figure that dark stars could have reached as much as 100,000 solar masses or more before they burned out their fuel and collapsed. They analyzed how frequently neutralinos would flow into dark stars and get captured by atoms, concluding that dark matter particles could have fueled the growth of dark stars for much longer than first thought.

After supermassive dark stars ran out of dark matter, they would have contracted, triggering nuclear fusion and continuing on as regular stars for roughly a million years. These stars would not have gone supernovae—

"they are too big," Freese says—instead they collapsed into black holes of the same mass. Several of them could have then merged into giants within a billion years of the big bang.

Supermassive dark stars would have been up to one billion times as bright as the sun and yet able to shine at our sun's temperature with a yellow light. Freese hopes the James Webb Space Telescope, currently scheduled for launch in 2014, will see far enough to detect such fluffy giants. But no dark stars are likely to be forming today, because the density of dark matter now averages 1/8,000th of its dark star past, when the universe was far more compact.

Not everyone is convinced dark stars are real. Astrophysicist Brian O'Shea of Michigan State University contends the idea depends on too many assumptions regarding dark matter's properties—for instance, if dark matter were instead made of another theoretical particle dubbed the invisible ax-

Supersonic Bathtub Physics

Sonic booms in your bathtub? Apparently, a hard object falling into a pool can push a jet of air out of the water so fast that it briefly breaches the sound barrier.

Physicists at the University of Twente in the Netherlands and at the University of Seville in Spain set up an experiment in which they pulled a disk-shaped object flat down into water so that it hit the water at the relatively leisurely speed of one meter per second (roughly equivalent to dropping the disk from a height of a few centimeters). The disk displaced the water and created an air bubble in its wake as it sank.

As the water closed in to form the bubble, it pushed air up through a narrower and narrower neck, accelerating the air. "It's like a little nozzle which closes," explains Twente's Detlef Lohse, similar to what happens in a rocket engine. To track the air's motion, the team filled it with glycerin droplets produced by a smoke machine of the type used in dance clubs.

Using a high-speed camera and computer simulations, the researchers estimated that the jet reached a speed of 350 meters per second at its peak, or just above the speed of sound. Their report appears in the January 15 *Physical Review Letters.* Although the details change for objects of different shapes and sizes, "the physics is the same," Lohse says. "By dropping a stone into the water, you create a supersonic jet." —*Davide Castelvecchi*

SUPERSONIC SPLASH: A disk pulled into water by a piston at a leisurely one meter per second creates a bubble that, as it collapses, briefly forces air to move faster than sound.

FROM "SUPERSONIC AIR FLOW DUE TO SOLID-LIQUID IMPACT," BY STEPHAN GEKLE, IVO R. PETERS, JOSÉ MANUEL GORDILLO, DEVARAJ VAN DER MEER AND DETLEF LOHSE, IN *PHYSICAL REVIEW LETTERS*, VOL. 104; JANUARY 15, 2010 (*splash sequence*) ion, which does not self-annihilate, dark stars could not form.

Still, astrophysicist Paul R. Shapiro of the University of Texas at Austin thinks dark stars "are reasonable consequences of a reasonable model for dark matter."

And if scientists do find dark stars, they could help elucidate more than just black holes—they would hint at what dark matter actually might be. "If dark stars do exist, they would be incredibly cool," O'Shea notes.

Technology

Easy Flier

A build-it-yourself flying motorcycle could be ready soon BY JIM NASH

UP IN THE AIR or down on the ground, Samson's Switchblade, a three-wheeled flying motorcycle, is meant to do both.

COURTESY OF SAMSON MOTORWORKS

It is safe to bet that a flying motorcycle will never be a practical transportation option. Yet that has not stopped Samson Motorworks, a small engineering firm in California's Sierra Nevada foothills, from playing the long odds. The company is building a prototype called the Switchblade Multi Mode Vehicle, and it hopes to sell a do-it-yourself kit as early as 2011.

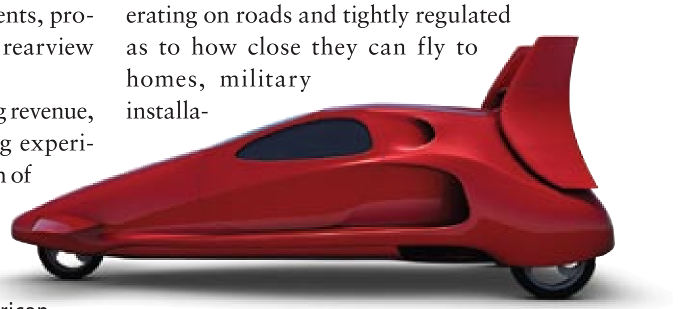
Sexy design and the promise of air-ground transport have kept alive dreams of a flying vehicle in every garage. Samson chose a three-wheel design because it meets the definition of a motorcycle, which is not as highly regulated as cars are. For example, motorcycles need not have bumpers, which would add weight and expense to a flying vehicle.

As the company envisions it, occupants would sit in the aerodynamic Switchblade side by side in leather seats and in climate-controlled luxury, behind an aggressively angled nose and canard. Samson is working with a third-party avionics maker to create an instrument display that switches from air to ground readings on landing. The Switchblade's stubby wings would open on pivots and behind the cockpit as a box kite–like stabilizer extends from the rear. On solid ground, the wings would swing into clamshell compartments, protected by a steel keel. Two large rearview mirrors would then swing out.

To contain costs while building revenue, design skills and manufacturing experience, Samson is following the path of other would-be aviation entrepreneurs by offering the Switchblade as a kit aircraft, in which no more than 49 percent of a craft can be preassembled by the manufacturer. It plans to sell the body for $60,000, but do-it-yourselfers will need to lay out another $25,000 for the engine and avionics. The craft would require a 120- to 150-horsepower engine (candidates on the market include Lycoming's O-320 aircraft engine, Suzuki's Hayabusa motorcycle engine and Kawasaki's Jet Ski personal watercraft engine). Samson president Sam Bousfield says he is also watching the development by entrepreneurs of small rotary engines that run cleaner than conventional piston motors.

The Switchblade will succeed, Bousfield believes, because it will morph easily between transportation mediums. If pilots encountered bad weather, they could put down at a small airstrip—at least 610 meters in length, according to Bousfield—fold in the wings, and finish the trip on the ground with no manual disassembly.

The reality is a bit more complicated, given that aircraft are prohibited from operating on roads and tightly regulated as to how close they can fly to homes, military installa-



tions, environmentally sensitive regions and other areas. It has competitors, too, such as the helicopterlike Butterfly Super Sky Cycle; the half-car, half-plane Terrafugia Transition; and the still unproved M400 Skycar. But the Switchblade appears to be the most practical air-ground hybrid.

The Switchblade might even have "green" appeal. The engines suitable for the craft all use ordinary unleaded gas and meet California emissions standards, which are stricter than those issued by the U.S. That in itself would be environmentally notable because private-aircraft engines are subject to vanishingly few emissions controls. Private planes make up a small percentage of all combustion-engine polluters, which makes them a less obvious target for environmental regulation.

The flying motorcycle's body is also designed to be more environmentally friendly than a car's: the Switchblade exterior will be made of self-reinforced (and technically, recyclable) polypropylene—aka "number 5" plastic on food containers—around a steel tubing frame.

"From a scientific point of view, it is definitely possible to build an aircraft that can also negotiate a highway," says N. C. Nataraj, chair of Villanova University's mechanical engineering department. Still, any reasonably complex system is optimized to do one thing, he says.

So for a flying motorcycle, design and functional compromises would almost certainly have to be made to accommodate twin missions, Nataraj adds. For instance, civilian aircraft must be much more robust than cars. "If you get a ding in your [car] door, no problem," he says. "Get a ding in your wing, and you will not be flying." General aviation pilot and flight instructor Jeffrey Geibel of Belmont, Mass., says a craft like the Switchblade would have to be maintained per the stringent standards of the Federal Aviation Administration.

None of this is lost on Bousfield, and like many a pioneer before him, he is pushing onward and upward. His next step will be wind-tunnel testing. An FAA-approved prototype is expected by year's end. And after that, the rest could possibly be personal transportation history.

Jim Nash is based in Chicago.

Invasion of the Drones

Unmanned aircraft take off in polar exploration BY DAVIDE CASTELVECCHI

A MULTINATIONAL, ROBOTIC AIR CORPS is quietly invading the polar regions of the earth. Some catapult from ships; some launch from running pickup trucks; and

UNMANNED AIRCRAFT **for polar science, such as the Meridian (shown during a test flight in Antarctica), are less expensive and safer to operate than ordinary airplanes.**

COURTESY OF UNIVERSITY OF KANSAS AEROSPACE ENGINEERING FLIGHT TEST TEAM

some take off the old-fashioned way, from icy airstrips. The aircraft range from remote-controlled propeller planes—of the type found at Toys “R” Us—to sophisticated, high-altitude jets. All are specially outfitted, not with weapons but with scientific instruments.

Unmanned aircraft have made headlines in the mountains of Afghanistan, but the technology has quickly trickled down to scientists seeking a less expensive, safer way to study the earth’s poles. Researchers have begun to put unmanned aerial systems, or UASs, to a variety of tasks, from monitoring the ozone layer to counting seal populations. Thanks to lower costs and improved technologies, “it’s absolutely exploded in the past couple of years,” says Elizabeth Weatherhead, who is an environmental scientist at the University of Colorado at Boulder.

The planes can be loaded with a variety of instruments, from radar (or lidar, the laser-based version) to chemical analysis tools and infrared sensors; some simply carry cameras. Last summer Weatherhead counted at least six different teams of scientists using UASs on a single Norwegian island. Her own group used a converted reconnaissance drone in two different Greenland missions. One mission was to count ice seal populations; another was to map melt ponds to help explain “why the edges of Greenland are melting so quickly,” she says. The team’s small UAS surveyed two melt ponds in a few days, Weatherhead says. “That’s something that previously would have taken researchers weeks for a single lake.”

Many of the aircraft cost several millions of dollars and are not exactly expendable. But at least if one goes down, there’s no loss of human life: polar crashes are “often beyond rescue capabilities,” Weatherhead says.

Some teams have learned to design and build their own aircraft. Richard Hale of the University of Kansas’s Center for Remote Sensing of Ice Sheets was in Antarctica this austral summer to test the Meridian, a new, single-prop unmanned plane built by a team mostly of Kansas students. The half-ton UAS, with a wingspan of eight meters and a range of 1,750 kilometers, will conduct radar surveys of the ice masses and of the underlying land.

Many of the planes fly preprogrammed routes by autopilot and are only remotely controlled for takeoff and landing (although some small ones are clotheslined by a strong wire). Small UASs are fuel-efficient, which is especially important in a place like Antarctica, where all the fuel has to be flown in at great expense. “We burn 1/20th of the fuel” of a conventional airplane, Hale said in January, speaking over a satellite link from the National Science Foundation’s McMurdo Station.

In an age of constant satellite surveys, airplanes are still necessary. They can, for example, “map the ice sheet at a resolution that modelers can use to really understand the dangers we’re seeing,” explains atmospheric scientist David Braaten of the University of Kansas. Braaten was a member of a team last year that mapped the Gamburtsev Mountains in Antarctica, a chain the size of the Alps buried under thousands of meters of ice. That survey was done with radar mounted on an ordinary twin-engine propeller airplane based in East Antarctica. (Robin Bell of Columbia University’s Lamont-Doherty Earth Observatory chronicled the effort in her blog on ScientificAmerican.com.) If a UAS had been available at the time, that project might have been “a lot cheaper,” Braaten figures.

Even better, a UAS with a long enough range could survey Antarctica while being based in Chile. This possibility may actually become true in the next few years. In October, NASA conducted the first test flights of its newly acquired Northrop Grumman RQ-4 Global Hawk, a jet-powered drone that can fly at altitudes up to 65,000 feet (where it can avoid the rough weather of polar regions) for more than 31 hours at a time. It can literally fly to the other end of the earth on a single tank of fuel.

The agency hopes to start science missions in March. NASA atmospheric physicist Paul Newman says the drone’s first task will be to help the agency calibrate satellite measurements of the ozone layer. “We’ll also have a number of instruments that measure aerosols,” Newman adds. “We’ll use this to estimate the cross-Pacific transport of air pollution and aerosols.” No doubt, robot aircraft for science are really taking off.

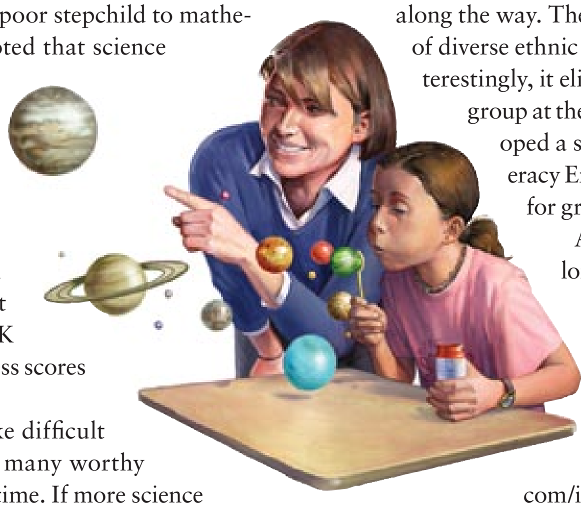
Start Science Sooner

Excellence in science education must begin in kindergarten

BY THE EDITORS

Good science education at the earliest grades is supremely important, but in most classrooms it gets short shrift. Studies have found that children in kindergarten are already forming negative views about science that could cast a shadow across their entire educational careers. When researchers interviewed kindergartners from typical classrooms, barely a third of the children showed any knowledge of science, whether from school or other sources. Many children said that science was for older kids and adults, not kindergartners like them. They talked of science being about magic potions or dangerous chemicals; they said science is hard, science is not interesting, and "I am not good at science." Ask a room of five-year-olds to draw a scientist, and you will likely get lots of pictures of white-coated men in laboratories. Furthermore, even before first grade, fewer girls than boys say they like science.

It is perilous to generalize about anything in the U.S. education system—quality varies enormously from classroom to classroom—but science has long been a poor stepchild to mathematics and reading. One report noted that science instruction in the early grades "occurs sporadically and rarely engages children in practices that encourage rigorous and reflective science learning." Science is high on the list of subjects that early-grade teachers feel ill prepared to teach. A 2009 study found that Head Start children in Florida ended their pre-K year with significantly lower readiness scores in science than in any other domain.



Of course, teachers need to make difficult trade-offs in the classroom, where many worthy subjects compete for precious little time. If more science is to be taught in kindergarten, what should be removed to make way for it?

Maybe nothing. Educational psychology researchers at Purdue University have developed an approach for teaching science in kindergarten that integrates it with language. The combination not only makes science instruction more appealing to teachers who are very mindful of language arts core curriculum requirements. It also enhances language learning by providing situations in which written language is used for a genuine purpose—recording and reporting predictions and observations—instead of a task devoid of any real context. And the kindergartners delight in learning words they would usually never encounter in kindergarten lessons, such as "excrete" (even if they cannot always spell them correctly).

The Purdue approach, the Scientific Literacy Project (www.purduescientificliteracyproject.org), introduces children to the most fundamental idea—that science is about carefully conducted inquiry to learn about the world—and shows them that everyone can do science. The lessons do not depend on expensive equipment or the latest in animations and computer games. Low-tech methods suffice, including experiments as simple as seeing if salt will dissolve, reading well-chosen nonfiction books—which many adults mistakenly imagine to be inappropriate or uninteresting to such young children—and maintaining individual science journals.

The researchers found that students participating in their project showed significant gains relative to those taking traditional classes. The kindergartners readily developed skills related to asking questions, conducting observations and experiments, drawing conclusions and sharing their findings—and had tremendous fun along the way. The project showed its worth for children of diverse ethnic and social backgrounds, and, most interestingly, it eliminated the gender gap in attitudes. A group at the University of Illinois at Chicago developed a similar project—Integrated Science-Literacy Enactments (www.uic.edu/educ/ISLE/)—for grades 1 through 3.

An emphasis on "inquiry science" has long been advocated by the National Research Council, whose national science education standards stress science as inquiry and grasp of a few fundamental concepts, ahead of the more traditional focus on a wide smattering of content knowledge (see tinyurl.com/inquirysci). The approach does, however, depend on the instructors understanding how to carry out inquiry-based lessons effectively. The teachers need training in how to teach science. It is not enough to give them courses to bolster their science content knowledge—or to fast-track science graduates into teaching with insufficient schooling in the science of how children learn.

Children are natural scientists: not only are they inquisitive and energetic, but they have an instinct for controlled experimentation. The goal of science education at the earliest levels should be to encourage and refine children's innate love of exploring the world around them and to help that enthusiastic behavior grow into true scientific literacy. ■

ILLUSTRATION BY MATT COLLINS

What's the fastest way to learn a language?

ACT LIKE A BABY.

It's not the advice you'd expect. Learning a new language seems formidable, as we recall from years of combat with grammar and translations in school. Yet infants begin at birth. They communicate at eighteen months and speak the language fluently before they go to school. And they never battle translations or grammar explanations along the way.

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Three characteristics of the child's language-learning process are crucial for success:

First, and most importantly, a child's natural language-learning ability emerges only in a speech-soaked, immersion environment free of translations and explanations of grammar.

Second, a child's language learning is dramatically accelerated by constant feedback from family and friends. Positive correction and persistent reinforcement nurture the child's language and language skills into full communicative expression.

Third, children learn through play, whether it's the arm-waving balancing act that announces their first step or the spluttering preamble to their first words. All the conversational chatter skittering through young children's play with parents and playmates—"…what's this…" "…clap, clap your hands…" "…my ball…"—helps children develop language skills that connect them to the world.

Adults possess this same powerful language-learning ability that orchestrated our language success as children. Sadly, our clashes with vocabulary drills and grammar explanations force us to conclude it's hopeless. We simply don't have "the language learning gene."

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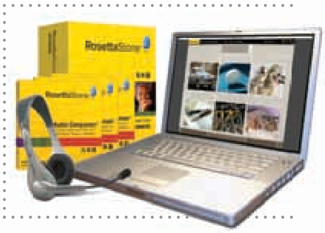

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Breaking the Climate Debate Logjam

Some steps to speed action toward a low-carbon economy

BY JEFFREY D. SACHS

There is a growing possibility that the U.S. will pass no climate change legislation in this session of Congress: the uphill climb is at least as steep, and probably steeper, as it is for health care legislation. President Barack Obama cannot presume to hold his own party in line on climate change. Several Democratic senators have already asked him to stop pushing for a bill in 2010, given the proximity to the midterm elections.

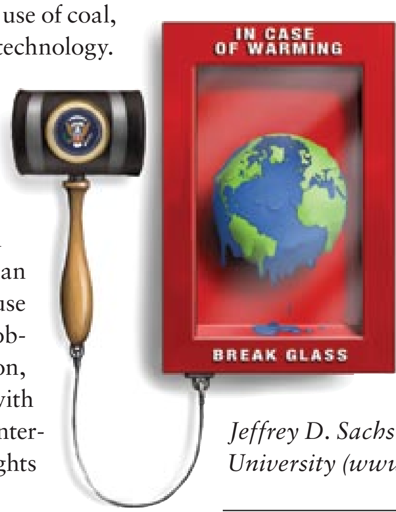
The fracture lines are countless, but probably the most important one runs through public opinion. A recent poll showed only 36 percent of Americans believing that the evidence of human-induced climate change is firm, down from 47 percent in early 2008. The rise of unemployment has perhaps made people more reluctant to accept adverse news on living standards. There is also considerable public confusion about climate science and possible remedies.

Vested interests, especially coal and oil, play their predictable role. Half the states produce at least some coal, and around 30 states produce at least a bit of oil. In the dozen or so major coal or oil states, opposition to climate change action is politically powerful and well organized. Oil-producing states in the Gulf of Mexico tend to resist climate action even though the Gulf is probably already experiencing damage from rising hurricane intensity.

The environmental community is also divided. Many environmental groups oppose nuclear power and any use of coal, even with carbon capture and sequestration technology. Conservationists have fought many renewable energy projects, opposing wind power near farms and coastlines, solar thermal plants in the desert and high-voltage transmission lines near residential communities.

Another factor is the bargaining approach to climate legislation. Rather than defining a plan toward a low-carbon economy, the White House has left the negotiations to Congress and the lobbyists. The result is sprawling draft legislation, hard for the public to understand and replete with hidden and overt financial transfers to vested interests, especially in the allocation of emissions rights under a complex cap-and-trade system.

Perhaps the legislation can still narrowly pass, which at this point would be the best option. If it stalls this spring, however, the climate and the rest of the world can't wait.



A different approach is needed. Here are some components.

First, the Environmental Protection Agency has the mandate to move under the Clean Air Act. It could impose a timetable of emissions standards for electric utilities and for vehicles, which together account for around three fourths of carbon emissions. There is also broad support for needed R&D funds and important scope for energy efficiency through weatherproofing and green building codes.

Second, if cap-and-trade stalls, the administration and Congress should rethink their opposition to the much simpler option of a carbon tax. A predictable carbon tax would be much more effective than the cumbersome and nontransparent cap-and-trade system and might win broader assent as part of a package of deficit reduction.

Third, the public needs to hear a plan. The administration has embraced a goal of 17 percent reduction of greenhouse gas emissions by 2020, but it hasn't told us how that would be achieved. The public is scared that even this modest goal would slam jobs and living standards. It's time to spell out the changes in power generation, automobile technology and energy efficiency that can take us to our goals at modest cost and huge social benefit.

Fourth, it's time to step up the response to the climate skeptics, who have misled the public. The *Wall Street Journal* leads the campaign against climate science, writing editorials charging that scientists are engaged in a massive conspiracy. I have made repeated invitations to the *Journal* editors to meet with climate scientists publicly for an open discussion or debate, but all have been rebuffed.

Let's hear more from the president's science adviser, John P. Holdren, Nobel laureate energy secretary Steven Chu, the National Academy of Sciences and other authorities. The public will learn to appreciate that the scientific community is working urgently, rigorously and ingeniously to better understand the complex climate system, for our shared safety and well-being. ■

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

SCI AM An extended version of this essay is available at **www.ScientificAmerican.com/mar2010**

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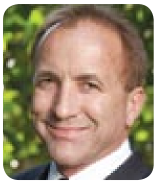
Surviving Death on *Larry King Live*

Obscurantism and obfuscation on national television

BY MICHAEL SHERMER



Have you ever died and come back to life? Me neither. No one has. But plenty of people say that they have, and their experiences were the subject of an episode of *Larry King Live* last December on which I appeared as the token skeptic among a tableful of believers, including CNN's medical correspondent Sanjay Gupta, New Age author Deepak Chopra, a football referee who "died" on the playing field, and an 11-year-old boy named James Leininger who believes he is the reincarnation of a World War II fighter pilot.

Dr. Gupta started us off by recalling that when he was in medical school the residents were taught to mark the time of death to the minute, when death can often take anywhere from a couple of minutes to a couple of hours to occur, depending on the conditions. As Gupta noted, people who have fallen into freezing lakes and "died" were not quite dead, and their core body temperatures dropped so rapidly that their vital tissues were preserved long enough for subsequent resuscitation. In other words, people who have near-death experiences (NDEs) are not actually dead!

The same definitional problem arose when guest host Jeff Probst (of *Survivor* fame, fittingly) introduced the football referee: "A man died on a football field seven years ago and came back to life." Gupta added that he "was dead for two minutes and 40 seconds." When I was asked for an explanation, I said: "He wasn't dead! You started this hour off with Sanjay Gupta explaining we can't say somebody's dead at one given moment at a particular time on the clock. That's not how it works. It takes two, three, five, 10 minutes to go through a dying process. The ref wasn't dead. He was in a near-death state." In fact, moments after collapsing, the ref had his heart restarted by an automated external defibrillator. There was nothing miraculous to explain.

Fuzzy language is pervasive in such discussions, and no one uses it better than Dr. Chopra, as in this explanation for NDEs: "There are traditions that say the in-body experience is a socially induced collective hallucination. We do not exist in the body. The body exists in us. We do not exist in the world. The world exists in us." Here is Chopra on death: "Birth and death are spacetime events in the continuum of life. So the opposite of life is not death. The opposite of death is birth. And the opposite of birth is death. And life is the continuum of birth and death, which goes on and on." When I asked what had happened to little James Leininger's soul if his body is now occupied by the soul of a World War II fighter pilot, Chopra offered this jewel of Deepakese: "Imagine that you're looking at an ocean and you see lots of waves today. And tomorrow you see a fewer number of waves.... What you call a person actually is a pattern of behavior of a universal consciousness." Indicating our host, he continued, "There is no such thing as Jeff, because what we call Jeff is a constantly transforming consciousness that appears as a certain personality, a certain mind, a certain ego, a certain body. But, you know, we had a different Jeff when you were a teenager. We had a different Jeff when you were a baby. Which one of you is the real Jeff?" Jeff looked as confused as I felt.

When Gupta was asked how a physician deals with such apparent medical miracles, he fell into the fallacy of the argument from ignorance: "When I was researching this for a long time, I thought I was going to explain it all away physiologically. But things that I heard and validated and subsequently believed convinced me that there were things that I could not explain. There were things that were happening at that moment, that near-death experience moment, that simply could not be explained with existing scientific knowledge."

So what? The fact that we cannot fully explain a mystery with natural means does not mean it requires a supernatural explanation. It just means that we don't know everything. Such uncertainty is at the very heart of science and is what makes it such a challenging enterprise. ■

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

PHOTOGRAPH BY BRAD SWONETZ; ILLUSTRATION BY MATT COLLINS

End-of-Days Danger

If 2012 marks the start of the apocalypse, it will be our own fault, not nature's or God's

BY LAWRENCE M. KRAUSS

I don't know how many e-mails I have received from children who are terrified that 2012 will somehow involve the end of life as we know it, all because of an unfounded fringe religious prophecy that has received mass-market exposure with the release of a recent Hollywood movie. I have tried to reassure those children (and not a few adults) that this date represents nothing more cosmically special than the year of the next presidential election.

Having said that, however, I just realized there might be a genuine connection between 2012 and an end-of-days menace!

On the conclusion of the less than stellar Copenhagen Conference on Climate Change in December, ex-governor and former vice presidential candidate Sarah Palin, who many think may make a White House run herself in 2012, twittered the world with the following:

"arrogant&naive2say man overpwers nature"

Although the Copenhagen conference could have been criticized on many fronts, it is hard to imagine that Palin's remarkable statement represents anything other than a misplaced religious end-of-days argument of the type that asserts confidence in human dominion over the earth—and that God will ensure the planet remains fine in the face of human progress, until God decides to end it all and the worthy ascend to heaven.

As we look around the world, there is hardly a place where humans have *not* "overpowered nature," if I take that phrase to mean affecting the large-scale features of our natural environment. Global transportation allows me to circumnavigate the globe in less than three days with jet planes. Modern medicine has eradicated the once unstoppable scourge of smallpox, allowed in vitro fertilization and freezing of embryos for women who would otherwise be barren, and developed prenatal surgical techniques for correcting fetal heart defects in the womb. We are living in an era with one of the greatest extinction rates in recorded history, which began with wholesale slaughter of entire species for food and has progressed as we have dismembered a large part of what was the dominant incubator of life on earth, the rain forests. The nature of commercial fishing, something the ex-governor should know about given the importance of the Alaskan fishing fleet, has changed as we have literally fished out whole regions of the world's seas.

These are just a few obvious examples, but because the future Fox News pundit was talking about climate change let's consider something that is indisputable: the *measured* rise of carbon dioxide in the earth's atmosphere is numerically consistent with that predicted from the output of human industrial activity.

This fact is not in dispute. What is in dispute, apparently by Palin, is whether this rise will have any effect on "nature." It already has. Forget the change in temperature over the past decades. Increased carbon dioxide in the atmosphere boosts, by gas-liquid equilibrium, the amount of carbonic acid in the ocean, which in turn lowers the marine pH level. And *measurements* of the pH level in the ocean over the past two decades show precisely the slow reduction that is expected from such a rise in carbon dioxide. As that pH level continues to fall on its present trajectory, it will eventually reach a point where calcium carbonate—a dominant component of shelled animals and coral reefs—will dissolve in seawater.

One should be free to question the detailed nature of model predictions about the future, but the evidence that humans can, do and will continue to "overpower" nature is so incontrovertible that to deny this fact is to live in a fantasy world. That reality is what we most need to grapple with to address environmental challenges and stimulate the economies of both the developing and the developed worlds. The thought that anyone whose beliefs could so override the evidence of those realities might be a serious contender for the White House scares me more than any Hollywood disaster movie could. ■

Lawrence M. Krauss, a theoretical physicist and science commentator, is Foundation Professor and director of the Origins Initiative at Arizona State University (www.krauss.faculty.asu.edu). His newest book, Quantum Man, *will appear in 2010.*

PHOTOGRAPH BY JOHN BOSWELL; ILLUSTRATION BY MATT COLLINS

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The Moon That Would Be a Planet

Titan, Saturn's largest natural satellite, scarcely deserves to be a called a mere moon. It has an atmosphere thicker than Earth's and a surface that is almost as varied

By Ralph Lorenz and Christophe Sotin

KEY CONCEPTS

- Before the Cassini/Huygens mission, Titan was a cipher—the largest expanse of unglimpsed terrain left in the solar system, larger than the planet Mercury.
- Having penetrated the haze with infrared images, radar and a descent probe, the mission has discovered a dynamic landscape of rivers, lakes, dunes, mountains and possibly volcanoes. It is a frigid version of Earth, where methane substitutes for water, water substitutes for rock, and weather cycles last centuries.
- Studying Titan is already elucidating the geologic processes of our own planet, such as dune formation and climate change.

—The Editors

If we had not known the images were coming back from Titan, we might have guessed they were new pictures of Mars or Earth. Some people in the control room saw the California coast, some saw the French Riviera, and one person even said that Saturn's biggest moon looked like his backyard in Tucson. For three weeks, the Huygens probe had coasted, dormant, after detaching from the Cassini spacecraft and being sent on its way to Titan. Those of us watching anxiously felt a deep personal connection with the probe. Not only had we worked on the mission for a large part of our careers, but we had developed its systems and instrumentation by putting our minds in its place, to think through how it would function on an alien and largely unknown world. We imagined Titan might be like the comparably large moons of the outer solar system, such as Jupiter's cratered Callisto or grooved Ganymede.

And so on the morning of January 14, 2005, at the European Space Operations Center in Darmstadt, Germany, the pictures caused jubilation and puzzlement in equal measure. None of us expected the landscape to look so Earth-like. As Huygens parachuted down, its aerial pictures showed branching river channels cut by rain-fed streams. It landed on the damp, pebble-covered site of a recent flash flood. What was alien about Titan was its eerie familiarity.

Now, five years on, we have had time to digest the probe's findings and put them in the bigger picture that Cassini, having flown past Titan more than 60 times in its looping orbit around Saturn, has gradually pieced together. In size (bigger than Mercury), dynamism (more active than Mars) and atmosphere (thicker than Earth's), Titan is a planet by any other name. A wide variety of geologic processes shape its surface. Methane plays the role that water does on Earth. It evaporates from lakes, forms clouds, precipitates out, carves valleys and flows back

RON MILLER

IT WAS a dark and stormy night on Titan. It often is. Smoggy haze all but obscures the sun and Saturn. In the distance, the rain falls in torrents.

into lakes. If only the atmosphere had some oxygen and the temperature were not –180 degrees Celsius, you would feel at home on Titan.

Seas of Sand, Seas of Methane

Before Cassini, our perspective on Titan was very one-dimensional. When the Voyager spacecraft flew by in 1980 and 1981, it saw only a haze-shrouded, orangish billiard ball, and the best that observatories in the mid-1990s could manage was a crude infrared map showing vaguely dark and bright areas [see "Saturn at Last!" by Jonathan I. Lunine; SCIENTIFIC AMERICAN, June 2004]. Scientists talked in terms of Titan's surface or its atmosphere, as if a single measured quantity or descriptive phrase could capture an entire world. These generalizations have withered under the barrage of new data. We now have to refer to the low-latitude sand seas, or the atmosphere above the north pole in summer, or a cloudy day in the southern lake district.

Titan's low latitudes are a mix of rugged, bright hills, most notably the vast area named Xanadu, and dark sand seas, once thought to be liquid seas. (Astronomers are always tempted to call dark areas "seas," the lunar mares being the most obvious example.) Sand dunes 100 meters high, like the largest dunes found on Earth, stretch for tens to hundreds of kilometers. The dark sand on Titan is not made of silicate minerals such as quartz, as on Earth, but of hydrocarbons, looking rather like heaps of coffee grounds.

Around the poles, we find liquid hydrocarbons: small lakes in steep pits a few tens of kilometers across; shallow playa such as Ontario Lacus, slightly larger than its namesake of Lake Ontario; and seas such as Kraken Mare, as big as the Caspian. The surface level of these lakes appears to have changed with time. Wedged in between the desertlike tropics and the wet polar regions are the strangely inscrutable midlatitudes, with heavily eroded landscapes and evidence of flowing liquid.

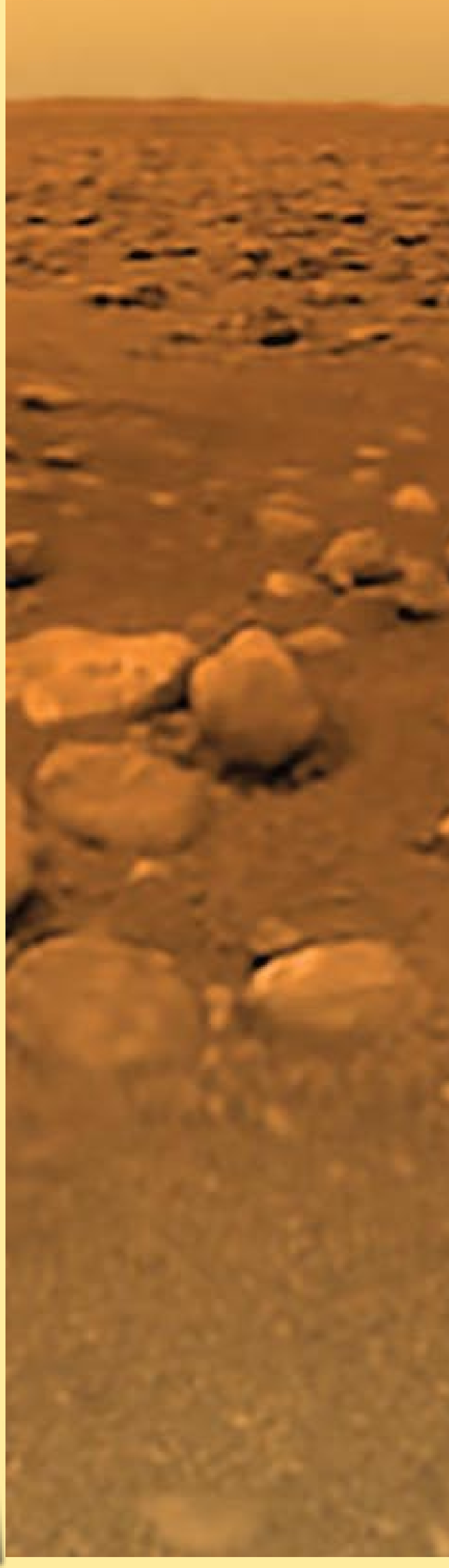
Planetary scientists recognized after the Voyager encounters that Titan might have a methane cycle with clouds, rain and seas analogous to the hydrologic cycle on Earth. This speculation was based in part on a single data point: the surface temperature of Titan was close to the triple point of methane, just as the Earth's is close to that of water. At this temperature, gas, solid and liquid can coexist. Did it mean that transitions among these three phases of matter regulated Titan's temperature, or was it coinci-

ESA/NASA/JPL/UNIVERSITY OF ARIZONA (*landing site*); NASA/JPL/SPACE SCIENCE INSTITUTE (*Titan* and *sand dunes in Belet region*); SOURCE: USGS NATIONAL CENTER FOR EROS AND NASA LANDSAT PROJECT OFFICE (*Namibia dunes*); NASA/JPL/USGS (*large north polar region*); NASA/JPL/UNIVERSITY OF ARIZONA/DLR (*Kraken Mare glinting*); NASA/JPL (*close-up of Kraken Mare*); NASA/JPL/ESA/UNIVERSITY OF ARIZONA (*close-up of river channels*)

[SURFACE]

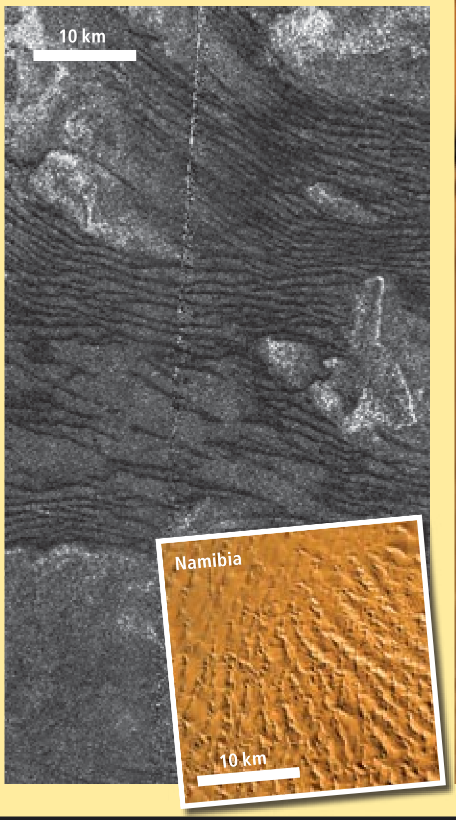
A Tour of Titan

The Cassini orbiter and Huygens descent probe have given humanity its first real view of Titan's surface, one of the most varied in the solar system.



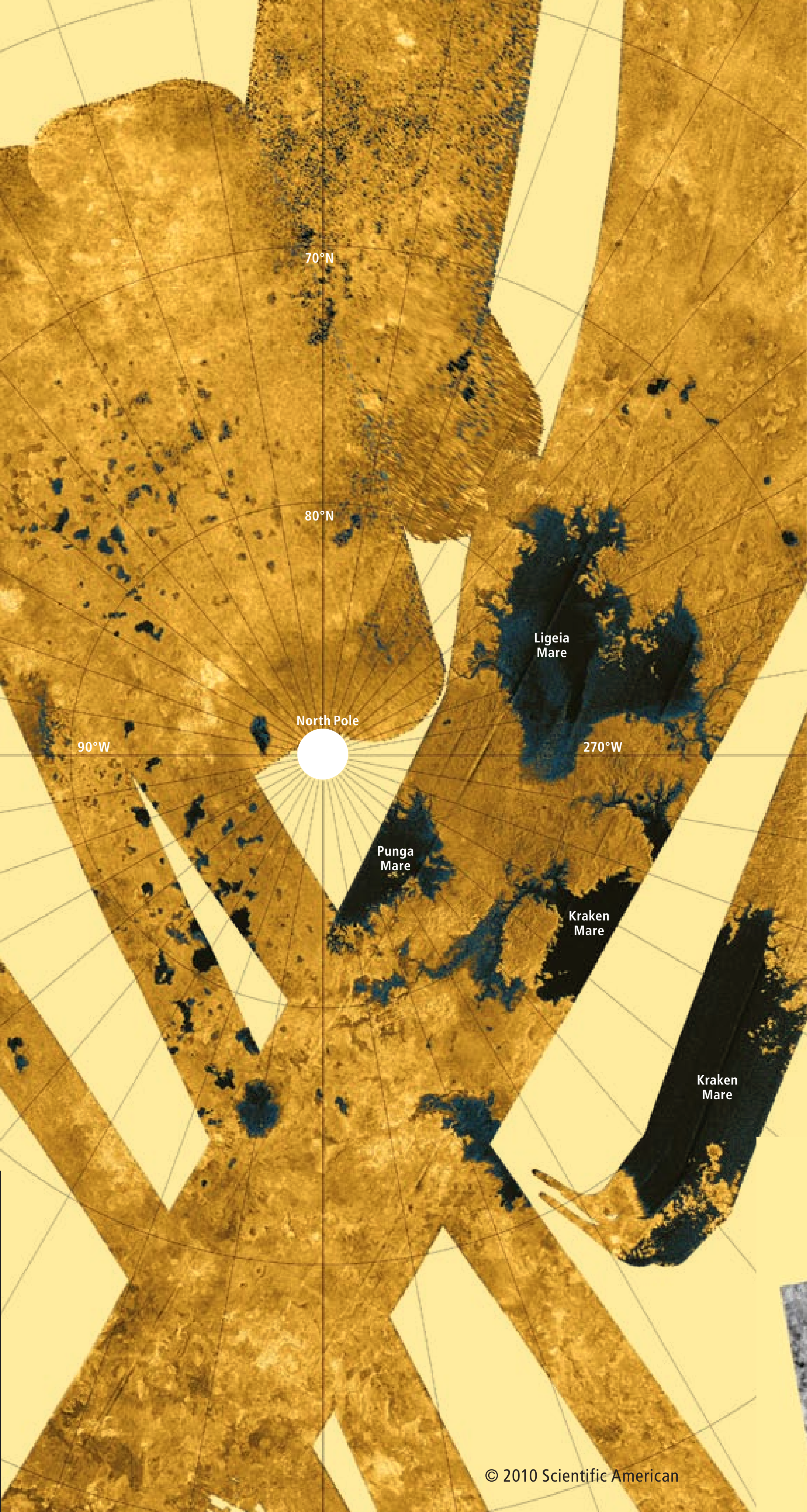
▶ Huygens saw a landscape of fist-size chunks of ice strewn on moist sand. Their rounded shapes suggest they were eroded by flowing liquid, presumably methane.

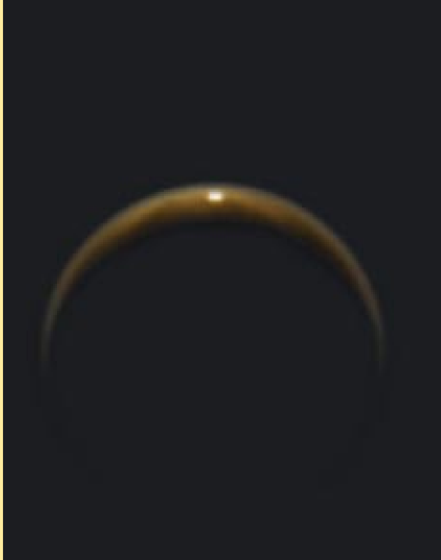
▼ Sand dunes in the Belet region show up as dark streaks on a radar image. Tens to hundreds of kilometers long, they run parallel to the average wind direction and break around bright mounds. The sand is thought to be made of hydrocarbon molecules, like coagulated smog. Despite this exotic composition, the dunes have the same spacing and height as the largest on Earth, such as those in the Namib Desert (*inset*)—perhaps because the atmospheric boundary layer, the turbulent lowest layer of air, is the same thickness on both worlds.



◀ **TITAN ON THE EVE OF CASSINI**

In 1980 Voyager 1 mission scientists had to decide between making a close flyby of Titan and aiming for an eventual rendezvous with Pluto. They chose Titan. And all they saw was a featureless haze—a "fuzzy, seamless tennis ball," in the words of team member Tobias Owen [see "Titan," by Tobias Owen; SCIENTIFIC AMERICAN, February 1982]. The Voyager 2 team decided to skip Titan. Although the images were disappointing, Voyager 1's ultraviolet, infrared and radio instruments discovered that the atmosphere is mostly nitrogen and that conditions allow for methane clouds, rain and even oceans. Clearly, something interesting lurked under the haze.

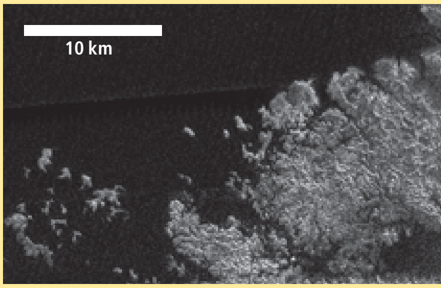




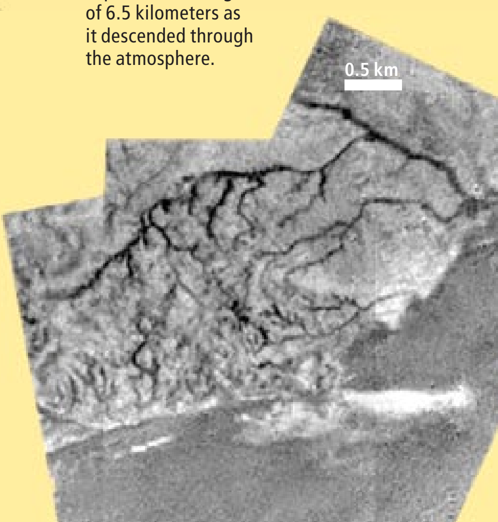
▲ Sunlight glints off Kraken Mare, as seen last July by Cassini's infrared imager. The lake had been in winter darkness for 15 years and passed into spring in August.

◀ Cassini radar images of Titan's north polar region show dark areas that are presumably lakes of methane and ethane, including Titan's three largest (*labeled*). Liquid appears dark for the same reason that a wet road looks dark when you are driving at night: the smooth surface reflects the radar or headlight beams away from your eye. Dry, rough terrain looks bright (*gold*).

▼ A close-up of Kraken Mare shows islands, cays and other features evocative of Earthly seas.



▼ River channels may have been carved by liquid methane flowing from a series of ridges (about 200 meters high) down to a lakebed (now dry). The pattern of tributaries suggests that the methane rained down on the surface. Huygens captured this image from an altitude of 6.5 kilometers as it descended through the atmosphere.



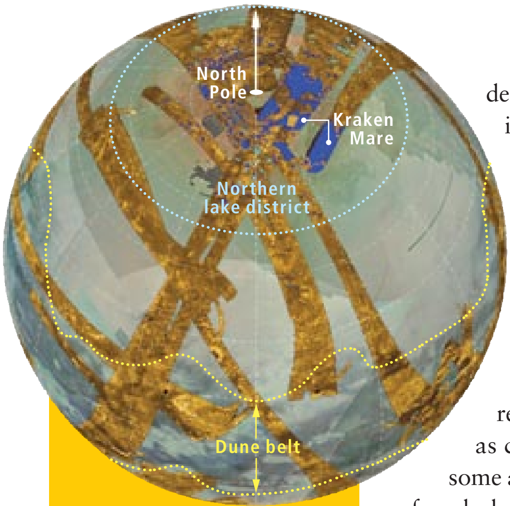
dence? The first good evidence that the idea held water, so to speak, was the detection by ground-based telescopes in the late 1990s of transient clouds at the altitudes at which methane would be expected to condense. Better telescopic observations, and then Cassini, were able to see these clouds in action, puffing upward just like terrestrial cumulus and then dissipating as cloud droplets turned into rain. In some areas, Cassini has observed the surface darken after clouds have passed over, perhaps indicating that rain fell there.

Cassini has not directly observed precipitation, but the Huygens aerial photographs leave no doubt that at least parts of Titan's landscape have been shaped by rainfall and the rapid flow of liquid across the surface. The probe's landing site was about 10 degrees south of the equator, at the edge of some bright, icy hills in the midst of a vast sand sea. The imagery shows a couple of long dunes in the distance, but the immediate area around the landing site is more like a streambed, littered with rounded cobbles on top of sand. A penetrometer designed and built by one of us—Lorenz, as a graduate student some 12 years before the hardware got to its destination—poked into the ground and measured its mechanical properties, showing it was somewhat soft but cohesive, much like wet sand or clay.

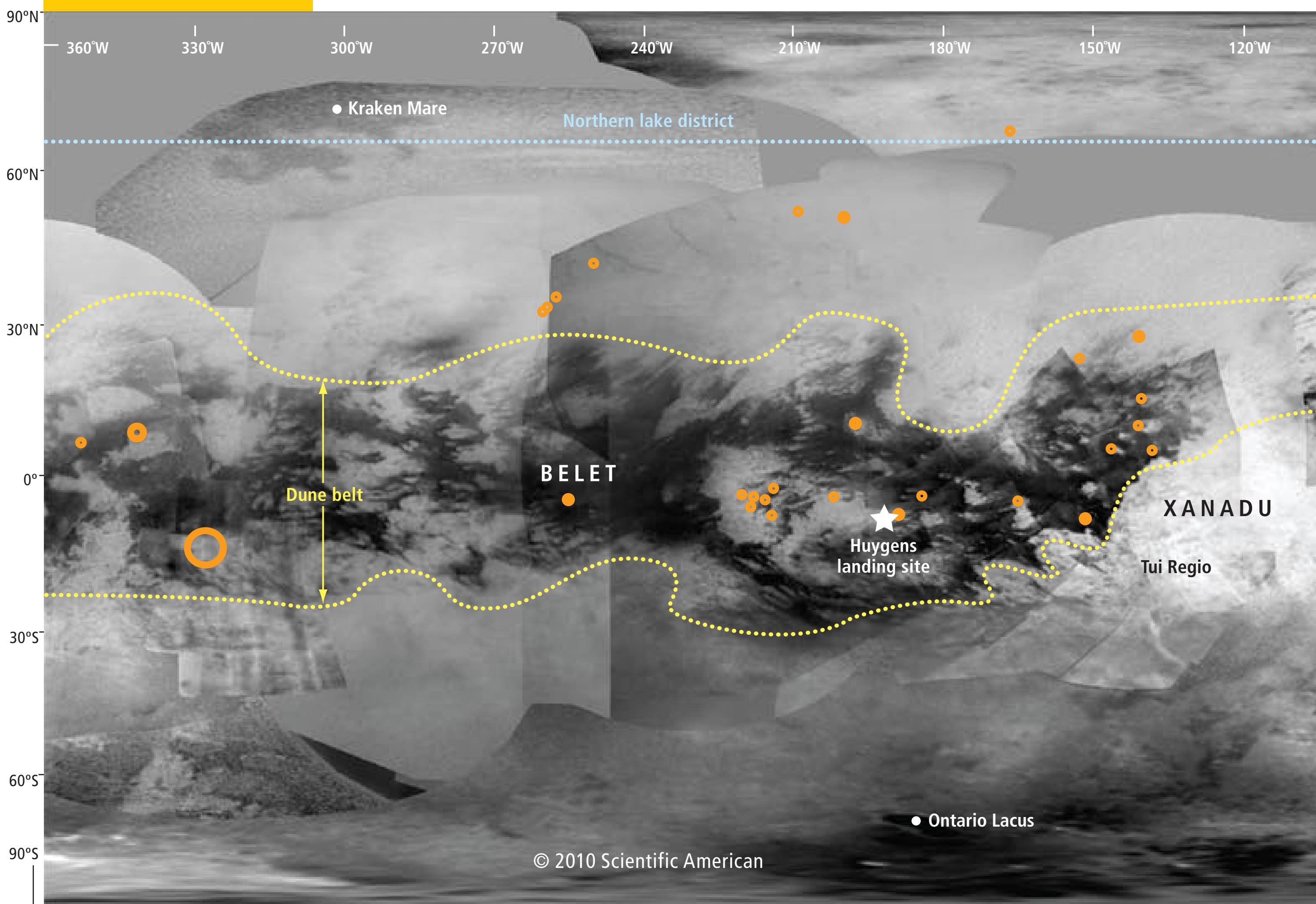
Thermometers indicated that heat was wicked away from the probe so quickly that the ground must have been damp—just as a finger stuck into moist sand at the beach feels colder than one in dry sand. Recent work suggests that methane vapor may have also condensed on the cold baffle of the Huygens camera, and one image shows the distinctive pattern of light reflected by a dewdrop as it falls across the camera's field of view—the first close-up shot of liquid on an extraterrestrial world.

Planet Gone Wild

Titan is to the hydrologic cycle what Venus is to the greenhouse effect : a terrestrial process taken to extremes. On Earth, solar energy is enough to evaporate about one meter of water per year. The atmosphere can hold only a couple of centimeters' worth of moisture before clouds and rain form, so terrestrial weather is broadly char-



GLOBAL MAP of Titan has been gradually assembled by Cassini's main camera, observing in near-infrared light, supplemented by partial radar coverage (*gold, above*). It reveals the general variation of terrain with latitude, as well as a paucity of impact craters (*orange, below*)—a sign that the surface is geologically young.

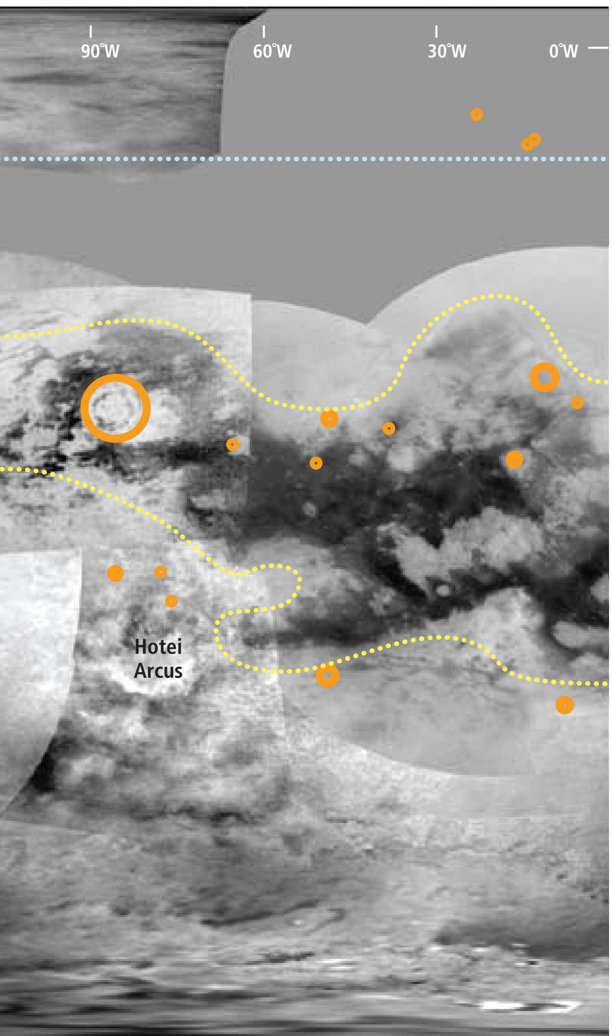


acterized by showers dropping a few centimeters of rain every week or two.

On Titan, the feeble sunlight allows only about one centimeter of evaporation per year. But the atmosphere can hold the equivalent of about 10 meters of liquid. So Titan's weather should feature torrential downpours, causing flash floods, interspersed by centuries of drought. The Huygens landing site was probably the scene of a flash flood, which could have happened a month before the landing—or a millennium before. Titan's boom-bust weather cycle is an extreme version of what may be happening on Earth because of global warming. As our lower atmosphere, or troposphere, warms, it holds more moisture, and both rainstorms and droughts become more intense.

On Earth, the tropics are dominated by the Hadley circulation. Warm air rises at the equator and, as it flows toward the poles, is sheared by the planet's rotation. At about 30 degrees latitude, air descends toward the surface. Because the down-welling air is dry, most terrestrial deserts are found at this latitude. But Titan rotates very slowly, only once every 15 days, so the corresponding circulation pattern extends from the summer midlatitudes all the way to the winter pole, with the overall result that the entire equatorial region gets dried out—hence the extensive sand seas centered on the equator.

NASA/JPL/SPACE SCIENCE INSTITUTE (*surface mosaic*); NASA/JPL/CALTECH/UNIVERSITY OF ARIZONA/CASSINI IMAGING TEAM (*global map*); KEVIN HAND (*cutaway view*); COURTESY OF RALPH LORENZ (*Lorenz*); COURTESY OF BRIGITTE SOTIN (*Sotin*)



Though much colder, Titan's atmosphere has a temperature profile similar to Earth's. The troposphere is warmed by a greenhouse effect, and temperatures fall with height. Above it is the stratosphere, which is warmed by the absorption of solar radiation. On Earth, the absorber is ozone, whereas on Titan it is the opaque haze that envelops the world—underscoring the recurring theme of Titan science, familiar physics with unfamiliar substances.

To analyze the haze, Cassini has sampled the upper atmosphere at an altitude of around 1,000 kilometers as it sweeps past Titan. Before Cassini, we expected the haze to consist of a comparatively light hydrocarbon molecule such as ethane, with an atomic weight of 30. Yet Cassini has detected a dramatic and unexpected abundance of heavy organic molecules, including benzene, anthracene and macromolecules with atomic weights of 2,000 or more. This material has formed by the action of sunlight on atmospheric methane. Presumably the material eventually coagulates into larger grains and settles to the surface to create the seas of sand, but how that happens is not at all understood.

A Global Apocalypse?

Along with the short-term water cycle driven by solar energy, Earth has a long-term cycle driven by plate tectonics. It involves the exchange of water between the interior and surface. Over hundreds of millions of years water is released from the interior at volcanic hotspots and mid-ocean ridges and recycled into the interior at subduction zones, the areas where crustal plates collide and sink. Were it not for this cycle, water would have built up in the atmosphere and ultimately escaped to space.

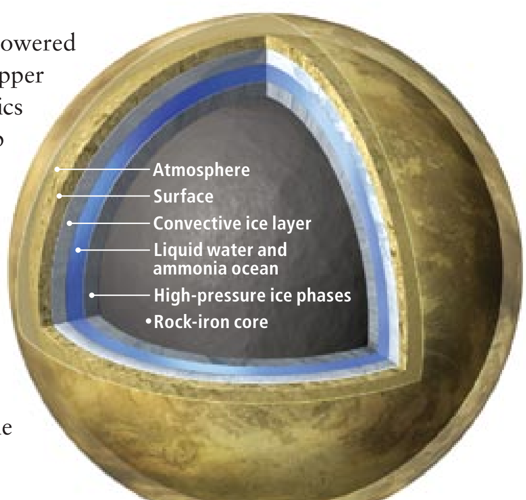
What about Titan? The sun-powered photochemical reactions in the upper atmosphere produce heavier organics at such a rate that they would use up all the methane in the atmosphere and on the surface within a few million years unless it were replenished [see "The Mystery of Methane on Mars and Titan," by Sushil K. Atreya; Scientific American, May 2007]. Therefore, Titan must have underground reservoirs of methane that feed the

[THE AUTHORS]


Ralph Lorenz helped to design and build the Huygens probe, made the first maps of Titan with the Hubble Space Telescope and led the team that planned Cassini's radar observations of Titan. He is now at the Johns Hopkins University Applied Physics Laboratory. Among his many books is *Spinning Flight,* for which he instrumented frisbees to study their aerodynamics. **Christophe Sotin** has been involved in making and analyzing observations of Titan's surface with Cassini's Visual and Infrared Mapping Spectrometer. He is now at the Jet Propulsion Laboratory of the California Institute of Technology. He remembers, as a 10-year-old, camping in a remote area of Brittany and listening to the radio as Neil Armstrong stepped out onto the moon.

GOOEY ON THE INSIDE

Titan's density indicates the moon is half rock (the core) and half water (the mantle and crust), with a veneer of hydrocarbons. Models predict that the upper 50 kilometers of ice is warm and pliable enough to undergo slow convection. Underneath it may be an ocean of liquid water mixed with ammonia. The ocean could be hundreds of kilometers thick and may once have been even thicker. Some scientists have speculated that the ocean could support life.



gas into the atmosphere—a rough analogue of Earth's long-term water cycle.

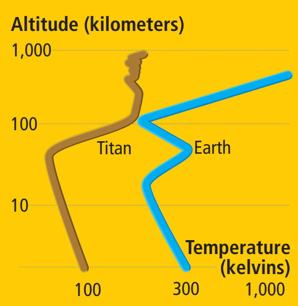
Cassini has seen no volcanic hotspots or plate tectonic features, but it has discovered at least two areas that look like frozen volcanic flows, Hotei Arcus and Tui Regio. They are brighter in near-infrared light than any other area on Titan, showing that they are compositionally distinct. Some have suggested that the bright material is a coating of carbon dioxide or ammonia frost from an eruption, but its composition and origin remain a mystery. Another sign of geologic activity is the almost complete lack of impact craters, a sign that volcanism or similar processes pave them over. Given the expected impact rate, the surface is between 200 million and one billion years old.

Because Titan appears to lack plate tectonics,

[ATMOSPHERE]

LIKE EARTH, ONLY COLDER

Titan's atmosphere, like Earth's, has a troposphere (a lower, dynamic layer where weather takes place) and a stratosphere (a stable layer heated by solar ultraviolet radiation). These and other layers are defined by the change of temperature with height (*right*). Titan's atmosphere is more than 200 degrees colder and, because of the satellite's weaker gravity, vertically stretched. Multiple layers of haze, consisting of hydrocarbon particulates akin to smog, play the same role as Earth's ozone layer.



its interior cycling may not occur continuously, as on Earth, but in fits and starts. In one proposed reconstruction of Titan's history, the interior released methane into the atmosphere during three periods: the formation of Titan 4.5 billion years ago; the onset of convection in the core 2.5 billion years ago; and the onset of convection in the ice crust within the past billion years. The most recent episode would have unleashed a global volcanic apocalypse that repaved the entire surface, much like the cataclysm that befell Venus a billion years ago or so [see "Global Climate Change on Venus," by Mark A. Bullock and David H. Grinspoon; Scientific American, March 1999]. Immediately after the injection of methane, the surface may have been even wetter than it is today. In between these intense episodes, Titan was tectonically quiet, and the flow of methane from the interior was a dribble at best. Such a model explains not only the low crater density but also the detailed isotopic composition of the atmosphere.

As well as deep reserves of methane, Titan may also have an underground ocean of liquid water, as mathematical models describing its interior evolution predict. Electrical measurements made by Huygens hinted at an electrically conductive layer of material about 45 kilometers below the surface, and water is the prime candidate. Cassini radar measurements suggested that the crust rotates faster than the core, as though a liquid layer acted as a giant bearing that allowed the two to spin at different rates; a recent reanalysis questions this conclusion, however.

Unfortunately, Titan's atmosphere prevents Cassini from approaching the surface more closely to look for the secondary magnetic field that Saturn would induce in an ocean. Such fields were crucial to the case for oceans on the Jovian satellites [see "The Hidden Ocean of Europa," by Robert T. Pappalardo, James W. Head and Ronald Greeley; Scientific American, October 1999]. As scientists debate whether the secondary field might still be detectable, they have drawn up plans to search for the magnetic signal, as well as telltale distortions of Titan's gravitational field, in the coming decade.

Titan's Ice Ages

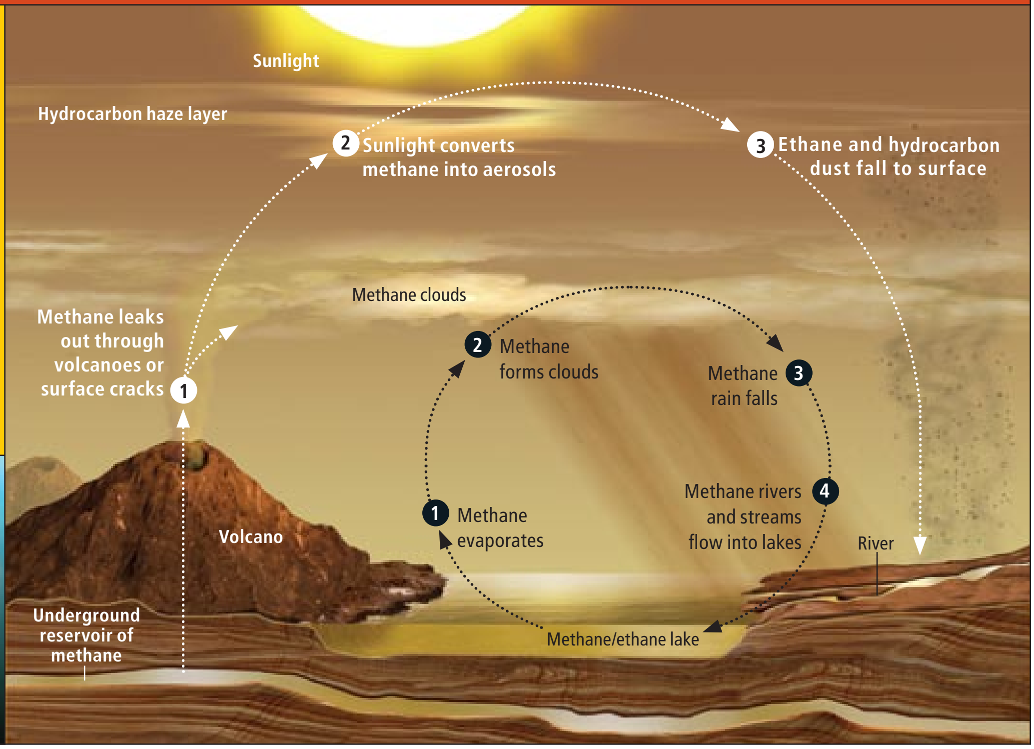
In addition to weather patterns occurring on a seasonal cycle and atmospheric replenishment occurring over geologic time, both Titan and Earth undergo climate change over intermediate periods of tens of thousands to millions of years. As first realized by 19th-century Scottish

LUCY READING-IKKANDA (*top*); KEVIN HAND (*bottom*)

[THE METHANOLOGICAL CYCLE]

FORECAST: A DELUGE OF METHANE

Methane undergoes a short-term cycle (*black*) much like the water cycle on Earth. Over geologic time there is an episodic one-way flow (*white*) of methane from interior reservoirs to the upper atmosphere, where solar radiation converts it to ethane and heavier hydrocarbon—forming the haze. The particulates settle onto the surface as what Carl Sagan called "manna from heaven."



Methane clouds over south polar region

scientist James Croll and later refined by Serbian geophysicist Milutin Milanković in the early 20th century, gravitational forces exerted by the other planets slowly shift Earth's tilt and orbit, altering the intensity of solar heating and giving rise to the cycle of ice ages.

On Titan, the southern summer is shorter but more intense than it is in the north, because Saturn (and therefore Titan) has an elliptical orbit around the sun. It is about 10 percent closer to the sun during southern midsummer. These asymmetric seasons may pump volatile compounds such as methane and ethane from the south to the north, which now has far more lakes and seas. Over time, however, the relative alignment of Titan's pole and Saturn's elliptical orbit shifts. In 30,000 years the northern summer will be the more intense one. Lakes will dry up in the north, and new ones will form in the south. It is yet another way that Titan is more like a terrestrial planet than an icy moon.

Cassini's findings of an exotic yet familiar landscape are prompting scientists to look at Earth in a new way. For example, Titan's fields of linear sand dunes resemble those in the Namib or Saharan deserts, where the dunes line up along the average of two dominant wind directions. Yet atmospheric simulations for Titan have trouble reproducing the dune orientations. The discrepancy may be a sign that scientists do not fully understand the formation of such dunes or that Titan's winds are controlled by effects not yet included in the simulations.

Moreover, observations of Titan's lakes so far show them to be dead flat, with no waves on the surface, even though the lower gravity and thicker air should, if anything, increase the wave strength. What does this stillness mean for our understanding of wind-wave generation? Titan's rotation rate may vary slightly with the seasons as the atmosphere and surface spin each other up and down like giant flywheels—an effect that is also seen, albeit much weaker, on Earth.

Thus, as is often the case in planetary exploration, Cassini's findings are prompting deeper questions. The rich range of scientific problems posed by Titan and the complex surface-atmosphere interactions will ultimately require a series of missions—just like NASA's Mars program—including landers, rovers, even balloons. Meanwhile Cassini continues to fly by Titan every few weeks. Last August marked the northern spring equinox on Titan, and as the sun progressively moves north, the atmospheric circulation and cloud patterns will change before our eyes. As the northern polar regions, which have been in cold, stagnant darkness, warm up, the one thing we can expect is the unexpected. ■

➥ MORE TO EXPLORE

Episodic Outgassing as the Origin of Atmospheric Methane on Titan. Gabriel Tobie, Jonathan I. Lunine and Christophe Sotin in *Nature,* Vol. 440, pages 61–64; March 2, 2006.

Titan Unveiled: Saturn's Mysterious Moon Explored. Ralph Lorenz and Jacqueline Mitton. Princeton University Press, 2008.

Titan: Exploring an Earthlike World. Athena Coustenis and Fredric W. Taylor. World Scientific, 2008.

Rivers, Lakes, Dunes, and Rain: Crustal Processes in Titan's Methane Cycle. Jonathan I. Lunine and Ralph D. Lorenz in *Annual Review of Earth and Planetary Sciences,* Vol. 37, pages 299–320; May 2009.

Titan from Cassini-Huygens. Edited by Robert H. Brown, Jean-Pierre Lebreton and J. Hunter Waite. Springer, 2009.

NASA/JPL/UNIVERSITY OF ARIZONA/UNIVERSITY OF NANTES (*methane clouds*); KEVIN HAND (*methane cycle*)

The Brain's (Dark Energy)

Brain regions active when our minds wander may hold a key to understanding neurological disorders and even consciousness itself

By Marcus E. Raichle

KEY CONCEPTS

- Neuroscientists have long thought that the brain's circuits are turned off when a person is at rest.
- Imaging experiments, however, have shown that there is a persistent level of background activity.
- This default mode, as it is called, may be critical in planning future actions.
- Miswiring of brain regions involved in the default mode may lead to disorders ranging from Alzheimer's to schizophrenia.

—The Editors

Imagine you are almost dozing in a lounge chair outside, with a magazine on your lap. Suddenly, a fly lands on your arm. You grab the magazine and swat at the insect. What was going on in your brain after the fly landed? And what was going on just before? Many neuroscientists have long assumed that much of the neural activity inside your head when at rest matches your subdued, somnolent mood. In this view, the activity in the resting brain represents nothing more than random noise, akin to the snowy pattern on the television screen when a station is not broadcasting. Then, when the fly alights on your forearm, the brain focuses on the conscious task of squashing the bug. But recent analysis produced by neuroimaging technologies has revealed something quite remarkable: a great deal of meaningful activity is occurring in the brain when a person is sitting back and doing nothing at all.

It turns out that when your mind is at rest—when you are daydreaming quietly in a chair, say, asleep in a bed or anesthetized for surgery—dispersed brain areas are chattering away to one another. And the energy consumed by this ever active messaging, known as the brain's default mode, is about 20 times that used by the brain when it responds consciously to a pesky fly or another outside stimulus. Indeed, most things we do consciously, be it sitting down to eat dinner or making a speech, mark a departure from the baseline activity of the brain default mode.

Key to an understanding of the brain's default mode has been the discovery of a heretofore unrecognized brain system that has been dubbed the brain's default mode network (DMN). The exact role of the DMN in organizing neural activity is still under study, but it may orchestrate the way the brain organizes memories and various systems that need preparation for future events: the brain's motor system has to be revved and ready when you feel the tickle of a fly on your arm. The DMN may play a critical role in

JEAN-FRANCOIS PODEVIN

synchronizing all parts of the brain so that, like racers in a track competition, they are all in the proper "set" mode when the starting gun goes off. If the DMN does prepare the brain for conscious activity, investigations of its behavior may provide clues to the nature of conscious experience. Neuroscientists have reason to suspect, moreover, that disruptions to the DMN may underlie simple mental errors as well as a range of complex brain disorders, from Alzheimer's disease to depression.

Probing Dark Energy

The idea that the brain could be constantly busy is not new. An early proponent of that notion was Hans Berger, inventor of the familiar electroencephalogram, which records electrical activity in the brain with a set of wavy lines on a graph. In seminal papers on his findings, published in 1929, Berger deduced from the ceaseless electrical oscillations detected by the device that "we have to assume that the central nervous system is always, and not only during wakefulness, in a state of considerable activity."

But his ideas about how the brain functions were largely ignored, even after noninvasive imaging methods became a fixture in neuroscience laboratories. First, in the late 1970s, came positron-emission tomography (PET), which measures glucose metabolism, blood flow and oxygen uptake as a proxy for the extent of neuronal activity, followed in 1992 by functional magnetic resonance imaging (fMRI), which gauges brain oxygenation for the same purpose. These technologies are more than capable of assaying brain activity, whether focused or not, but the design of most studies inadvertently led to the impression that most brain areas stay pretty quiet until called on to carry out some specific task.

Typically neuroscientists who run imaging experiments are trying to pinpoint the brain regions that give rise to a given perception or behavior. The best study designs for defining such regions simply compare brain activity during two related conditions. If researchers wanted to see which brain areas are important during reading words aloud (the "test" condition) as opposed to viewing the same words silently (the "control" condition), for instance, they would look for differences in images of those two conditions. And to see those differences clearly, they would essentially subtract the pixels in the passive-reading images from those in the vocal image; activity of neurons in the areas that remain "lit up" would be assumed to be the ones necessary for reading aloud. Any of what is called intrinsic activity, the constant background activity, would be left on the cutting-room floor. Representing data in this way makes it easy to envision areas of the brain being "turned on," during a given behavior, as if they were inactive until needed by a particular task.

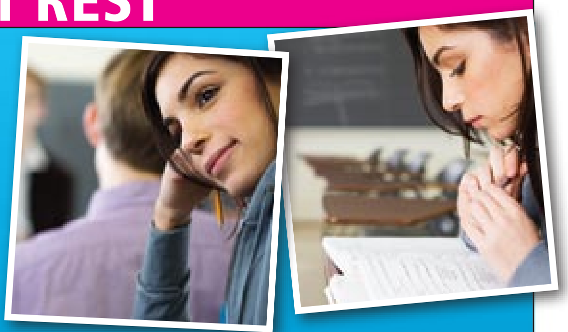
Over the years, however, our group, and others, became curious about what was happening when someone was simply resting and just letting the mind wander. This interest arose from a set of hints from various studies that suggested the extent of this behind-the-scenes activity.

One clue came from mere visual inspections of the images. The pictures showed that areas in many regions of the brain were quite busy in both the test and the control conditions. In part because of this shared background "noise," differentiating a task from the control state by look-

[COMPETING THEORIES]

BRAINS AT REST

Noninvasive methods, such as positron-emission tomography and functional magnetic resonance imaging, did not initially capture signs of background activity in the brain when a subject was doing nothing and so provided an inaccurate picture of neural activity.



No activity, such as daydreaming

Focused activity, such as reading

OLD VIEW ▸

Brain scans originally seemed to suggest that most neurons were quiet until needed for some activity, such as reading, at which point the brain fired up and expended energy on the signaling needed for the task.

No activity in brain

High activity in brain

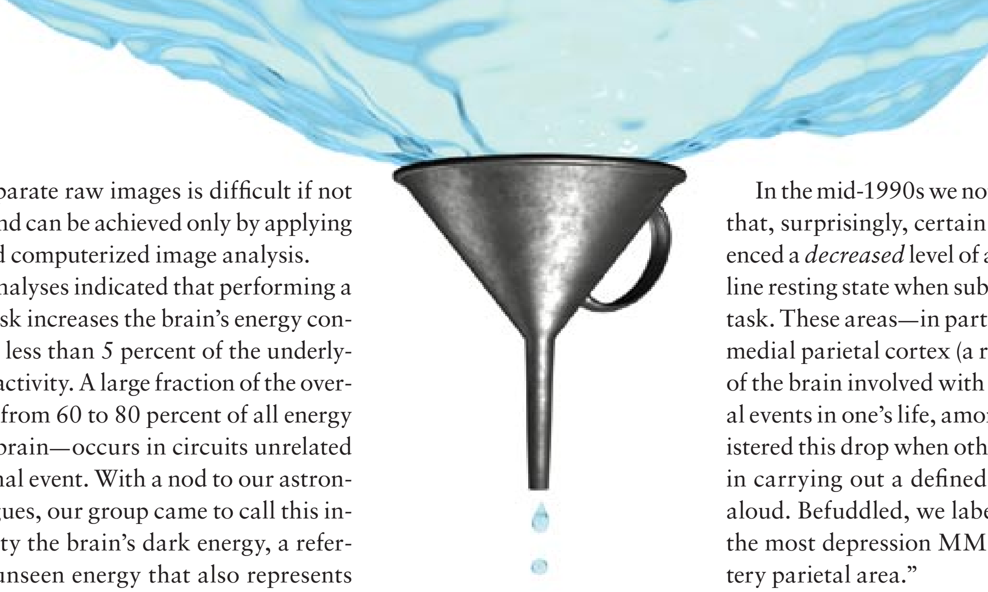
NEW VIEW ▸

In recent years additional neuroimaging experiments have shown that the brain maintains a high level of activity even when nominally "at rest." In fact, reading or other routine tasks require minimal additional energy, no more than a 5 percent increment, over what is already being consumed when in this highly active baseline state.

High activity in brain

Higher activity in brain

SIMON JARRATT *Corbis* (*images of woman*); JEAN-FRANCOIS PODEVIN (*cogs and lightbulbs*)



ing at the separate raw images is difficult if not impossible and can be achieved only by applying sophisticated computerized image analysis.

Further analyses indicated that performing a particular task increases the brain's energy consumption by less than 5 percent of the underlying baseline activity. A large fraction of the overall activity—from 60 to 80 percent of all energy used by the brain—occurs in circuits unrelated to any external event. With a nod to our astronomer colleagues, our group came to call this intrinsic activity the brain's dark energy, a reference to the unseen energy that also represents the mass of most of the universe.

The question of the existence of neural dark energy also arose when observing just how little information from the senses actually reaches the brain's internal processing areas. Visual information, for instance, degrades significantly as it passes from the eye to the visual cortex.

Of the virtually unlimited information available in the world around us, the equivalent of 10 billion bits per second arrives on the retina at the back of the eye. Because the optic nerve attached to the retina has only a million output connections, just six million bits per second can leave the retina, and only 10,000 bits per second make it to the visual cortex.

After further processing, visual information feeds into the brain regions responsible for forming our conscious perception. Surprisingly, the amount of information constituting that conscious perception is less than 100 bits per second. Such a thin stream of data probably could not produce a perception if that were all the brain took into account; the intrinsic activity must play a role.

Yet another indication of the brain's intrinsic processing power comes from counting the number of synapses, the contact points between neurons. In the visual cortex, the number of synapses devoted to incoming visual information is less than 10 percent of those present. Thus, the vast majority must represent internal connections among neurons in that brain region.

Discovering the Default Mode

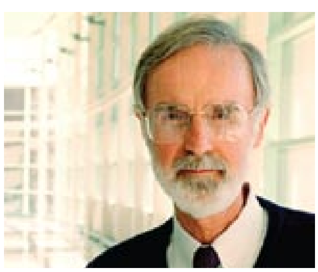
These hints of the brain's inner life were well established. But some understanding was needed of the physiology of the brain's intrinsic activity—and how it might influence perception and behavior. Happily, a chance and puzzling observation made during PET studies, later corroborated with fMRI, set us on a path to discovering the DMN.

A CLUE TO THE NEW VIEW

Researchers have known for some time that only a trickle of information from the virtually infinite flood in the surrounding environment reaches the brain's processing centers. Although six million bits are transmitted through the optic nerve, for instance, only 10,000 bits make it to the brain's visual-processing area, and only a few hundred are involved in formulating a conscious perception—too little to generate a meaningful perception on their own. The finding suggested that the brain probably makes constant predictions about the outside environment in anticipation of paltry sensory inputs reaching it from the outside world.

[THE AUTHOR]

Marcus E. Raichle is professor of radiology and neurology at the Washington University School of Medicine in St. Louis. For many years Raichle has led a team that investigates human brain function using positron-emission tomography and functional magnetic resonance imaging. He was elected to the Institute of Medicine in 1992 and to the National Academy of Sciences in 1996.



In the mid-1990s we noticed quite by accident that, surprisingly, certain brain regions experienced a *decreased* level of activity from the baseline resting state when subjects carried out some task. These areas—in particular, a section of the medial parietal cortex (a region near the middle of the brain involved with remembering personal events in one's life, among other things)—registered this drop when other areas were engaged in carrying out a defined task such as reading aloud. Befuddled, we labeled the area showing the most depression MMPA, for "medial mystery parietal area."

A series of PET experiments then confirmed that the brain is far from idling when not engaged in a conscious activity. In fact, the MMPA as well as most other areas remains constantly active until the brain focuses on some novel task, at which time some areas of intrinsic activity decrease. At first, our studies met with some skepticism. In 1998 we even had a paper on such findings rejected because one referee suggested that the reported decrease in activity was an error in our data. The circuits, the reviewer asserted, were actually being switched on at rest and switched off during the task. Other researchers, however, reproduced our results for both the medial parietal cortex—and the medial prefrontal cortex (involved with imagining what other people are thinking as well as aspects of our emotional state). Both areas are now considered major hubs of the DMN.

The discovery of the DMN provided us with a new way of considering the brain's intrinsic activity. Until these publications, neurophysiologists had never thought of these regions as a system in the way we think of the visual or motor system—as a set of discrete areas that communicate with one another to get a job done. The idea that the brain might exhibit such internal activity across multiple regions while at rest had escaped the neuroimaging establishment. Did the DMN alone exhibit this property, or did it exist more generally throughout the brain? A surprising finding in the way we understand and analyze fMRI provided the opening we needed to answer such questions.

The fMRI signal is usually referred to as the blood oxygen level–dependent, or BOLD, signal because the imaging method relies on changes in the level of oxygen in the human brain induced by alterations in blood flow. The BOLD signal from any area of the brain, when observed in a state of quiet repose, fluctuates slowly with cycles occurring roughly every 10 seconds. Fluctua-

COURTESY OF MARCUS E. RAICHLE (*Raichle*); JEAN-FRANCOIS PODEVIN (*funnel*) tions this slow were considered to be mere noise, and so the data detected by the scanner were simply eliminated to better resolve the brain activity for the particular task being imaged.

The wisdom of discarding the low-frequency signals came into question in 1995, when Bharat Biswal and his colleagues at the Medical College of Wisconsin observed that even while a subject remained motionless, the "noise" in the area of the brain that controls right-hand movement fluctuated in unison with similar activity in the area on the opposite side of the brain associated with left-hand movement. In the early 2000s Michael Greicius and his co-workers at Stanford University found the same synchronized fluctuations in the DMN in a resting subject.

Because of the rapidly accelerating interest in the DMN's role in brain function, the finding by the Greicius group stimulated a flurry of activity in laboratories worldwide, including ours, in which *all* of the noise, the intrinsic activity of the major brain systems, was mapped. These remarkable patterns of activity appeared even under general anesthesia and during light sleep, a suggestion that they were a fundamental facet of brain functioning and not merely noise.

It became clear from this work that the DMN is responsible for only a part, albeit a critical part, of the overall intrinsic activity—and the notion of a default mode of brain function extends to all brain systems. In our lab, discovery of a generalized default mode came from first examining research on brain electrical activity known as slow cortical potentials (SCPs), in which groups of neurons fire every 10 seconds or so. Our research determined that the spontaneous fluctuations observed in the BOLD images were identical to SCPs: the same activity detected with different sensing methods.

We then went on to examine the purpose of SCPs as they relate to other neural electrical signals. As Berger first showed and countless others have since confirmed, brain signaling consists of a broad spectrum of frequencies, ranging from the low-frequency SCPs through activity in excess of 100 cycles per second. One of the great challenges in neuroscience is to understand how the different frequency signals interact.

It turns out that SCPs have an influential role. Both our own work and that of others demonstrate that electrical activity at frequencies above that of the SCPs synchronizes with the oscillations, or phases, of the SCPs. As observed recently by Matias Palva and his colleagues at the University of Helsinki, the rising phase of an SCP produces an increase in the activity of signals at other frequencies.

The symphony orchestra provides an apt metaphor, with its integrated tapestry of sound arising from multiple instruments playing to the same rhythm. The SCPs are the equivalent of the conductor's baton. Instead of keeping time for a collection of musical instruments, these signals coordinate access that each brain system requires to the vast storehouse of memories and other information needed for survival in a complex, ever changing world. The SCPs ensure that the right computations occur in a coordinated fashion at exactly the correct moment.

But the brain is more complex than a symphony orchestra. Each specialized brain system—one that controls visual activity, another that actuates muscles—exhibits its own pattern of SCPs. Chaos is averted because all systems are

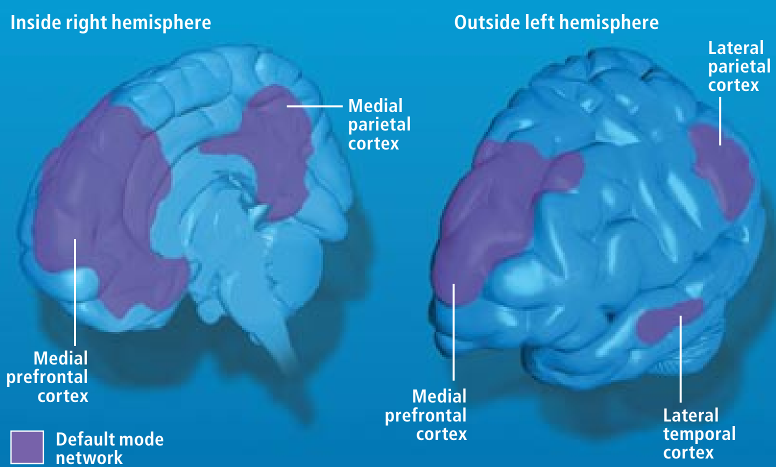
[A BRAIN CONTROLLER]

THE DEFAULT MODE NETWORK

A collaborating group of brain regions known as the default mode network (DMN) appears to account for much of the activity that occurs when the mind is unfocused and to have a key role in mental functioning.

COMMAND STATION ▼

The DMN consists of several widely separated brain areas, including those depicted below.



ORCHESTRATOR OF THE SELF ►

The DMN is thought to behave something like an orchestra conductor, issuing timing signals, much as a conductor waves a baton, to coordinate activity among different brain regions. This cuing—among the visual and auditory parts of the cortex, for instance—probably ensures that all regions of the brain are ready to react in concert to stimuli.

EDDY RISCH *EPA/Corbis* (*conductor*); JEAN-FRANCOIS PODEVIN (*brains*) not created equal. Electrical signaling from some brain areas takes precedence over others. At the top of this hierarchy resides the DMN, which acts as an über-conductor to ensure that the cacophony of competing signals from one system do not interfere with those from another. This organizational structure is not surprising, because the brain is not a free-for-all among independent systems but a federation of interdependent components.

At the same time, this intricate internal activity must sometimes give way to the demands of the outside world. To make this accommodation, SCPs in the DMN diminish when vigilance is required because of novel or unexpected sensory inputs: you suddenly realize that you promised to pick up a carton of milk on the drive home from work. The internal SCP messaging revives once the need for focused attention dwindles. The brain continuously wrestles with the need to balance planned responses and the immediate needs of the moment.

Consciousness and Disease

The ups and downs of the DMN may provide insight into some of the brain's deepest mysteries. It has already furnished scientists with fascinating insights into the nature of attention, a fundamental component of conscious activity. In 2008 a multinational team of researchers reported that by watching the DMN, they could tell up to 30 seconds before a subject in a scanner was about to commit an error in a computer test. A mistake would occur if, at that time, the default network took over and activity in areas involved with focused concentration abated.

And in years to come, the brain's dark energy may provide clues to the nature of consciousness. As most neuroscientists acknowledge, our conscious interactions with the world are just a small part of the brain's activity. What goes on below the level of awareness—the brain's dark energy, for one—is critical in providing the context for what we experience in the small window of conscious awareness.

Beyond offering a glimpse of the behind-the-scenes events that underlie everyday experience, study of the brain's dark energy may provide new leads for understanding major neurological maladies. Mental gymnastics or intricate movements will not be required to complete the exercise. A subject need only remain still within the scanner while the DMN and other hubs of dark energy whir silently through their paces.

Already this type of research has shed new light on disease. Brain-imaging studies have found altered connections among brains cells in the DMN regions of patients with Alzheimer's, depression, autism and even schizophrenia. Alzheimer's, in fact, may one day be characterized as a disease of the DMN. A projection of the brain regions affected by Alzheimer's fits neatly over a map of the areas that make up the DMN. Such patterns may not only serve as biological markers for diagnosis but may also provide deeper insights into causes of the disease and treatment strategies.

Looking ahead, investigators must now try to glean how coordinated activity among and within brain systems operates at the level of the individual cells and how the DMN causes chemical and electrical signals to be transmitted through brain circuits. New theories will then be needed to integrate data on cells, circuits and entire neural systems to produce a broader picture of how the brain's default mode of function serves as a master organizer of its dark energy. Over time neural dark energy may ultimately be revealed as the very essence of what makes us tick. ■

[MISWIRED CIRCUITS]

DISEASE AND THE NETWORK

The default mode network overlaps areas involved with major brain disorders, suggesting that damage to the network may be involved. Discerning precisely which aspects of the network are affected by Alzheimer's, depression and other disorders may lead to new diagnostics and treatments.

ALZHEIMER'S
Brain areas that atrophy in Alzheimer's overlap very closely with major centers of the DMN.

DEPRESSION
Patients exhibit decreased connections between one area of the DMN and regions involved with emotion.

SCHIZOPHRENIA
Many regions of the DMN demonstrate increased levels of signaling. The importance of this finding is still being investigated.

KENT LARSSON *Getty Images*

➥ MORE TO EXPLORE

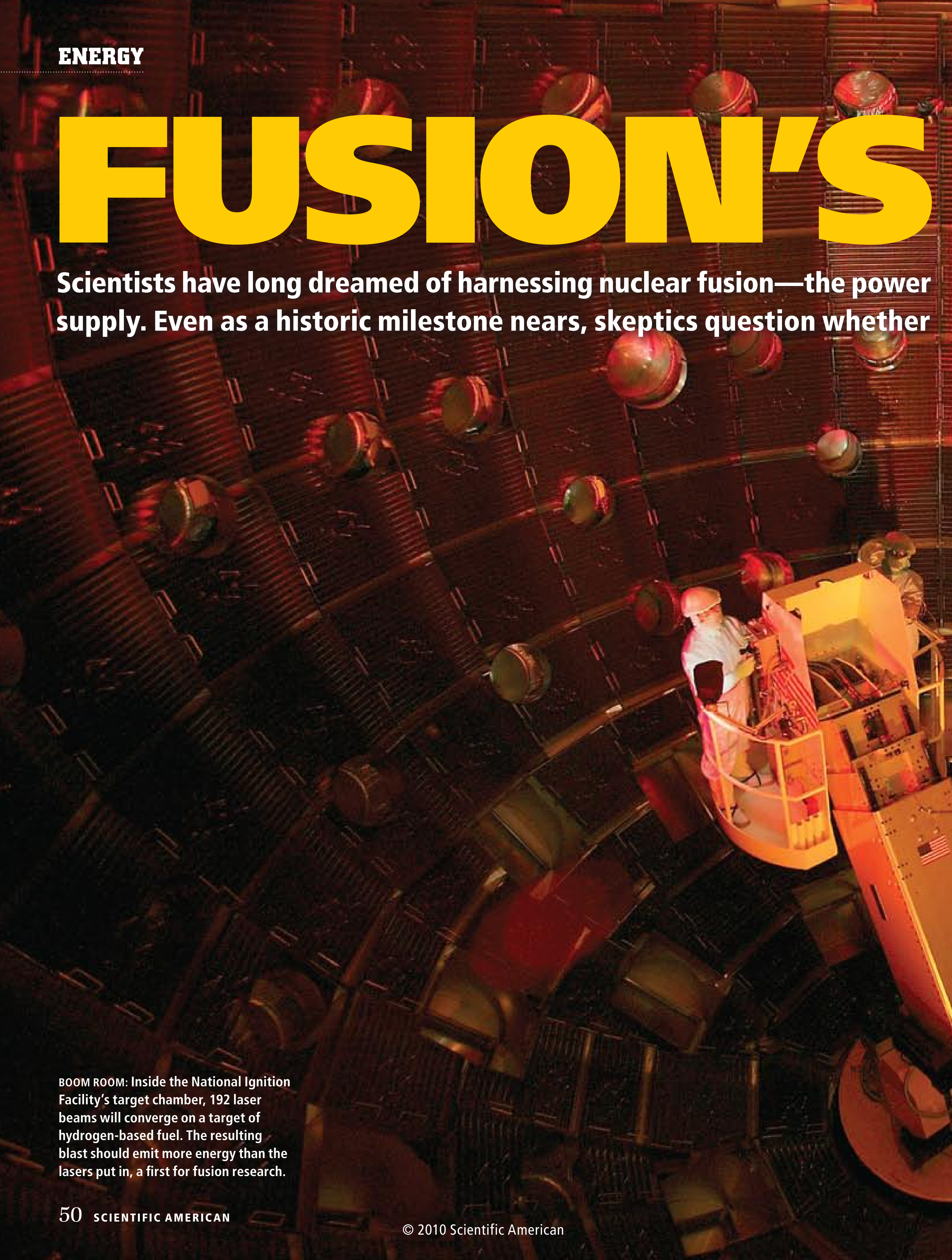
Spontaneous Fluctuations in Brain Activity Observed with Functional Magnetic Resonance Imaging. Michael D. Fox and Marcus E. Raichle in *Nature Reviews Neuroscience,* Vol. 8, pages 700–711; September 2007.

Disease and the Brain's Dark Energy. Dongyang Zhang and Marcus E. Raichle in *Nature Reviews Neurology,* Vol. 6, pages 15–18; January 2010.

Two Views of Brain Function. Marcus E. Raichle in *Trends in Cognitive Science* (in press).

FUSION'S

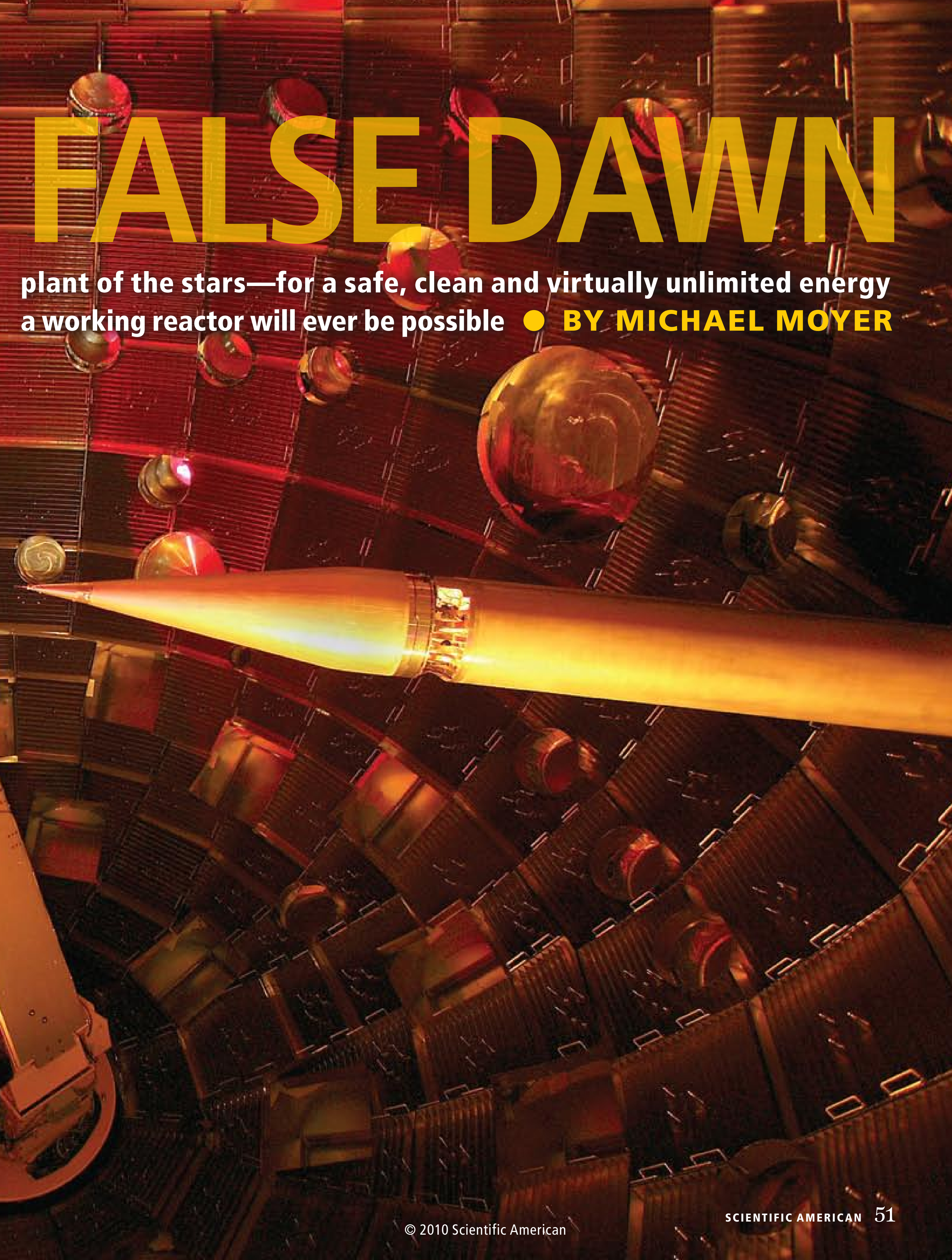
Scientists have long dreamed of harnessing nuclear fusion—the power supply. Even as a historic milestone nears, skeptics question whether



BOOM ROOM: Inside the National Ignition Facility's target chamber, 192 laser beams will converge on a target of hydrogen-based fuel. The resulting blast should emit more energy than the lasers put in, a first for fusion research.

FALSE DAWN

plant of the stars—for a safe, clean and virtually unlimited energy
a working reactor will ever be possible ● BY MICHAEL MOYER



KEY CONCEPTS

- The fusion of hydrogen isotopes is expected to soon emit more energy than is required to make the particles fuse together—a critical milestone in the many-decade quest for fusion energy.
- If this excess energy could be harnessed, it could form the basis for a revolutionary power plant.
- Yet scientists are now uncovering serious engineering challenges that could forestall the construction of such a plant for years to come.

—The Editors

Ignition is close now. Within a year or two the 192 laser beams at the National Ignition Facility (NIF)—the world's largest and most powerful laser system, a 13-year, $4-billion enterprise—will focus their energy onto a pellet no bigger than a peppercorn. Energy from the laser beams will crush the pellet's core with such force that the hydrogen isotopes inside will fuse together and release energy, an H-bomb in miniature.

The trick has been tried before—and with success. But every time scientists have fused together these isotopes, they have had to pump far more energy into the lasers than the reaction spat out. This time the ledger will flip. The boom at the pellet's center will release more energy than the lasers squeezed in, a switch more important than mere accounting would suggest. In theory, this excess energy could be collected and made to run a power plant. Its fuel would be materials found in ordinary seawater; its emissions—both atmospheric and nuclear—would be zero. It would be like capturing a star to run the machines of the earth. It would feed humanity's endless thirst for energy, and it would do so forever.

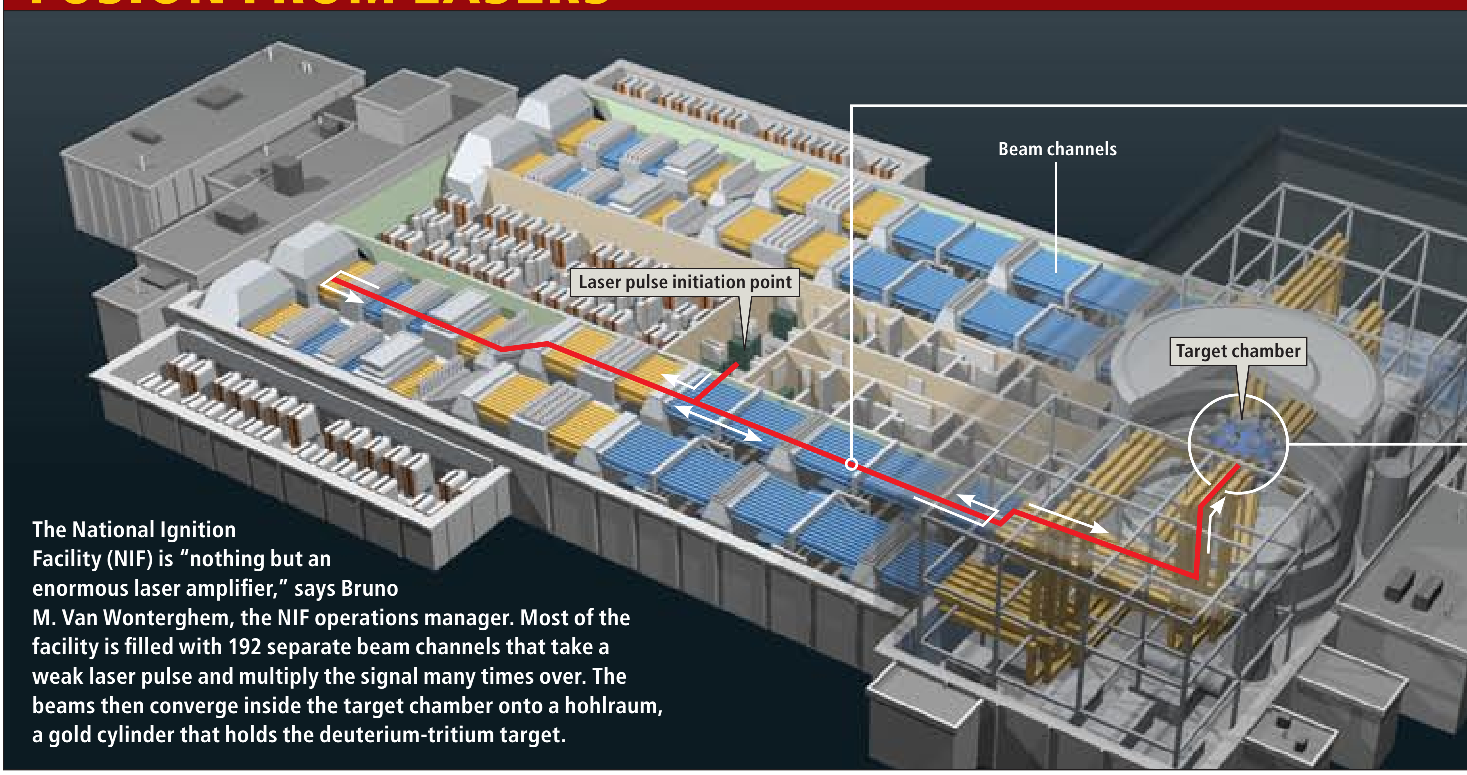
Construction has also begun at the world's other major fusion facility, a $14-billion project based outside the village of Cadarache in the south of France. ITER (pronounced "eater") will not rely on a vise of lasers; its superconducting magnets will hold hydrogen isotopes together and heat them to 150 million degrees Celsius—25,000 times hotter than the surface of the sun. This experiment is also expected to produce a net energy gain. Moreover, unlike the laser system's intermittent bursts of energy, magnets will be able to hold the plasma together for tens or perhaps hundreds of seconds, generating a continuous blaze of power.

The achievements will be a milestone in the quest, fervent since the dawn of the nuclear age, to tame the processes at work in the center of stars and manipulate them for our own ends. Yet the flash of ignition may be the easy part. There is a growing recognition among veteran fusion scientists that the challenges of constructing and operating a fusion-based power plant could be more severe than the physics challenge of generating the fireballs in the first place. Some physicists who are not directly involved with fusion research question whether the feat is possible even in theory. A working reactor would have to be made of materials that can withstand temperatures of millions of degrees for years on end. It would be constantly bombarded by high-energy nuclear particles—conditions that turn ordinary

COURTESY OF LAWRENCE LIVERMORE NATIONAL LABORATORY *(preceding pages)*

HOW IT WORKS

FUSION FROM LASERS



The National Ignition Facility (NIF) is "nothing but an enormous laser amplifier," says Bruno M. Van Wonterghem, the NIF operations manager. Most of the facility is filled with 192 separate beam channels that take a weak laser pulse and multiply the signal many times over. The beams then converge inside the target chamber onto a hohlraum, a gold cylinder that holds the deuterium-tritium target.

materials brittle and radioactive. It has to make its own nuclear fuel in a complex breeding process. And to be a useful energy-producing member of the electricity grid, it has to do these things pretty much constantly—with no outages, interruptions or mishaps—for decades on end.

"The idea has been that 'okay, these are hard problems, but they are solvable problems, and let's concentrate on the fusion core itself,' " says Richard D. Hazeltine, director of the Institute for Fusion Studies at the University of Texas at Austin. "That may have been a mistake."

Nature's Promise

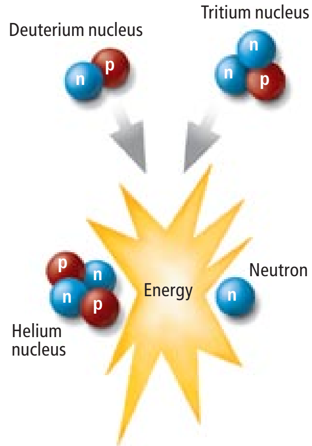
Fusion—or rather, the lack thereof—has been confounding scientists since at least the 1860s. Charles Darwin's new theory of evolution by natural selection required billions of years of incremental change to explain the incredible diversity of life on earth. Yet the era's best estimate of the sun's age—provided by the eminent British physicist William Thompson (better remembered as Lord Kelvin)—concluded that the sun could not be more than a few tens of millions of years old. As Charles Seife recounts in his excellent book *Sun in a Bottle* (Viking, 2008), Darwin considered Thompson's critique one of the gravest blows to the theory of evolution. He lamely countered that scientists should hold off on judgment, so incomplete was our understanding of the laws of the cosmos.

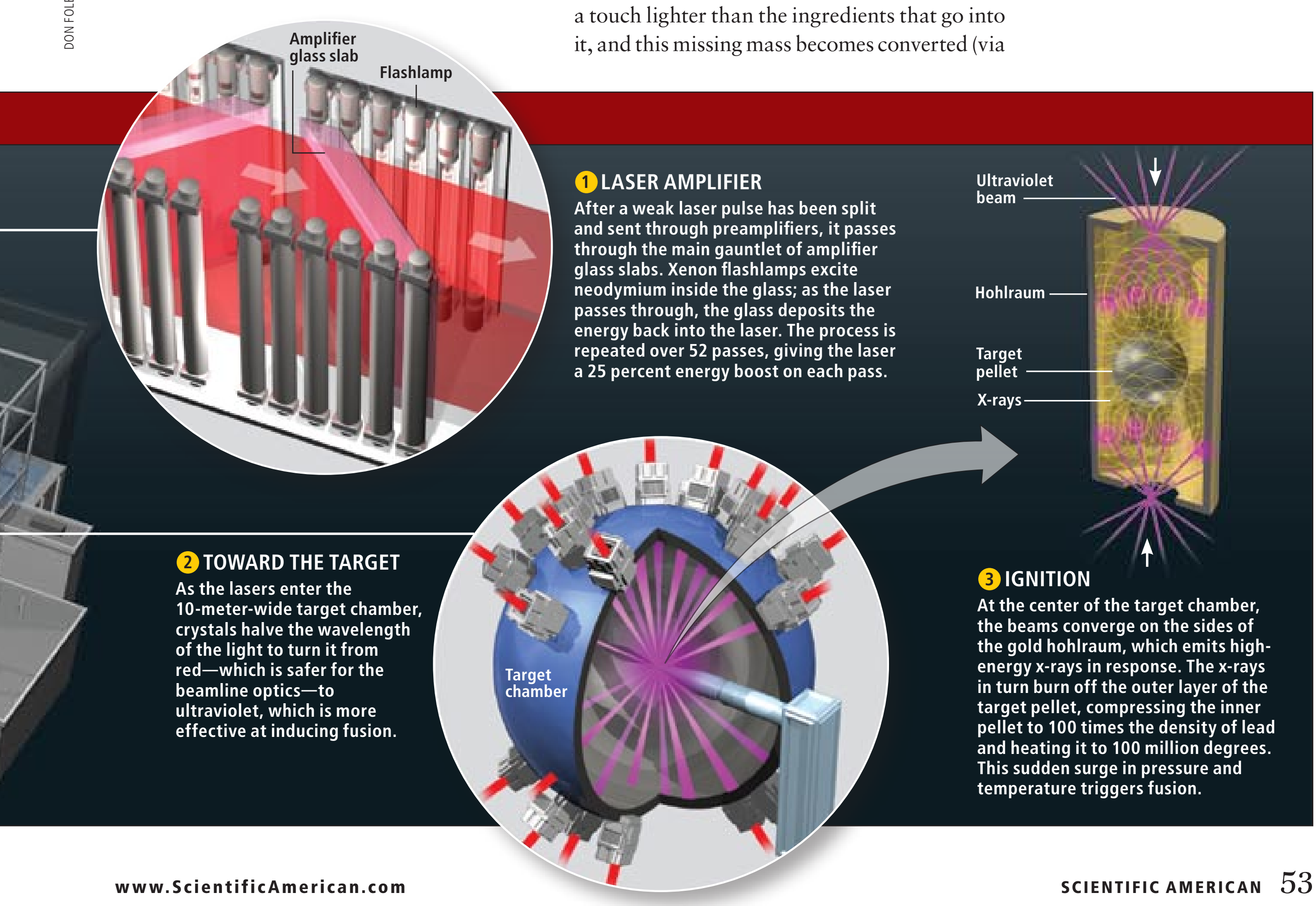
Darwin was right. It would be another seven decades before scientists would develop the tools necessary to understand what made the sun shine. By the 1930s scientists knew that all matter is made of atoms and that these atoms have a nucleus of positively charged protons and neutral neutrons. (Hydrogen is the sole exception—its nucleus has only a proton.) Albert Einstein had demonstrated via $E = mc^2$ that mass can become energy. And spectrographic studies showed that the sun is not made of molten rock, as Thompson assumed—it is composed mostly of hydrogen, along with some helium.

In 1938 physicist Hans Bethe realized that at the center of the sun, the pressure must be so great that individual hydrogen nuclei would be squeezed together with such force that they could overcome the repulsion that ordinarily keeps ions of like charge apart. Bethe laid out the four-step chain by which hydrogen ions fuse together. The final products of the reaction are a touch lighter than the ingredients that go into it, and this missing mass becomes converted (via

THE D-T REACTION

When the hydrogen isotopes deuterium and tritium are forced close together (via high temperatures and pressures), they overcome their mutual electromagnetic repulsion and fuse. The reaction forms helium, a neutron and a surfeit of energy.





DON FOLEY (*facility*); JESSICA HUPPI (*d-t reaction*)

$E = mc^2$) into the energy that powers the sun.

This complex chain reaction requires pressures that exist only in the center of stars. A comparatively easy way to induce fusion is to start with two isotopes of hydrogen—deuterium, which has a proton and a neutron in its nucleus, and tritium, which has one proton and two neutrons. Bring deuterium and tritium close enough together, and they will join to form helium (two protons, two neutrons), a neutron, and a burst of energy. The reaction requires relatively little in the way of temperature and pressure, yet it still generates the monumental energies that characterize fusion reactions.

If scientists could catalyze fusion in a controlled environment, the world's energy problems would disappear. The fuels are abundant: deuterium is found in seawater, and tritium can be generated inside a reactor. And unlike in ordinary fission-based nuclear reactors, fusion does not create long-lived radioactive by-products—nuclear waste, as it is more commonly known. In theory, a gallon of deuterium-infused water could produce as much energy as a supertanker full of oil, with a puff of helium as its only exhaust. "You have no geopolitics, clean energy and a limitless supply of fuel," says Edward I. Moses, director of the National Ignition Facility. "It is too good to be true."

And indeed it was. The first designs for fusion reactors came in the early 1950s, when Lyman Spitzer, a professor at Princeton University, estimated that his "Stellarator" (from the Latin for "star") would produce 150 million watts of power, enough to power 150,000 homes. His design relied on the fact that at the high temperatures required for fusion, all electrons would be torn from their parent atoms. This forms a soup of charged particles called a plasma that can be controlled with magnetic fields. Spitzer's Stellarator was essentially a magnetic bottle that would hold the plasma in place even as it was heated to temperatures of millions of degrees.

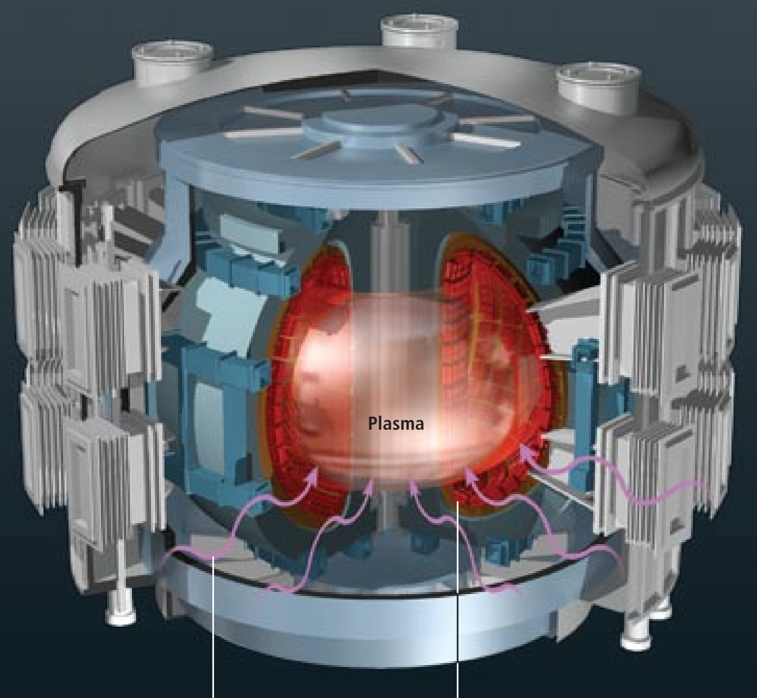
Yet Spitzer and others who would follow him did not have a thorough understanding of how plasmas behaved. What they were soon to learn—much to their disappointment—is that plasmas do not behave very well at all.

Imagine holding a large, squishy balloon. Now squeeze it down to as small as it will go. No matter how evenly you apply pressure, the balloon will always squirt out through a space between your fingers. The same problem applies to plasmas. Anytime scientists tried to clench them down into a tight enough ball to induce fusion, the plasma would find a way to squirt out the sides. It is a paradox germane to all types of fusion reactors—the hotter you make the plasma and the tighter you squeeze it, the more it fights your efforts to contain it.

INSIDE LOOK

FUSION FROM MAGNETS

The ITER project in southern France will attempt to create fusion by heating a plasma of deuterium and tritium. The plasma is held in place by powerful superconducting magnets, and beams of microwaves are used to heat the plasma to 150 million degrees Celsius. The process is not intermittent like the laser-based NIF is, so fusion could be sustained for tens or even hundreds of seconds.



DON FOLEY

The lasers will crush the target with a pulse that outshines the nation's entire electricity consumption.

In the six decades since, scientists have struggled to tame plasmas using ever larger magnetic bottles. Every time physicists unveiled an improved machine that was designed to correct the problems that turned up on the last go-around, the higher energies uncovered new varieties of problems. "No matter what you do with them," says Charles Baker, former director of fusion programs at Argonne and Oak Ridge national laboratories and current chair of the U.S. ITER technical advisory committee, "plasmas are always a little unstable."

The energy crisis of the 1970s also saw the birth of a parallel research program toward fusion, one that would attempt to avoid some of the problems related to magnetically confined plasmas. These techniques used a bevy of lasers to compress and heat a pellet made of deuterium and tritium. The research—carried out at Lawrence Livermore National Laboratory, home of the U.S. fusion weapons programs—started with a simple two-beam test bed. Advances in laser power led to Shiva (named for the Hindu god of creation and destruction) in 1977, then Nova in 1984. Each program defeated Livermore's own world records for production of the most powerful laser blast on the planet, but as in the magnetic programs, they still could not reach breakeven—the point where fusion produced as much energy as the lasers put in. For that, Livermore would need a laser 70 times more potent than any that had come before. In 1997 construction began on the National Ignition Facility.

Little Blasts

From the outside, the National Ignition Facility doesn't look like much. It is windowless, about the size of an airplane hanger, and painted in a muted beige that would not be out of place in a suburban office park. But like most big-science projects—the Large Hadron Collider comes immediately to mind—it is the deep-buried guts of the project that inspire awe. Inside, dozens of meter-wide tubes stretch far across the facility. The tubes lead to the target chamber, a three-story-high sphere studded with portholes for the lasers to pass through. At the center of this chamber, the deuterium-tritium target is held in place by what looks like a giant pencil tip. The lasers will focus to within millimeters of the center point, crushing the target with a pulse that—at least for small fraction of a second—outshines the nation's entire electricity consumption.

Although the NIF is designed to reach breakeven, its primary mission relates to national security. In 1996 President Bill Clinton signed the comprehensive test ban treaty and outlawed all U.S. nuclear weapons testing. To ensure that the weapons in the stockpile will continue to operate as intended—that is, individual warheads will detonate if the president orders a strike and never otherwise—the nation's nuclear weapons laboratories at Los Alamos and Livermore instituted the stockpile stewardship program, a system of maintenance and testing designed to ensure the reliability of the estimated 5,200 warheads currently in the stockpile.

Most nuclear weapons maintenance is simply routine inspection and replacement of parts. Another key component is computer modeling of nuclear explosions. Such computer models are exquisitely sensitive to the initial conditions; the NIF is designed to provide data from miniature deuterium-tritium blasts to feed into the models. (The facility will also be used for pure-science experiments—one of the first involves a study of the shock waves of a supernova.)

Yet when the facility finally came online last May, its potential for power generation garnered most of the ink. A column by Thomas Friedman in the *New York Times* that ran under the title "The Next Really Cool Thing" provides a typical example. In it, he wrote "each crushed pellet gives off a burst of energy that can then be harnessed to heat up liquid salt and produce massive amounts of steam to drive a turbine and create electricity for your home—just like coal does today."

In theory, yes. But the NIF was never intended to be a machine that could generate usable energy. Under the current operating plan, the NIF will begin experiments with deuterium-tritium fusion later this year and then, if all goes well, hit breakeven a year or so after that. Mind you, this is not "power plant breakeven," as Moses explains. This is just getting more energy out of the pellet than the laser system puts in (the net energy that goes into creating the 4.2-million-joule laser and the losses that occur en route to the target are written off of this ledger). Even still, it should reach the milestone more than 15 years before ITER.

Reactor Roadblocks

No matter how you make fusion happen—whether you use megajoule lasers or the crunch of magnetic fields—energy payout will come in the currency of neutrons. Because these particles are neutral, they are not affected by electric or magnetic fields. Moreover, they pass straight through most solid materials as well.

The only way to make a neutron stop is to have it directly strike an atomic nucleus. Such collisions are often ruinous. The neutrons coming out of a deuterium-tritium fusion reaction are so energetic that they can knock out of position an atom in what would ordinarily be a strong metal—steel, for instance. Over time these whacks weaken a reactor, turning structural components brittle.

Other times the neutrons will turn benign material radioactive. When a neutron hits an atomic nucleus, the nucleus can absorb the neutron and become unstable. A steady stream of neutrons—even if they come from a "clean" reaction such as fusion—would make any ordinary container dangerously radioactive, Baker

THE SHORT HISTORY OF FUSION

1950: Soviet scientist Andrei Sakharov designs a magnetic bottle, called a tokamak, that can hold a plasma. Sakharov's nuclear weapons work pulls him away from the project.

1951: Lyman Spitzer of Princeton University introduces the Stellarator, another magnet-based fusion reactor.

1952: The U.S. detonates Ivy Mike, the world's first hydrogen bomb.

1969: Western scientists travel to Moscow to investigate Sakharov's tokamak design. They find that it produces a much hotter, denser plasma than their stellarators. Tokamaks begin to dominate magnetic fusion research.

1977: The Shiva laser attempts to induce fusion with laser blasts.

2010: The National Ignition Facility should begin deuterium-tritium fusion experiments later this year.

2018 (est.): Construction on ITER is scheduled to be complete. The first deuterium-tritium fusion tests are planned for 2026.

says. "If someone wants to sell you any kind of nuclear system and says there is no radioactivity, hang onto your wallet."

A fusion-based power plant must also convert energy from the neutrons into heat that drives a turbine. Future reactor designs make the conversion in a region surrounding the fusion core called the blanket. Although the chance is small that a given neutron will hit any single atomic nucleus in a blanket, a blanket thick enough and made from the right material—a few meters' worth of steel, perhaps—will capture nearly all the neutrons passing through. These collisions heat the blanket, and a liquid coolant such as molten salt draws that heat out of the reactor. The hot salt is then used to boil water, and as in any other generator, this steam spins a turbine to generate electricity.

Except it is not so simple. The blanket has another job, one just as critical to the ultimate success of the reactor as extracting energy. The blanket has to make the fuel that will eventually go back into the reactor.

Although deuterium is cheap and abundant, tritium is exceptionally rare and must be harvested from nuclear reactions. An ordinary nuclear power plant can make between two to three kilograms of it in a year, at an estimated cost of between $80 million and $120 million a kilogram. Unfortunately, a magnetic fusion plant will consume about a kilogram of tritium a week. "The fusion needs are way, way beyond what fission can supply," says Mohamed Abdou, director of the Fusion Science and Technology Center at the University of California, Los Angeles.

For a fusion plant to generate its own tritium, it has to borrow some of the neutrons that would otherwise be used for energy. Inside the blanket channels of lithium, a soft, highly reactive metal, would capture energetic neutrons to make helium and tritium. The tritium would escape out through the channels, get captured by the reactor and be reinjected into the plasma.

When you get to the fine print, though, the accounting becomes precarious. Every fusion reaction devours exactly one tritium ion and produces exactly one neutron. So every neutron coming out of the reactor must make at least one tritium ion, or else the reactor will soon run a tritium deficit—consuming more than it creates. Avoiding this obstacle is possible only if scientists manage to induce a complicated cascade of reactions. First, a neutron hits a lithium 7 isotope, which, although it consumes energy, produces both a tritium ion and a neutron. Then this second neutron goes on to hit a lithium 6 isotope and produce a second tritium ion.

Moreover, all this tritium has to be collected and reintroduced to the plasma with near 100 percent efficiency. "In this chain reaction you cannot lose a single neutron, otherwise the reaction stops," says Michael Dittmar, a particle physicist at the Swiss Federal Institute for Technology in Zurich. "The first thing one should do [before building a reactor] is to show that the tritium production can function. It is pretty obvious that this is completely out of the question."

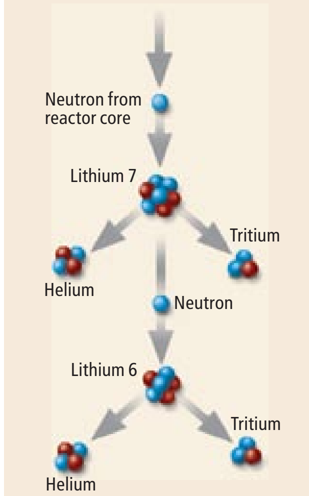
"This is a very fancy gadget, this fusion blanket," Hazeltine says. "It is accepting a lot of heat and taking care of that heat without overheating itself. It is accepting neutrons, and it is made out of very sophisticated materials so it doesn't have a short lifetime in the face of those neutrons. And it is taking those neutrons and using them to turn lithium into tritium."

ITER, unfortunately, will not test blanket designs. That is why many scientists—especially those in the U.S., which is not playing a large role in the design, construction or operation of ITER—argue that a separate facility is needed to design and build a blanket. "You must show that you can do this in a practical system," Abdou says, "and we have never built or tested a blanket. Never." If such a test facility received funding tomorrow, Abdou estimates that it would take between 30 and 75 years to understand the issues sufficiently well to begin construction on an operational power plant. "I believe it's doable," he says, "but it's a lot of work."

The Big Lie

Let's say it happens. The year is 2050. Both the NIF and ITER were unqualified successes, hitting their targets for energy gain on time and under budget. Mother Nature held no surprises as physicists ramped up the energy in each system; the ever unruly plasmas behaved as expected. A separate materials facility demonstrated how to build a blanket that could generate tritium and convert neutrons to electricity, as well as stand up to the subatomic stresses of daily use in a fusion plant. And let's assume that the estimated cost for a working fusion plant is only $10 billion. Will it be a useful option?

Even for those who have spent their lives pursuing the dream of fusion energy, the question is a difficult one to answer. The problem is that fusion-based power plants—like ordinary fission plants—would be used to generate baseload



THE T TRICK

Fusion reactors must generate their own tritium fuel via a complex chain of reactions. A neutron first hits a lithium 7 ion implanted in a region surrounding the reactor called the blanket. This reaction creates helium, tritium and a neutron. This second neutron then goes on to hit a lithium 6 ion, which is also implanted in the blanket. This produces another helium ion and a tritium ion.

CHALLENGES

Before fusion can be a viable energy source, scientists must overcome a number of problems.

Heat: Materials that face the reactions must withstand extremely high temperatures for years on end.

Structure: The high-energy neutrons coming from fusion reactions turn ordinary materials brittle.

Fuel: A fusion reactor will have to "breed" its own tritium in a complex series of reactions [*see box above*].

Reliability: Laser reactors produce only intermittent blasts; magnet-based systems must maintain a plasma for weeks, not seconds.

JESSICA HUPPI

power. That is, to recoup their high initial costs, they would need to always be on. "Whenever you have any system that is capital-intensive, you want to run it around the clock because you are not paying for the fuel," Baker says.

Unfortunately, it is extremely difficult to keep a plasma going for any appreciable length of time. So far reactors have been able to maintain a fusing plasma for less than a second. The goal of ITER is to maintain a burning plasma for tens of seconds. Going from that duration to around-the-clock operation is yet another huge leap. "Fusion will need to hit 90 percent availability," says Baker, a figure that includes the downtime required for regular maintenance. "This is by far the greatest uncertainty in projecting the economic reliability of fusion systems."

NIF director Moses thinks he has the answer. He has introduced a proposed design for a hybrid fusion-fission reactor—one that uses the neutrons from laser-driven fusion reactions to drive fission reactions in a blanket of ordinary nuclear waste. He calls his system LIFE—for laser inertial fusion engine—and says he can have one connected to the grid in 20 years.

The system relies on the fact that only 5 percent of the uranium that goes into power plants gets used before it is pulled out and put into long-term storage. LIFE would bombard this spent fuel with neutrons, thus accelerating its decay into lighter and less radioactive elements, all the while producing heat that could be used for electricity. "Our studies show that we would be competitive with all the energy sources that are available today," Moses says. "Or even cheaper than them."

Of course, LIFE is not without its pitfalls. "You want to look at the big lie in each program," says Edward C. Morse, a professor of nuclear engineering at the University of California, Berkeley. "The big lie in [laser-based] fusion is that we can make these target capsules for a nickel a piece." The target capsules, the peppercorn-size balls of deuterium-tritium fuel, have to be exquisitely machined and precisely round to ensure that they compress evenly from all sides. Any bump on the pellet and the target won't blow, which makes current iterations of the pellets prohibitively expensive. Although Livermore, which plans to make its pellets on site, does not release anticipated costs, the Laboratory for Laser Energetics at the University of Rochester also makes similar deuterium-tritium balls. "The reality now is that the annual budget to make targets that are used at Rochester is several million dollars, and they make about six capsules a year," Morse says. "So you might say those are $1 million a piece."

And unlike in the current iteration of the NIF, which is capable of blasting one pellet every few hours, targets will cycle through the chamber with the speed of a Gatling gun. "This is a 600-rpm machine," Moses says. "It's like a million-horsepower car engine—except no carbon." A LIFE plant working around the clock will consume almost 90,000 targets a day.

Of course, it is impossible to predict what the worldwide energy situation will be 20 years out. Perhaps the need for fusion energy will be greater than ever. Or it could be that a breakthrough in solar, wind or some other as yet unforeseen alternative energy makes fusion appear expensive and unwieldy by comparison. "It is possible that people will say, 'Yeah, it works, that's great, but we don't need it anymore, because we've got a list of other things,' " Hazeltine says.

It used to be that fusion was held apart from these considerations. It was fundamentally different from dirty fossil fuels or dangerous uranium. It was beautiful and pure—a permanent fix, an end to our thirst for energy. It was as close to the perfection of the cosmos as humans were ever likely to get.

Now those visions are receding. Fusion is just one more option and one that will take decades of work to bear fruit. Ignition may be close, but the age of unlimited energy is not. ■

MORE TO EXPLORE

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HOT GLOW: **A look at the plasma inside the Korea Superconducting Tokamak Advanced Research (KSTAR) project, which began operations in 2008.**

COURTESY OF NATIONAL FUSION RESEARCH INSTITUTE

Evolution of Minerals

BY ROBERT M. HAZEN

Looking at the mineral kingdom through the lens of deep time leads to a startling conclusion: most mineral species owe their existence to life

KEY CONCEPTS

- Only a dozen minerals (crystalline compounds) are known to have existed among the ingredients that formed the solar system 4.6 billion years ago, but today Earth has more than 4,400 mineral species.
- Earth's diverse mineralogy developed over the eons, as new mineral-generating processes came into play.
- Remarkably, more than half of the mineral species on Earth owe their existence to life, which began transforming the planet's geology more than two billion years ago.

—The Editors

Once upon a time there were no minerals anywhere in the cosmos. No solids of any kind could have formed, much less survived, in the superheated maelstrom following the big bang. It took half a million years before the first atoms—hydrogen, helium and a bit of lithium—emerged from the cauldron of creation. Millions more years passed while gravity coaxed these primordial gases into the first nebulas and then collapsed the nebulas into the first hot, dense, incandescent stars.

Only then, when some giant stars exploded to become the first supernovas, were all the other chemical elements synthesized and blasted into space. Only then, in the expanding, cooling gaseous stellar envelopes, could the first solid pieces of minerals have formed. But even then, most of the elements and their compounds were too rare and dispersed, or too volatile, to exist as anything but sporadic atoms and molecules among the newly minted gas and dust. By not forming crystals, with distinct chemical compositions and atoms organized in an orderly array of repeating units, such disordered material fails to qualify as minerals.

Microscopic crystals of diamond and graphite, both pure forms of the abundant element carbon, were likely the first minerals. They were soon joined by a dozen or so other hardy microcrystals, including moissanite (silicon carbide), osbornite (titanium nitride), and some oxides and silicates. For perhaps tens of millions of years, these earliest few species—"ur-minerals"—were the only crystals in the universe.

Earth today, in contrast, boasts more than 4,400 known mineral species, with many more yet to be discovered. What caused that remarkable diversification, from a mere dozen to thousands of crystalline forms? Seven colleagues and I recently presented a new framework of "mineral evolution" for answering that question. Mineral evolution differs from the more traditional, centuries-old approach to mineralogy, which treats minerals as valued objects with distinctive chemical and physical properties, but curiously unrelated to time—the critical fourth dimension of geology. Instead our approach uses Earth's history as a frame for understanding minerals and the processes that created them.

We quickly realized that the story of mineral evolution began with the emergence of rocky planets, because planets are the engines of min-

HOLLY LINDEM

[TIMELINE]

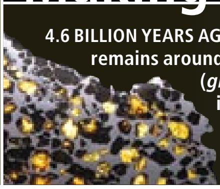
Snapshots of Mineral Genesis

In the 4.6 billion years since the solar system formed, the suite of minerals present has evolved from modest beginnings—about a dozen minerals in the presolar nebula—to better than 4,400 minerals found on Earth today. The planet has passed through a series of stages, represented at the right and in the following pages by five snapshots, involving a variety of mineral-forming processes. Some of these processes generated completely new minerals, whereas others transformed the face of the planet by turning former rarities into the commonplace.

Making Earth

4.6 BILLION YEARS AGO: Millions of planetesimals form in the disk of dust and gas that remains around the recently ignited sun (*in background*) and collide to form Earth (*glowing planet*). More than 200 minerals, including olivine and zircon, develop in the planetesimals, thanks to melting of their material, shocks from collisions, and reactions with water. Many of these minerals are found in ancient chondritic meteorites.

◀ Zircon



◀ Olivine crystals in pallasite (meteorite)

▶ Chondrite (meteorite)

[THE AUTHOR]

Robert M. Hazen, senior staff scientist at the Carnegie Institution's Geophysical Laboratory and Clarence Robinson Professor of Earth Science at George Mason University, received his Ph.D. in earth science at Harvard University in 1975. He is author of 350 scientific articles and 20 books, including *Genesis: The Scientific Quest for Life's Origin*, and he frequently presents science to nonscientists through radio, television, public lectures and video courses. Hazen's recent research focuses on the role of minerals in the origin of life. The mineral hazenite, which is precipitated by microbes in the highly alkaline Mono Lake in California, is named after him.

eral formation. We saw that over the past four and a half billion years Earth has passed through a series of stages, with novel phenomena emerging at each stage to dramatically alter and enrich the mineralogy of our planet's surface.

Some details of this story are matters of intense debate and will doubtless change with future discoveries, but the overall sweep of mineral evolution is well-established science. My colleagues and I are not presenting controversial new data or radical new theories about what occurred at each stage of Earth's history. We are, rather, recasting the larger story of that history in the light of mineral evolution as a guiding concept.

I do, however, want to emphasize one intriguing insight: most of Earth's thousands of minerals owe their existence to the development of life on the planet. If you think of all the nonliving world as a stage on which life plays out its evolutionary drama, think again. The actors renovated their theater along the way. This observation also has implications for the quest to find signs of life on other worlds. Sturdy minerals rather than fragile organic remains may provide the most robust and lasting signs of biology.

Making Earth

Planets form in stellar nebulas that have been seeded with matter from supernovas. Most of a nebula's mass rapidly falls inward, producing the central star, but remnant material forms a vast rotating disk around the star. These leftovers progressively clump into larger and larger bits: sand-, pebble- and fist-size fluff balls of primordial dust harboring a limited repertoire of a dozen or so ur-minerals, along with other miscellaneous atoms and molecules.

Dramatic changes occur when the nascent star ignites and bathes the nearby concentrations of dust and gas with a refining fire. In our own solar system, stellar ignition occurred almost 4.6 billion years ago. Pulses of heat coming from the infant sun melted and remixed elements and produced crystals representing scores of new minerals. Among the crystalline novelties of this earliest stage of mineral evolution were the first iron-nickel alloys, sulfides, phosphides, and a host of oxides and silicates. Many of these minerals are found in the most primitive meteorites as "chondrules": chilled droplets of once molten rock. (These ancient chondritic meteorites also provide the evidence for the ur-minerals that predated chondrules. Mineralogists find the ur-minerals in the form of nanoscopic and microscopic grains in the meteorites.)

In the ancient solar nebula, chondrules quickly clumped into planetesimals, some of which grew to more than 100 miles in diameter—large enough to partially melt and differentiate into onionlike layers of distinctive minerals, includ-

COURTESY OF THE TEACHING COMPANY (*Hazen*); RON MILLER (*illustrations*); NATURAL HISTORY MUSEUM, LONDON (*pallasite*); SCIENTIFIC A *Getty Images* (*zircon*); MASSIMO BREGA *Photo Researchers, Inc.* (*chondrite*)

Black Earth

4.4 BILLION YEARS AGO: The surface of lifeless Hadean Earth is largely black basalt, a rock formed from molten magma and lava. The next two billion years see about 1,500 minerals produced. Repeated partial melting of rock concentrates scarce, dispersed elements such as lithium (found in lepidolite), beryllium (in beryl) and boron (in tourmaline). Chemical reactions and weathering by the early oceans and the anoxic atmosphere also contribute. Minerals formed under high pressure, such as jadeite, are brought to the surface by plate tectonics.

▲ Lepidolite

▶ Beryl

ing a dense, metal-rich core. Frequent collisions in the crowded solar suburbs introduced intense shocks and additional heat, further altering the minerals in the largest planetesimals. Water also played a role; it had been around from the beginning, as ice particles in the presolar nebula, and in the planetesimals these melted and aggregated in cracks and fissures. Chemical reactions with the resulting water generated new minerals.

Perhaps 250 different mineral species arose as a consequence of these dynamic planet-forming processes. Those 250 minerals are the raw materials from which every rocky planet must form, and all of them are still found today in the diverse suites of meteorites that fall to Earth.

Black Earth

Primordial Earth grew ever larger. Big planetesimals swallowed smaller ones by the thousands until only two major rivals remained in our orbital zip code, the proto-Earth and a much smaller Mars-size body sometimes known as Theia, after the mother of the Greek goddess of the moon. In a final paroxysm of unimaginable violence, Theia sideswiped the proto-Earth, vaporizing its outer layers and blasting 100 million trillion tons of incandescent rock vapors into space to become the moon. This scenario explains the high angular momentum of the Earth-moon system and many unusual features of the moon, including why its bulk composition matches that of Earth's mantle (the nearly 2,000-mile-thick layer that extends from Earth's iron-nickel core to the three- to 30-mile-thick crust at Earth's surface).

◀ Tourmaline

Repeated partial melting of granites concentrated rare "incompatible" elements.

Following this moon-spawning collision about 4.5 billion years ago, the molten Earth began the cooling that continues to this day. Although Earth's primitive surface included dozens of rare elements—uranium, beryllium, gold, arsenic, lead and many more—that were capable of forming a diverse assortment of minerals, Theia's impact had served as a cosmic "reset." It left Earth's outer layers thoroughly mixed, with these less common elements far too dispersed to form separate crystals. Our planet was a desolate, hostile world, incessantly bombarded by nebular debris and largely covered by a veneer of black basalt, a kind of rock that is formed even in modern times when lava solidifies.

Earth's mineralogical diversity gradually increased through the aptly named Hadean eon (prior to about four billion years ago), primarily from repeated melting and solidifying of the rocky crust, as well as from weathering reactions with the early oceans and atmosphere. Over countless cycles, this partial melting and resolidifying of volumes of rock, and interactions between rock and water such as the dissolution of selected compounds, gradually concentrated uncommon elements enough to form new generations of exotic minerals.

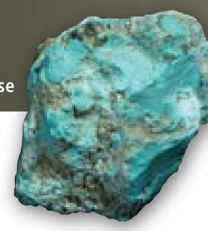
Not every planet possesses this great mineral-

BIOPHOTO ASSOCIATES *Photo Researchers, Inc.* (lepidolite); SCIENTIFICA *Getty Images* (beryl); JACANA *Photo Researchers, Inc.* (tourmaline)

Red Earth

2 BILLION YEARS AGO: Photosynthetic living organisms have given Earth's atmosphere a small percentage of oxygen, dramatically altering its chemical action. Ferrous (Fe^{2+}) iron minerals common in black basalt are oxidized to rust-red ferric (Fe^{3+}) compounds. This "Great Oxidation Event" paves the way for more than 2,500 new minerals, including rhodonite (found in manganese mines) and turquoise. Microorganisms (*green*) lay down sheets of material called stromatolites, made of minerals such as calcium carbonate.

◀ Fossil stromatolite cross section



▶ Turquoise

▼ Rhodonite

forming potential. Tiny, dehydrated Mercury and Earth's equally dry moon became frozen before much melting could occur. Consequently, we estimate that no more than about 350 different mineral species will be found on those worlds. Mars, with a modest water budget, might have fared a little better as a result of hydrous species such as clays and evaporite minerals that form when oceans dry up. We estimate that NASA probes might eventually identify as many as 500 different minerals on the Red Planet.

Earth is bigger, hotter and wetter and thus has a few other mineral-forming tricks to play. All the rocky planets experienced volcanism that poured basalt across their surfaces, but Earth (and maybe Venus, which is about equal in size) had enough inner heat to remelt some of that basalt to form a suite of igneous rocks called granitoids, including the familiar tan and gray granites of curbstones and countertops. Granites are coarse-grained blends of minerals, including quartz (the most ubiquitous grains of sand at the beach), feldspar (the commonest of all minerals in Earth's crust), and mica (which forms shiny, sheetlike mineral layers). All these minerals were produced earlier in very small quantities in large planetesimals, but they first appear in great abundance in Earth's geologic record thanks to the planet's granite-forming processes.

On Earth, repeated partial melting of granites concentrated rare "incompatible" elements that are unable to find a comfortable crystallographic home in common minerals. The resulting rocks feature more than 500 distinctive minerals, including giant crystals of species rich in lithium, beryllium, boron, cesium, tantalum, uranium, and a dozen other rare elements. It takes time—some scientists estimate more than a billion years—for these elements to achieve mineral-forming concentrations. Earth's planetary twin, Venus, may have been sufficiently active for long enough to progress this far, but neither Mars nor Mercury has yet revealed significant surface signs of granitization.

Earth gained even more mineral diversity through the planetary-scale process of plate tectonics, which generates fresh crust along chains of volcanoes, while old crust is swallowed up in subduction zones, where one plate slips under another and is returned to the mantle. Immense quantities of wet, chemically diverse rocks subducted from the crust were partially melted, causing further concentration of scarce elements. Hundreds of new minerals were produced in massive sulfide deposits, which today provide some of Earth's richest bodies of metal ore. Hundreds more mineral species first appeared at Earth's surface when tectonic forces uplifted and exposed deep rock domains with their hoard of distinctive minerals that form under high pres-

In a geologic instant, photosynthesis by new kinds of algae brought about the Great Oxidation Event.

RON MILLER (*illustrations*); SCIENTIFICA *Getty Images* (*rhodonite*); TED KINSMAN *Photo Researchers, Inc.* (*stromatolite*); E. R. DEGGINGER *Photo Researchers, Inc.* (*turquoise*)

White Earth

700 MILLION YEARS AGO: Climate change covers the entire planet surface with one mineral—ice—for millions of years. Eventually carbon dioxide from volcanoes triggers runaway global warming, and the planet cycles between hothouse and snowball. In the hothouse phases, weathering adds large quantities of fine-grained clay minerals such as kaolinite to the landscape. Distinctive "cap carbonate" layers deposited in shallow, warming oceans include crystals six feet tall.

▲ Kaolinite

▶ Ice

sure, such as jadeite (one of two minerals better known as the gemstone jade).

All told, perhaps 1,500 different minerals found on or near Earth's surface might have been generated by dynamic crust and mantle processes during Earth's first two billion years. But mineralogists have catalogued more than 4,400 different mineral species. What happened to triple Earth's mineralogical diversity?

Red Earth

The answer is life. The biosphere distinguishes Earth from all other known planets and moons, and it has irrevocably transformed the near-surface environment—most conspicuously the oceans and atmosphere but also the rocks and the minerals.

Life's earliest manifestations—primitive single-celled organisms that "fed" on the chemical energy of rocks—cannot have had much effect on Earth's mineralogical diversity. To be sure, geologists have found biologically mediated rock formations dating back to 3.5 billion years ago, including reefs made of calcium carbonate and so-called banded iron formations (in which iron oxides apparently lock away the first oxygen produced by life). But the land was still barren, the atmosphere at large still lacked oxygen, surface weathering was slow, and the earliest life contributed almost nothing to alter the number of minerals present or their distribution.

▲ Cap carbonate

That situation changed in a geologic instant with the rapid rise of oxygen in the atmosphere, thanks to the innovation of oxygen-producing photosynthesis by new kinds of algae. Debate still rages about this transition, called the Great Oxidation Event. In particular, researchers have not settled exactly when and how rapidly it began. But by 2.2 billion years ago atmospheric oxygen had risen to greater than 1 percent of modern levels—a small amount but enough to forever transform Earth's surface mineralogy.

Chemical modeling by my colleagues and me suggests that the Great Oxidation Event paved the way for more than 2,500 new minerals, many of which are hydrated, oxidized weathering products of other minerals. These species of crystals are unlikely to form in an anoxic environment, so Earth's biochemical processes appear to be responsible, directly or indirectly, for the majority of Earth's 4,400 known mineral species.

Most of these new minerals occurred as thin coatings and rinds of altered material on existing rocks. Many rare mineral species are known from only a handful of precious crystals that weigh less than a gram. But the Great Oxidation Event had global mineralogical consequences as well. Most notably, the planet rusted—across the globe, the black basalt that previously dominated the landscape turned red as the ferrous iron (Fe^{2+}) of common basalt minerals oxidized to hematite and other rust-red ferric iron (Fe^{3+}) com-

COURTESY OF ALAN JAY KAUFMAN *(cap carbonate)*; TED KINSMAN *Photo Researchers, Inc. (kaolinite)*; SCIENCE SOURCE *Photo Researchers, Inc. (snow crystal)*

Green Earth

400 MILLION YEARS AGO: Multicellular organisms have emerged, and plants have colonized the land, followed by animals. Biochemical breakdown by plants and fungi increases the weathering of rock and production of clays (mixtures of hydrated minerals) by orders of magnitude. Earth's surface takes on its modern appearance for the first time—and its modern distribution of minerals. Life directly produces minerals such as aragonite and calcite (found in everything from trilobites to human skeletons), as well as extreme rarities such as hazenite, laid down by microbes.

▲ Aragonite

▶ Fossil trilobite

pounds. From space, Earth's continents two billion years ago might have looked something like Mars, albeit with blue oceans and white clouds providing dramatically colorful contrasts.

The red color of Mars is also caused by oxidation, but its oxygen was produced by sunlight dissociating water high in the atmosphere, with the hydrogen escaping to space. That process made enough oxygen to somewhat rust the small planet's surface, though not enough to create the thousands of minerals possible on the highly oxidized, more geologically active Earth.

▲ Hazenite

White Earth

For the billion years or so after the Great Oxidation Event, little of mineralogical interest seems to have happened. This interval, dubbed the Intermediate Ocean or, more whimsically, the Boring Billion, appears to have been a time of relative biological and mineralogical stasis. The "intermediate" of the name refers to oxygen levels: ocean waters near the surface were oxygenated, yet the depths remained anoxic. The interface between these two realms gradually got deeper, but no fundamentally new life-forms emerged, nor did many new mineral species arise.

In sharp contrast to the Boring Billion, the next few 100 million years saw remarkable changes at Earth's surface. About 800 million years ago most of the planet's continents were located in a single grand cluster near the equator, called Rodinia. Then plate tectonic forces broke up this large landmass, resulting in more coastline, greater rainfall and more rapid rock erosion—processes that sucked heat-trapping carbon dioxide from the atmosphere. As the greenhouse effect weakened and the climate cooled, the extent of polar ice grew.

The growing expanses of ice and snow reflected more sunlight back into space, reducing the sun's heating effect. The more the ice spread, the colder things got. For 10 million years or more Earth was a giant snowball, with only a few active volcanoes poking through the white veneer. By some estimates global average temperatures plunged to –50 degrees Celsius.

But Earth could not remain locked in ice forever. Volcanoes continued to belch carbon dioxide, and with no rainfall and little weathering to remove this greenhouse gas, its levels rose ever so slowly to hundreds of times modern levels, ultimately triggering a cycle of greenhouse warming. As equatorial ice melted, the runaway warming episode may have taken only a few hundred years to transform Earth from icebox to hothouse.

For the next 200 million years Earth cycled between these extremes perhaps two to four times. Although apparently few if any fresh mineral species arose during this tumultuous period, the distribution of surface minerals changed drastically with each new glacial cycle. During

RON MILLER (*illustration*); E. R. DEGGINGER *Photo Researchers, Inc.* (*aragonite*); COURTESY OF CHIP CLARK *Smithsonian Institution, National Museum of Natural History* (*trilobite*); COURTESY OF HEXIONG YANG (*hazenite*) the hothouse phases, production of fine-grained clay minerals and other weathering products increased sharply in the barren, eroding, rocky landscape. In shallow areas of the warming oceans, carbonate minerals precipitated in giant crystal fans.

The snowball/hothouse cycles had profound consequences for life. The ice ages shut down almost every ecosystem, whereas the warming periods saw abrupt increases in biological productivity. In particular, at the end of the last big glaciation, atmospheric oxygen rose sharply from no more than a few percent to about 15 percent, produced in part by vigorous and widespread coastal algal blooms. Many biologists suggest that such high levels of oxygen were an essential prelude to the origin and evolution of large animals, with their increased metabolic demands. Indeed, the earliest known multicellular organisms appear in the fossil record just five million years after the last great global glaciation.

The geosphere and biosphere have continued to co-evolve, especially as diverse microbes and animals learned to grow their own protective mineral shells. The innovation of carbonate skeletons led to deposition of massive limestone reefs, which punctuate the world's landscapes in countless cliffs and canyons. Such minerals were not new, but their prevalence was unprecedented.

Green Earth

For almost all of Earth's history, the land was uninhabitable. Ultraviolet radiation from the sun destroys essential biomolecules and kills most cells. With higher levels of atmospheric oxygen, a protective stratospheric ozone layer developed, shielding the land below from ultraviolet rays, enough to harbor a terrestrial biosphere.

Life on land took time to thrive. Algal mats may have lived in swampy terrains following the snowball Earth, but the biggest terrestrial transformation had to await the development of mosses—the first true land plants—about 460 million years ago. Widespread colonization of the land took another 10 million years, with the rise of vascular plants, whose roots penetrate rocky ground to provide an anchor and gather water.

Plants and fungi brought with them rapid modes of biochemical breakdown of rock, increasing weathering rates of surface rocks such as basalt, granite and limestone by an order of magnitude. The abundance of clay minerals and the rate of formation of soils increased vastly, providing an ever expanding habitat for more and larger plants and fungi.

By perhaps 400 million years ago, in the Devonian period, Earth's surface had for the first time evolved to a strikingly modern appearance—green forests thrived, populated with an ever widening cast of insects, tetrapods and other creatures. And thanks to the profound influence of life, Earth's near-surface mineralogy had also achieved its modern state of diversity and distribution.

The Future of Mineral Evolution

The view of Earth's mineralogy as a dynamic, changing story points to some exciting opportunities for research. For example, different planets achieve different stages of mineral evolution. Small, dry worlds like Mercury and the moon possess simple surfaces of low mineral diversity. Small, wet Mars fared a little better. Bigger planets like Earth and Venus, with their greater stores of volatiles and inner heat, can progress further through the formation of granitoids.

But the origin of life, and the resulting co-evolution of biology and minerals, sets Earth apart. As I noted earlier, minerals may be as valuable as organic remains for identifying the signature of life on other worlds. Only those with life would likely be extensively oxidized, for instance.

Worlds with different compositions may also undergo very different mineral evolutions. Jupiter's moon Io, which is rich in sulfur, and Saturn's frigid moon Titan, replete with hydrocarbons, will have quite distinct repertoires of minerals. The same is likely true of Europa and Enceladus (moons of Jupiter and Saturn, respectively), both believed to harbor liquid oceans of water below their icy surfaces and thus to be prime sites for possible extraterrestrial life.

Viewing minerals in an evolutionary context also elucidates a more general theme of evolving systems throughout the cosmos. Simple states evolve into increasingly complicated states in many contexts: the evolution of chemical elements in stars, mineral evolution in planets, the molecular evolution that leads to the origin of life, and the familiar biological evolution through Darwinian natural selection.

Thus, we live in a universe primed for complexification: hydrogen atoms form stars, stars form the elements of the periodic table, those elements form planets, which in turn form minerals abundantly. Minerals catalyze the formation of biomolecules, which on Earth led to life. In this sweeping scenario, minerals represent but one inexorable step in the evolution of a cosmos that is learning to know itself. ■

Minerals may be as valuable as organic remains for identifying the signature of life on other worlds.

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Toxic Gas, Lifesaver

Hydrogen sulfide, a lethal gas best known for smelling like rotten eggs, turns out to play key roles in the body—a finding that could lead to new treatments for heart attack victims and others

By Rui Wang

Imagine walking into a hospital emergency room, with its hand-sanitizer-adorned walls and every surface meticulously scrubbed free of contaminants, only to encounter the stench of rotten eggs. Distasteful though this juxtaposition might sound, the toxic gas synonymous with that smell—hydrogen sulfide (H_2S)—may well become a fixture in such settings in the future. Over the past decade scientists have discovered that H_2S is actually essential to a number of processes in the body, including controlling blood pressure and regulating metabolism. Our findings indicate that if harnessed properly, the gas could, among other benefits, help treat heart attack patients and keep trauma victims alive until they can undergo surgery or receive a blood transfusion.

A Whiff of Poison

Scholars have known about H_2S's toxic effects on humans for centuries. Today it constitutes the number-one occupational safety hazard at oil and gas field wellheads, along pipelines, in processing plants and in refineries. Our noses can detect H_2S at concentrations of 0.0047 part per million (ppm). At 500 ppm, it impairs breathing. Exposure to 800 ppm for five minutes leads to death. Yet, paradoxically, we need H_2S to survive.

To see how the human body came to rely on this malodorous gas, page back some 250 million years to a time when the outlook for life on earth was very grim indeed. The Permian era was drawing to a close, and the single most devastating extinction event of all time was under way. Back then, carbon dioxide emissions from massive volcanic eruptions in Siberia triggered a chain of environmental changes that left oxygen levels dangerously low in the world's oceans and, according to a leading extinction theory, was ultimately responsible for the die-off [see "Impact from the Deep," by Peter Ward; SCIENTIFIC AMERICAN, October 2006].

This shift in ocean chemistry was bad

KEY CONCEPTS

- The body manufactures tiny quantities of the poisonous gas hydrogen sulfide (H_2S).
- Mounting evidence indicates that the gas plays a beneficial role in the health of the cardiovascular system and other parts of the body.
- Based on these findings, researchers are developing H_2S-based therapies for conditions ranging from cardiovascular disease to irritable bowel syndrome.

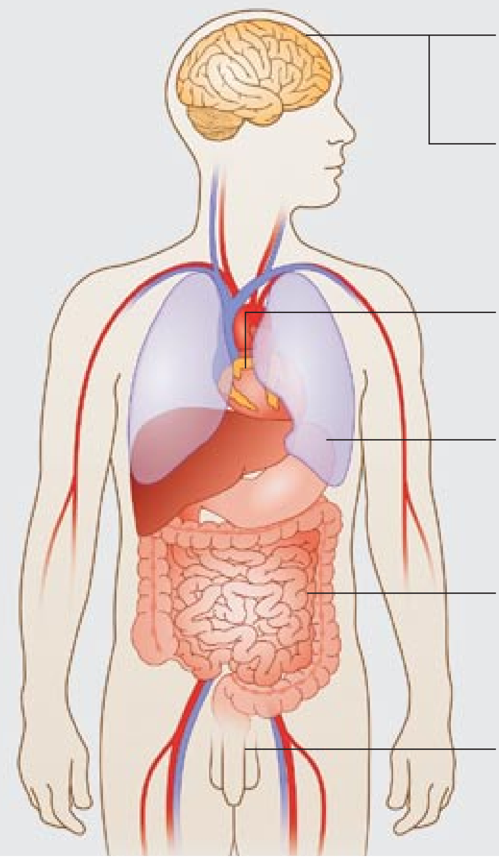
—The Editors

JAMIE CHUNG

[DISCOVERY]

A VITAL VAPOR

Scientists have determined that although hydrogen sulfide (H_2S) is toxic, it is actually made in small amounts in the body and may contribute to health in a number of ways, a representative selection of which is listed below. Not all the effects are beneficial, however: for example, too much H_2S can stymie the production of insulin, and some evidence suggests that it may worsen inflammation.



TAMI TOLPA

news for oxygen-breathing, or aerobic, marine species. But anaerobic organisms known as green sulfur bacteria flourished under the low-oxygen conditions. The success of these bacteria made the ocean even more inhospitable to most of its remaining aerobic inhabitants, because they generated vast quantities of hydrogen sulfide. Eventually, so the theory goes, the lethal gas in the ocean diffused into the air, wiping out plants and animals on land. By the end of the Permian extinction, 95 percent of marine species and 70 percent of terrestrial ones had perished.

The importance of H_2S in human physiological processes is probably a holdover from that long-ago time. The creatures that survived this catastrophe were the ones able to tolerate and, in certain cases, even consume hydrogen sulfide, and we humans have retained some of that affinity for the gas.

Follow Your Nose

Hydrogen sulfide is not the only noxious gas that has been found at work in the human body. In the 1980s researchers began to uncover evidence that nitric oxide (NO), also known as nitrogen monoxide, is made by the body in low concentrations, where it functions as a signaling molecule, influencing cell behavior. In work that would garner the 1998 Nobel Prize in Physiology or Medicine, this nitric oxide was shown to dilate blood vessels, regulate the immune system and transmit signals between neurons, among other functions. And carbon monoxide (CO), a colorless and odorless gas often called "the silent killer," has similar effects.

Having studied CO and NO, I was convinced that the body probably made and used other such gasotransmitters. By 1998 I was constantly brainstorming about what those gases might be. That summer an idea came to me. After a busy workday, I came home to find a stinky smell in the house. I eventually traced the source to a glass cabinet where all my family's treasures were exhibited. The smell was emanating from a cracked and rotten egg, one of many Easter eggs my older daughter had painted as a school project. It was then that I started to wonder whether this rotten-egg gas, hydrogen sulfide, was also produced by our body's organs and tissues.

Because my work on CO and NO had focused on their effects on the cardiovascular system, I decided to begin my search for H_2S there, too. It was a good place to start: a series of experiments revealed significant activity.

The initial tests I conducted with my colleagues quickly revealed small quantities of the gas in the blood vessel walls of rats. Because rodent physiology is very similar to that of humans, the discovery meant human vessels undoubtedly made it as well. This finding was encouraging, but to determine whether H_2S is important to the functioning of the body, we were going to have to demonstrate far more than its mere presence in vascular walls.

The next step was to figure out how the body makes H_2S. We decided to look at an enzyme called cystathionine-gamma-lyase (CSE), which was known to help produce the gas in bacteria. Previous studies had documented the presence of CSE in the liver, where it coordinates the construction of several amino acids, or protein building blocks, that contain sulfur. But no one knew whether CSE existed in blood vessels. Sure enough, we found the enzyme there, where it was combining with an amino acid called L-

Findings suggest that H_2S could be used to prevent or treat hypertension, heart attacks and strokes in humans.

cysteine to produce H_2S and two other compounds, ammonium and pyruvate.

Having established the source of H_2S in blood vessels, we could turn our attention to unraveling its role there. Because NO had been shown to relax the blood vessels, we reasoned that H_2S might serve a similar purpose. Subsequent experiments bore that hunch out: when we soaked rat blood vessels in a H_2S solution, they dilated.

It was starting to look as though H_2S, like NO, was a regulator of blood pressure. The molecular mechanism for this phenomenon was still unknown, however. Hints eventually came from our studies of single cells taken from animal blood vessels. The results, which we published in 2001, proved surprising. Whereas NO relaxes blood vessel walls by activating an enzyme called guanylyl cyclase that resides in smooth muscle cells, H_2S manages the same feat through an entirely different pathway. Specifically, H_2S activates proteins called K_{ATP} channels that control the flow of potassium ions out of smooth muscle cells. This flow generates an electric current that limits the amount of calcium ions that can enter the cells, a constraint that relaxes the muscles and dilates the vessels.

Progressing from the isolated cells to living animals, we injected rats with a H_2S solution and found that their blood pressure dropped—presumably because the gas opened up the arteries, facilitating the flow of blood. We had mounting evidence that H_2S relaxes blood vessels, thus participating in blood pressure control. But we could not be sure that our addition of the gas to the blood vessels was truly replicating what happens when the vessels make their own H_2S.

To better gauge the effects of the gas, in 2003 my colleagues and I developed a line of mice engineered to lack the CSE enzyme and, hence, the ability to make H_2S in the blood vessels. We spent the next five years collaborating with research teams led by Solomon Snyder of Johns Hopkins University and by Lingyun Wu of the University of Saskatchewan in Canada to study these so-called knockout mice. Our efforts paid off, and in 2008 we published a paper in *Science* detailing our findings. As the modified mice aged, their blood vessels contracted, and they developed significantly higher blood pressure than is normal (as measured by tiny blood pressure cuffs fitted around their tails). When we injected the mice with H_2S, however, their blood pressure lessened.

The work with the knockout mice established beyond a doubt that hydrogen sulfide plays a vital role in the cardiovascular system. It also elucidated a longstanding mystery. For years after the Nobel Prize–winning work on NO, investigators had known that not all blood vessel dilation could be attributed to that gasotransmitter. For one thing, in animals genetically engineered to not produce NO in the endothelial cells that line vessel walls, peripheral blood vessels (those that do not lead directly to or from the heart) could still relax. But what could be causing that relaxation in the absence of NO?

Our studies indicate that the mystery factor is likely H_2S. Although we initially showed that the H_2S-generating enzyme CSE occurs in smooth muscle cells, subsequent studies of endothelial cells obtained from mice, cows and humans revealed that they, too, contain CSE—and in even greater quantities than the smooth muscle cells do. Exactly how the vessel-relaxing responsibilities are divided between NO and H_2S remains unclear, although some evidence suggests that NO does most of the work in large vessels and that H_2S takes over in small ones.

A Pound of Cure?

The revelation that H_2S is produced in the cardiovascular system and helps to control blood pressure caught the attention of many other researchers who had been looking for novel ways to protect the heart against damage from oxygen deprivation, as occurs when a clot prevents blood from bringing oxygen to the heart, leading to the death of cardiac tissue (a heart attack). In 2006 Gary F. Baxter, now at the University of Cardiff in Wales, and his colleagues reported that in isolated rat hearts, which were first provided with saline solution to mimic blood supply and then deprived of the saline to mimic a heart attack, administering H_2S to these isolated hearts before halting the saline supply reduced the extent of cardiac muscle damage. And David Lefer of Emory University showed the following year that mice engineered to produce more H_2S in the heart were better able to tolerate oxygen deprivation caused by a clot and more resistant to the damage that often ensues when blood flow is restored to tissues after a period of deprivation (a condition known as reperfusion injury).

Findings such as these suggest that H_2S could be used to prevent or treat hypertension, heart attacks and strokes in humans. But the gas's ability to relax blood vessels means that its potential applications extend to other blood vessel prob-

WHY GARLIC IS GOOD FOR YOU

Studies suggest that garlic can soften blood vessel walls, prevent blood platelets from clumping together and lower blood pressure, thus lowering the risk of heart attack, stroke and kidney disease. Research has also linked eating garlic to improved immune system function and reduced risk of some forms of cancer.

The secret of garlic's apparent health benefits may lie in its relation to H_2S. In 2007 David W. Kraus of the University of Alabama reported that the sulfide-containing compounds found in garlic are converted into H_2S by molecules that occupy the membranes of red blood cells. Furthermore, garlic contains a compound called S-allyl-L-cysteine that boosts the production and circulation of H_2S in the body, according to findings published that same year by Yizhun Zhu of Fudan University in Shanghai and his colleagues.

[THE AUTHOR]

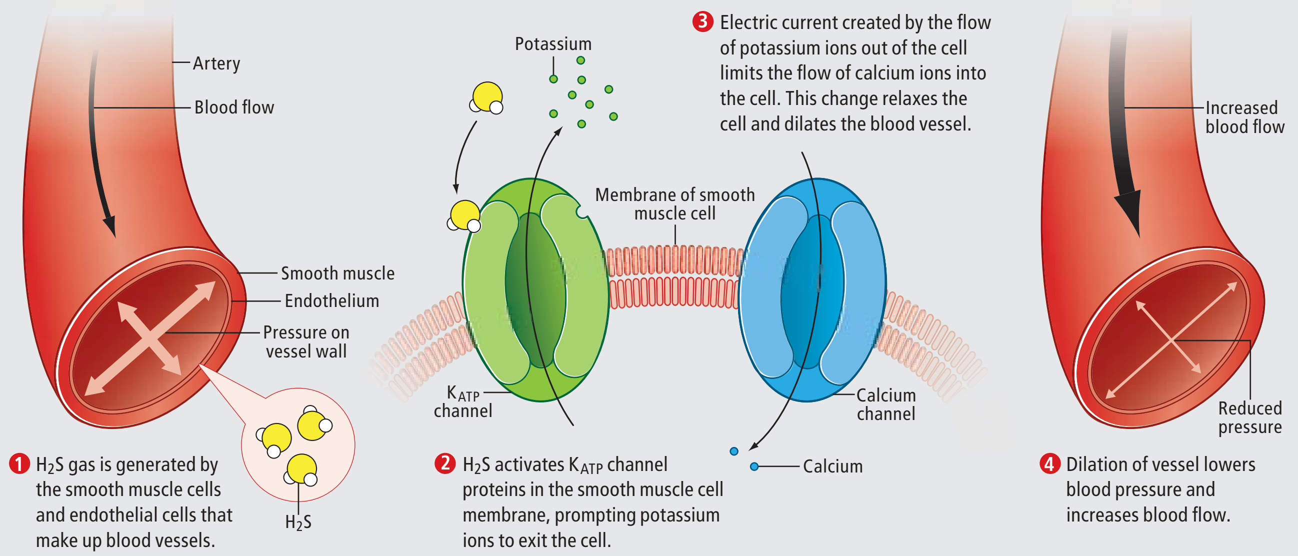
Rui Wang is a professor of biology and vice president of research at Lakehead University in Thunder Bay, Ontario. He is also president of the Canadian Physiological Society and a leader in the study of the metabolism and physiological functions of a group of small molecules of gas known as gasotransmitters, including nitric oxide, carbon monoxide and hydrogen sulfide. In 2008 Wang received the prestigious Pfizer Senior Scientist Award from the Canadian Society of Pharmacology and Therapeutics. He is an avid NBA basketball fan and loves science-fiction movies.

BRAND X PICTURES *Getty Images* (garlic); COURTESY OF RUI WANG (*Wang*)

[HOW H_2S WORKS]

RELAXING GAS

Hydrogen sulfide plays a key role in regulating blood pressure. Earlier studies had shown that another gas, nitric oxide, relaxes blood vessels by activating an enzyme called guanylyl cyclase located in the vessels' smooth muscle cells. Recently scientists have determined that H_2S has the same dilating effect on the vessels, but it acts through a completely different pathway, shown here.



lems, too—including erectile dysfunction. Penile erection is maintained by the dilation of blood vessels. In fact, Viagra works by prolonging the effect of NO in the penis, where the gas acts to relax the vessels, thereby enhancing blood flow. Studies suggest that H_2S could produce the same effect, although more work is needed to determine its exact role in human penile tissue. (CO, too, is produced in the penis, although it facilitates ejaculation, not erection.)

H_2S is not confined to the cardiovascular system. It is also made in the nervous system, though not by CSE but rather an enzyme known as cystathionine beta synthetase. Exactly what the gas does there is uncertain. Some studies suggest that it is a neuromodulator, making neural circuits more or less responsive to stimuli. It may participate in a process called long-term potentiation that facilitates cell communication and may thereby promote learning and memory. In addition, the gas has been shown to increase levels of the antioxidant glutathione in neuronal cells, suggesting that it protects these cells against stress. And it may help the body to sense pain so that it can react accordingly.

Moreover, the gas seems to help regulate metabolism—the chemical processes that manage energy use and synthesis in the body. In a stunning series of experiments, Mark B. Roth of the University of Washington and his colleagues administered low concentrations of H_2S to mice to decrease metabolism and thereby retard the progression of certain diseases. The animals' heart rate instantly dropped by half, sending them into a state of suspended animation in which metabolism slowed so much they were able to get by on an inhaled "diet" of H_2S and oxygen alone without obvious negative effects. During this "H_2S hibernation," it seems, the body maintains a baseline metabolism that protects the vital organs from damage until energy supply levels return to normal. Within 30 minutes of stopping H_2S inhalation, the animals resumed their usual metabolic rate [see "Buying Time in Suspended Animation," by Mark B. Roth and Todd Nystul; SCIENTIFIC AMERICAN, June 2005].

Whether H_2S hibernation can put life on hold while preserving critical brain functions, such as memory and reason, remains to be seen.

If proved to be effective and safe in humans, H_2S hibernation could be a boon for emergency medicine. Inhalation of H_2S at the site of a car accident or by a person experiencing a heart attack could conceivably buy the time needed to successfully transport a patient to the hospital for lifesaving treatment. H_2S could also conceivably keep a patient alive in a suspended state until a needed organ becomes available (the gas might also keep donated organs viable longer). Additionally, war zones and natural disaster zones could benefit from the availability of H_2S therapy, which could ease the demand for blood transfusions until a sufficient blood supply became available. In 2008 Roth and his colleagues reported that rats that inhaled H_2S after losing

TAMI TOLPA

60 percent of their blood fared far better than did rats that did not receive treatment, with only 25 percent of treated rats succumbing to the trauma as compared with 75 percent of the untreated rats.

Cautious Optimism

Yet not everything H_2S touches turns to gold. The jury is still out on whether the gas worsens or alleviates inflammation, for example. And studies in my laboratory and elsewhere suggest that the gas is a key player in type 1 diabetes, the kind that often occurs in childhood and leaves people dependent on insulin injections for survival. H_2S is produced in, among other places, insulin-producing cells in the pancreas called beta cells. In animals with type 1 diabetes, H_2S production is abnormally high in these cells. This surplus of the gas has two ill effects. First, it kills off a large number of beta cells, leaving behind too few to produce the insulin the body requires to break down glucose for energy. Second, it hinders the release of insulin from those remaining beta cells. In other words, H_2S may be partly to blame for the insufficient level of insulin in the blood in cases of type 1 diabetes.

Furthermore, some of the positive effects of H_2S documented in rats and mice have not been replicated in larger mammals. In a 2007 study conducted by a French team, for instance, sheep given the gas did not enter the quasi hibernation state seen in the rodents. And in another study, piglets that received H_2S showed an increase in metabolic rate rather than a decrease.

Neither is it clear whether H_2S hibernation, when it can be induced, impairs brain function. Although laboratory assessments have not detected such malfunctioning in treated animals, brain function changes are rather difficult to detect in experimental animals. It remains to be seen whether H_2S hibernation can put life on hold while preserving critical brain functions, such as memory and reason.

Nevertheless, the great therapeutic potential of H_2S has generated considerable interest in the pharmaceutical industry. Already several companies are developing products aimed at delivering doses of H_2S to the body. For example, CTG Pharma in Italy has generated various compounds that are hybrids of nonsteroidal anti-inflammatory drugs (called NSAIDs) and H_2S. Experiments in animals indicate that these drugs are effective in treating neuronal and gastrointestinal inflammation, erectile dysfunction, heart attack, and pathological changes to the structure of the blood vessels. Meanwhile New Jersey–based Ikaria, co-founded by Roth, recently launched phase II, or efficacy, trials of an injectable form of H_2S for people who have had heart attacks or are undergoing heart or lung surgery.

Despite people's natural inclination to avoid exposure to H_2S, it is clear from the research conducted over the past decade that this gas plays a critical role in the health of the heart and potentially in the brain and other organs. And it probably acts in other capacities that we have yet to identify. These breakthroughs will guide physiologists in developing a new conception of the molecular basis of human health. The ongoing work on hydrogen sulfide is still young, but chances seem good that it will eventually lead to treatments for some diseases whose cures have thus far eluded us. ■

[H_2S-BASED THERAPIES]

H_2S TO THE RESCUE

Drug developers are currently evaluating the potential of H_2S-based compounds for treating a number of conditions.

CONDITION	COMPOUND	COMPANY	STAGE OF DEVELOPMENT
■ Heart surgery ■ Heart attack ■ Kidney injury	**IK-1001**	Ikaria	Phase II efficacy trial Phase II efficacy trial Phase I safety trial
Inflammatory bowel disease	**ATB-429**	Antibes	Phase I safety trial
Acute and chronic joint pain	**ATB-429**	Antibes	Preclinical
Irritable bowel syndrome	**ATB-429**	Antibes	Preclinical
Arthritis	**ACS-15**	CTG Pharma*	Preclinical

**The author will be testing compounds for CTG Pharma.*

YO Getty Images (candles); IMAGE SOURCE Getty Images (pills)

A KEY TO LONGEVITY?

Preliminary work hints that hydrogen sulfide may influence longevity. In experiments with the nematode worm *Caenorhabditis elegans,* Mark B. Roth of the University of Washington and his colleagues found that worms raised in an environment containing a low concentration of the gas in the air lived 70 percent longer than untreated worms. Curiously, H_2S does not appear to have acted via any of the three main pathways known to control longevity in these creatures. The mechanism by which the gas extended the worm life span remains uncertain, but it may regulate a gene called *sir-2* that has been linked to long life in worms and other organisms. The researchers detailed their findings in the *Proceedings of the National Academy of Sciences USA* in 2007.

➥ MORE TO EXPLORE

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WORM CHAR

As Charles Darwin had suspected, earthworms that flee from ground vibrations do so to escape hungry moles—even though sometimes it is humans chasing them

KEY CONCEPTS

- Ground vibrations make certain earthworms race to the surface, a response that is exploited by bait collectors.
- Charles Darwin and others suggested that earthworms interpret the vibrations as a sign that moles are after them and come up to avoid being eaten.
- Experiments have shown that Darwin was correct and that a competing explanation—that earthworms interpret vibrations as rain—was not.

—The Editors

If you happen to be hiking in the right part of Florida at dawn, you might catch the sound of a predator hidden in the vegetation. Surely an alligator must be the source of these calls, you say to yourself. But the sound does not come from an alligator, or a mother bear, or some newly introduced predator from the Amazon. It comes from a human predator—a "worm grunter."

Worm grunters have mastered the art of charming worms out of their burrows so they can be collected and sold as bait. First, the hunters pound a stob, or wooden stake, into the soil, and then they rub the stake with a flat piece of metal called a rooping iron. The vibrations resonate through the ground. In response, hundreds of large earthworms emerge, some as far as 12 meters from the baiter.

Why would earthworms emerge in daylight and expose themselves to a host of potential predators, including baiters? It seems that it would make more sense for earthworms—a top item on the menu of many animals—to go deeper into the ground when they sense vibrations. Until recently, a common explanation among bait collectors held that earthworms interpret vibrations as rain and make haste for the surface to avoid drowning in saturated soil. After all, most of us have seen worms crawl on the pavement after a heavy rain. But I suspected something else was at work.

In the 1800s Charles Darwin heard similar stories in Europe of vibrations driving local earthworms from the ground, and he, too, wondered why the worms emerged. Some observers suggested the worms interpreted vibrations as a sign that hungry moles were after them and that immediate escape was imperative. My own recent studies and experiments put the question to rest and demonstrated in 2008 that the worms' behavior is indeed a response to moles.

Into the Forest

Darwin thought the mole explanation made sense, as he noted in 1881 in his last book, *The Formation of Vegetable Mould through the Action of Worms with Observation of Their Habits*. But when he tried to coax earthworms from the ground with vibrations, he had little success and thus did not get far investigating this strange behavior. But then, Darwin never met Gary and Audrey Revell.

The Revells are among the few professional bait collectors who still make their living by selling worms. Once a year, in April, you can find the couple at the annual worm-grunting festival in Sopchoppy, in Florida's panhandle. The festival celebrates local history and includes live music, food vendors, worm-grunting T-shirts, and the crowning of a worm-grunting queen.

Worm grunting has been handed down for generations in the southeastern U.S. but seems to have reached its peak in the Apalachicola National Forest—just outside Sopchoppy—in the 1960s and 1970s. When the practice began to attract media attention, the National Forest Service became concerned about possible overharvesting of the large earthworms in the area (*Diplocardia mississippiensis*), and it now requires a yearly permit for worm

MERS

By Kenneth Catania

grunting within the forest's boundaries.

The Apalachicola National Forest was the perfect place to test the "mole hypothesis." The area's *Diplocardia* are legendary for their responses to vibrations. Also, many worms found in North America technically are invasive species—introduced from Europe—but *Diplocardia* earthworms are native to the region. This feature means they have coevolved with the local predators, and so their behavior reflects adaptations to their current environment.

I enlisted the Revells' help to observe the worms' response to grunting. As Gary worked the stob and iron and as Audrey collected worms, I carefully marked where each worm emerged with a flag. When the last worm was collected, we were astonished to look back and see the number of markers spread out around Gary. Worms had emerged more than 12 meters from Gary's location.

I also observed the worms after they emerged, and I used geophones (devices for recording ground vibrations) to determine the frequency and magnitude of the vibrations generated by worm grunting at different locations.

The worms came out of the ground fast: if a worm could ever be described as running, I would say this was the time. The rapid early movement was consistent with an escape from an underground danger, followed by a more leisurely pace as they searched for a new place to burrow into the ground several meters away.

After about 10 minutes of crawling, the

BAIT COLLECTOR Audrey Revell

COURTESY OF KENNETH CATANIA

[THE AUTHOR]

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worms began the laborious task of burrowing back into the soil, an endeavor that could take anywhere from 10 minutes to more than an hour. The vast majority made it back unharmed. But some were attacked by ants, some were eaten by snakes, lizards or carnivorous beetles, and a few that emerged in hot, dry weather simply died from desiccation. It was clear that surfacing exacts a cost from the animals and, therefore, that they presumably have a compelling reason to do so.

To test the worm-mole connection more directly, I needed first of all to check that the worms actually are at risk of running into a mole—in this case, an eastern American mole (*Scalopus aquaticus*), the only one that lives in the Florida panhandle. The answer was clear as soon as I arrived at the Apalachicola National Forest: I had not set foot out of my car before I saw the signs of mole tunnels—raised ridges of dirt—crossing the forest's unpaved roads. After driving around for a few days, I marked 39 such road crossings by moles and caught several by waiting for them to make repairs where cars had crushed their tunnels flat. Many of these roads had daily traffic and hard-packed soil, where digging takes considerable effort. But the moles will do all they can to avoid coming out and exposing themselves to danger. Thus, an earthworm that has exited to the soil surface is safe from a nearby foraging mole.

Undercover Predator

I now needed a more quantitative way to measure the overlap between mole and worm habitat. Gary Revell pointed out that bait collectors leave stob holes behind throughout the forest. By locating these holes and measuring the distance to the nearest mole tunnels, I could get a good idea of mole-worm grunter—and thus of mole-worm—overlap. I checked eight different worm-grunting sites and found mole tunnels at every one. The average distance from a stob hole to a mole tunnel was only 20 meters, much shorter than I expected. It turns out the Apalachicola National Forest is full of moles.

How many worms might these moles eat? A single mole I captured in the Apalachicola National Forest ate the equivalent of its body weight in *Diplocardia* (40 grams, or about 20 worms) every day for two weeks. Thus, when given a chance, a mole will eat as much as 15 kilograms of worms a year, or perhaps 7,000 full-size worms. Clearly, earthworms have a strong reason to avoid moles at all costs. Things were looking interesting for Darwin's idea.

If worm grunters are imitating moles, then presumably a digging mole should create soil vibrations similar to a worm grunter's. I was not lucky enough to happen on an eastern mole actively foraging in the Apalachicola National Forest. But eastern moles are also found near my home, in Tennessee. With some patience,

"WORM GRUNTERS" of the southeastern U.S., such as Gary Revell (*shown in both photographs*), charm earthworms (*Diplocardia mississippiensis*) out of the ground using vibrations produced as they grind a flat piece of metal called a rooping iron on a stob, or wooden stake (*left*). The author placed flags wherever worms came to the surface (*right*), up to 12 meters from the stob.

COURTESY OF KENNETH CATANIA (*bottom two*); COURTESY OF DANIEL DUBOIS *Vanderbilt University (Catania)*

EASTERN AMERICAN **mole (*Scalopus aquaticus*) has forelimbs adapted for efficient digging. As it excavates tunnels, it creates vibrations that alert the *Diplocardia* earthworm to its presence. The worms attempt to escape this predator by coming to the surface. But sometimes it is other predators—including bait collectors but also animals such as wood turtles or herring gulls—that mimic the moles' vibrations to fool the worms into coming out.**

COURTESY OF KENNETH CATANIA

geophones and a laptop computer, I was able to record quite a lot of digging from a number of wild, foraging moles and film them as they wreaked havoc on the soil. The moles' vibrations—mainly created as their powerful forelimbs broke networks of grass roots—were actually audible as I stood several meters away. The recordings revealed a peak in the strength of the vibrations at frequencies that overlapped substantially with those made by the worm grunters (between 80 and 200 hertz).

Full Worm Speed

With all these observations in mind, I built meter-wide soil-filled arenas where I could observe, videotape and quantify the mole-earthworm interactions. But before starting these experiments, the Revells and I performed a simpler test. We happened to have a dirt-filled bucket containing dozens of worms, and I had a recently captured a mole. We could not resist putting the two together to see what happened. The mole dug down into the dirt, and within seconds the earthworms came streaming out.

Reactions in the larger, earth-filled arenas were equally dramatic. As the moles dug tunnels in various directions, the worms came spilling out of the soil in an apparent panic. In this much more natural setting, it was clear the worms were escaping from a feared predator as they came out at full (worm) speed. In separate experiments in smaller arenas rigged with speakers, the worms also fled from just the sound of a foraging mole played into the soil. The results made it quite clear: *Diplocardia* earthworms live in fear of moles and flee above ground at their approach. And apparently, to an earthworm in the Apalachicola National Forest, a worm grunter sounds like the mother of all moles.

Could the worms have evolved to escape from the ground when they feel raindrops falling? I tested that alternative explanation with several experiments. The most direct one was to simply wait for thunderstorms with heavy rain and observe the earthworms' response in outdoor arenas. In these cases, only two or three out of 300 earthworms surfaced after about half an hour. This observation fit well with a few previous studies, which found a slow surfacing response after many hours in saturated soil. Worms do not bolt from their burrows in the first minutes of a storm, as one would expect if the response were cued by the rain's vibrations and as occurs during worm grunting—and mole foraging!

So it seems that Darwin was right all along. Worm grunters take advantage of what evolutionary biologist Richard Dawkins has termed the "rare enemy effect." In this scenario, a predator catches its prey by exploiting a response that is usually a good strategy. Because moles are on the hunt day and night, all year long, it makes sense for a worm to flee to the surface when it detects a molelike vibration; the unlucky ones end up on a fishhook—or, sometimes, in the stomach of some other cunning predator. In fact, Dutch biologist and Nobel laureate Nikolaas Tinbergen had previously noted that herring gulls "paddle" the ground to bring up worms. Later, in the mid-1980s, John H. Kaufmann of the University of Florida described how wood turtles stomp on the ground to drive up worms for an easy dinner. Both these investigators concluded that the vibrations were mimicking moles. Kaufmann, a Florida native, even suggested that wood turtles were "grunting" for worms. The idea, though, had never been formally tested, until now.

As I packed up my equipment to leave from my last field trip to Florida, the Revells presented me with a rooping iron that had been in their family for decades. To me, it was a great honor. As I drove out of the forest, I stopped to feed a mole I had collected earlier in the day. I walked into the forest and tried my hand at worm grunting to get the mole some dinner. My new iron worked like a charm, and soon I had more than enough wriggling mole food. I also realized the bitter irony for those unlucky worms. They had fled from my imitation of a mole only to end up as dinner for the real thing. ■

➥ MORE TO EXPLORE

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➥ ON THE WEB

See videos at **www.ScientificAmerican.com/worm-charmers**

CLIMATE CHANGE: A CONTROLLED EXPERIMENT

Scientists have carefully manipulated grasslands and forests to see how precipitation, carbon dioxide and temperature changes affect the biosphere, allowing them to forecast the future

By Stan D. Wullschleger and Maya Strahl

KEY CONCEPTS

- Researchers are altering temperature, carbon dioxide and precipitation levels across plots of forests, grasses and crops to see how plant life responds.
- Warmer temperatures and higher CO_2 concentrations generally result in more leaf growth or crop yield, but these factors can also raise insect infestation and weaken plants' ability to ward off pests and disease.
- Future field experiments that can manipulate all three conditions at once will lead to better models of how long-term climate changes will affect ecosystems worldwide.

—The Editors

Thirty years ago Charles F. Baes, Jr., a chemist at the U.S. Department of Energy's Oak Ridge National Laboratory, wrote that the earth was undergoing a great "uncontrolled experiment," one that would soon reveal the global consequences of rising greenhouse gas concentrations. Today scientists know that deforestation, land use and the burning of fossil fuels are warming our planet. We are less certain, however, about how climate change will alter forests and grasslands, as well as the goods and services these ecosystems provide society.

Much of the climate change news in the mass media comes not from experiments but observations. Scientists monitor Arctic sea ice, glaciers and natural events such as the timing of leaf appearance and inform the public when changes fall outside normal expectations. Recording this kind of information over time is important. But rather than waiting to see how an evolving climate slowly alters the biosphere, climate change biologists are conducting field experiments, often at large scales, to see how ecosystems will respond to more or less precipitation, rising concentrations of carbon dioxide (CO_2) and warming temperatures. Experimental data are key to determining if and to what extent ecosystems will be affected by climate change in 10, 50 or 100 years and how those changes might feed back to further advance change. The results can help separate fact from fiction in the climate debate, which is charged with emotion.

For years researchers investigated how single plants—typically grown for several months inside climate-controlled chambers—responded to varied conditions. Understanding mechanisms at this scale is necessary. But we must also study plants in their proper context: actual ecosystems. Largely unknown to the public, several sizable outdoor experiments involving altered precipitation and CO_2 concentrations have been under way for more than a decade, including those that are described in boxes on the following pages. Temperature experiments have begun as well. Enough data have now been generated to improve models that predict climate and vegetation changes, providing a more accurate picture of how woodlands, prairies and agricultural crops may change in an increasingly warmer world that is subject to different precipitation patterns and blanketed in more CO_2.

Continued on page 82

MONDOLITHIC STUDIOS

PRECIPITATION: TIMING IS EVERYTHING

Issue: Although temperature and CO_2 levels will generally rise worldwide, climate models predict that precipitation increases and decreases will vary much more from place to place in coming decades.

Experiment: Scientists have built a variety of structures to lower or raise the amount of water that reaches plants in grasslands, forests and croplands, as well as the treeless tundra in northern latitudes. Domed canopies or troughs are most often used. The water can be sent off-site or redistributed across a nearby site to test greater precipitation there. Some shelters can be moved or retracted. Barriers or trenches can be built into the soil to prevent surface water from creeping into the study plots and to prevent plant roots from accessing water outside the plots.

Projects such as the Throughfall Displacement Experiment (TDE) near Oak Ridge, Tenn., employ elaborate trough and gutter systems in the understory of a forest to create dry and wet soil conditions (*photograph* and *illustration*). As many as 1,900 troughs may be distributed across zones the size of football fields. Similar designs can be placed between trees that are widely spaced, for example, in piñon-juniper woodlands of New Mexico, where Nathan McDowell of Los Alamos National Laboratory is studying the role of drought and insects in tree mortality.

TROUGHS at the Throughfall Displacement Experiment simulate drought by preventing rainfall from reaching the ground.

Results: On the Konza Prairie, studied by Kansas State University, some grasses have tolerated shifting precipitation patterns better than others. Competition between plants for water could rise in a warming world.

In temperate forests, such as the one being studied by Paul Hanson in his 13-year-long TDE project, mature trees with deep roots have withstood sustained reductions in precipitation. But many saplings and seedlings with shallow roots have died. This experiment has also revealed that trees are harmed more by excessively dry intervals during certain seasons; reduced rainfall during active stem expansion in early spring retarded growth more dramatically than reduced rainfall did at other times. Late-season droughts occurring after trees had stopped growing were of little consequence, as long as soil-water supplies were fully recharged before the subsequent growing season. In contrast, some large trees in the Amazon rain forests of Brazil perished during the fourth year of a drought created by researchers from the Woods Hole Research Center in Massachusetts. Yet saplings and small-diameter trees were less affected. Blocking 60 percent of the rainfall dried deep soils, but surface soils remained fairly moist, the opposite of TDE results. It is clear that complex interactions must be understood before models can faithfully represent climate change effects.

THROUGHFALL DISPLACEMENT EXPERIMENT

COURTESY OF OAK RIDGE NATIONAL LABORATORY (*photograph*); DAVID FIERSTEIN (*illustration*)

[AIR]

CO_2: GREATER GROWTH FOR SOME

Issue: Scientists estimate that the oceans and terrestrial ecosystems soak up at least half of the CO_2 released by burning fossil fuels. Plants do it by using the gas to produce carbohydrates during photosynthesis. But will that conversion continue at higher CO_2 concentrations? And will more CO_2 alter the sugars, carbohydrates and protective compounds in plants, in turn helping or hindering insects and pathogens?

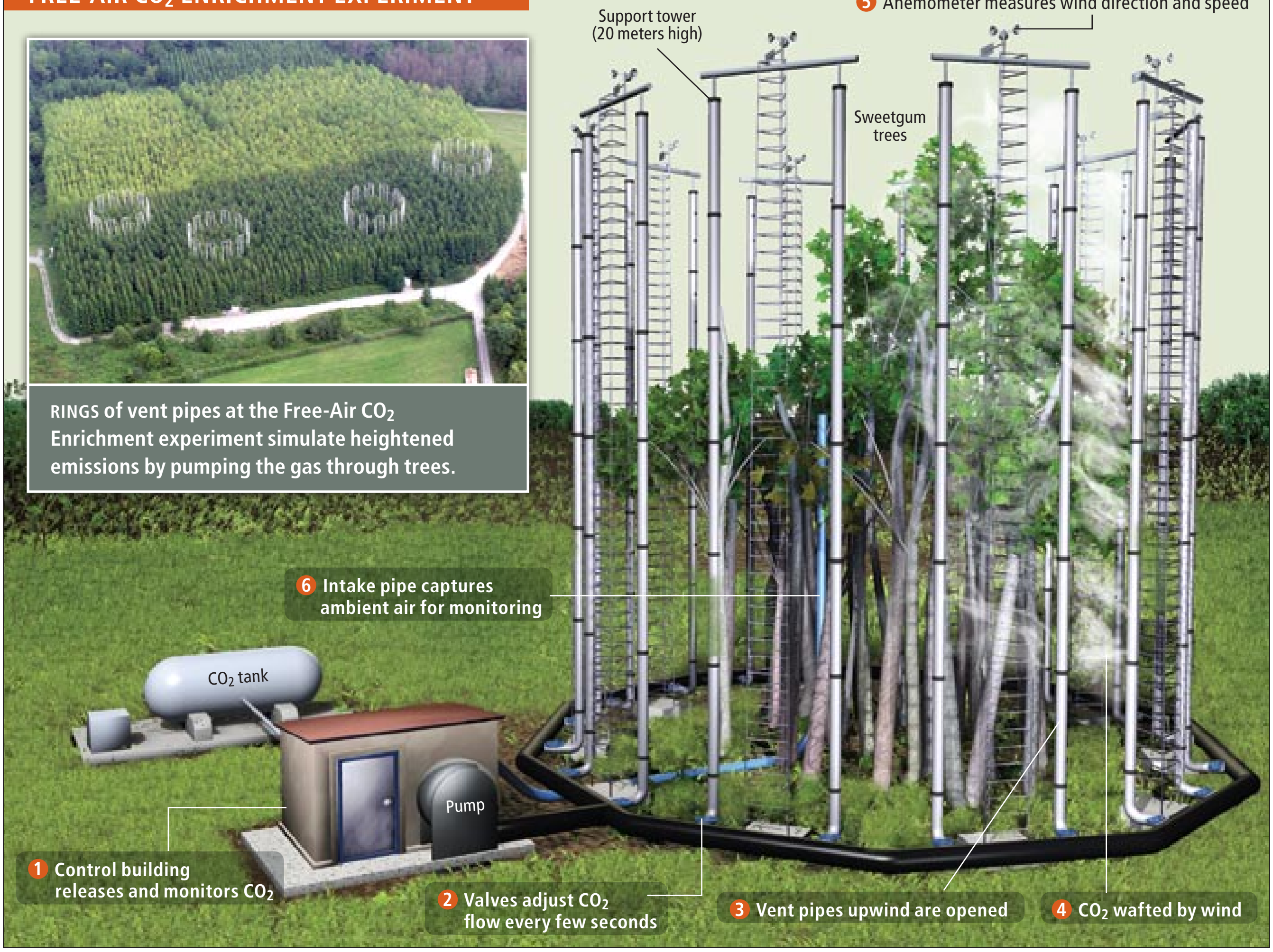
Experiment: The Free-Air CO_2 Enrichment (FACE) experiment has been running at Oak Ridge National Laboratory for more than 10 years, under Richard Norby. It consists of four study areas ringed by vent pipes suspended from towers (*photograph* and *illustration*). The pipes release CO_2 such that the trees all receive a selected amount. Similar FACE experiments operate at almost 35 other natural and managed ecosystems worldwide, ranging from one-meter-diameter plots in bogs, 23-meter plots on croplands and 30-meter plots on forest plantations.

Results: The data confirm that higher CO_2 levels stimulate photosynthesis, which incorporates more carbon into plant tissues. This net primary production (NPP) is also sustained over multiple growing seasons. NPP in forest experiments in Wisconsin, North Carolina, Tennessee and Italy has increased 23 percent annually when CO_2 is raised from the ambient level of 388 parts per million (ppm) to 550 ppm—a level that could arise within 100 years if nations do nothing to curb emissions. Recent modeling results suggest that plants will respond positively to elevated CO_2 levels, although gains may be tempered where soil contains insufficient nutrients such as nitrogen.

Increased NPP has been consistent across the FACE plots worldwide. But NPP indicates only the amount of carbon added to a plant; it does not reflect the long-term fate of that carbon. In the North Carolina loblolly pine forest, the additional carbon was stored primarily in stems and branches, where it might persist for decades. In Tennessee's sweetgum forest, however, the carbon appeared mostly in new, small roots. Such roots are advantageous, of course, but live for only a few weeks to a year; much of the carbon returns to the atmosphere as microbes decompose the roots. Scientists are trying to understand what drives carbon to one destination or another; we will learn more as trees are harvested and soils are excavated in the coming months at various sites.

FACE experiments have already paid off. James Randerson of the University of California, Irvine, and scientists at Oak Ridge, the National Center for Atmospheric Research in Boulder, Colo., and other institutions have used the data to evaluate and improve the Community Climate System Model, which simulates the physical, chemical and biological processes that drive the earth's climate system.

FREE-AIR CO_2 ENRICHMENT EXPERIMENT



RINGS of vent pipes at the Free-Air CO_2 Enrichment experiment simulate heightened emissions by pumping the gas through trees.

COURTESY OF OAK RIDGE NATIONAL LABORATORY (*photograph*); DAVID FIERSTEIN (*illustration*)

[HEAT]

TEMPERATURE: HIGHS AND LOWS

Issue: Future warming will vary by geographic location. By 2100 North America will be 3.8 to 5.9 degrees Celsius warmer in winter and 2.8 to 3.3 degrees C warmer in summer. The changes will affect plant metabolism as well as water and nutrient availability in soil, competition among plants, and the voracity of herbivores, insects and pathogens.

Experiment: Researchers have tried various ways to warm very small plots, including infrared-emitting lamps, electrical heating tapes in the soil and open-top chambers—cylindrical frames wrapped in transparent plastic and fitted with warm-air blowers. These approaches have proved useful but also have drawbacks. Most can heat only a small area, and many have heated only parts of the ecosystem. Heating tapes create unnatural hot spots in soils. Passively warmed chambers depend on time of day and season, and they influence rainfall, wind and sunlight in ways that complicate interpretation of outcomes.

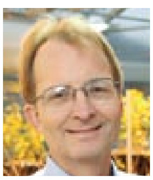
OPEN-TOP CHAMBERS at the Temperature Response and Adjustment Experiment warm saplings and small trees year-round.

Results: Arctic ecosystems and the boreal regions to their immediate south are particularly vulnerable to temperature changes. The International Tundra Experiment, led by Greg Henry of the University of British Columbia, uses passive chambers to warm small plots at more than a dozen sites in various countries. Results thus far show that a one- to three-degree C increase enhances growth and ground cover of deciduous shrubs and grasses as compared with mosses and lichens. This differential response supports the hypothesis that warming will cause a decline in biodiversity across high-latitude ecosystems. A shift from herbaceous to woody vegetation could also raise the energy absorbed by the earth versus that reflected back into space, further increasing global temperature.

Experiments at other latitudes are offering clues about local extinctions, range migrations and altered species composition. At Oak Ridge National Laboratory, Carla Gunderson has exposed four species of deciduous trees to temperatures up to four degrees C above ambient (*photograph* and *illustration*). Seedlings and saplings physiologically adjust, and more often than not they show enhanced growth. Trees produced leaves six to 14 days earlier in the spring, and they retained green leaves later into autumn, lengthening the growing season by up to three weeks. Anecdotal evidence suggests, however, that earlier spring growth might more frequently expose plants to a late, damaging frost.

Despite useful results, it is hard to extrapolate data from small plots to ecosystems. New ways to warm larger areas are needed. Techniques have primarily been powered by electricity, but natural gas or geothermal energy may be better options for remote locations.

[THE AUTHORS]



Stan D. Wullschleger is a climate change biologist and leader of the Plant Systems Biology Group at Oak Ridge National Laboratory in Tennessee. He has conducted experiments exploring the effects of carbon dioxide enrichment, warming and drought on natural forests, plantations and old fields. Currently he is designing and testing warming technology for Arctic tundra and boreal forests. **Maya Strahl** is a plant biologist at Cold Spring Harbor Laboratory in New York and is a former participant in the Higher Education Research Experiences program at Oak Ridge.

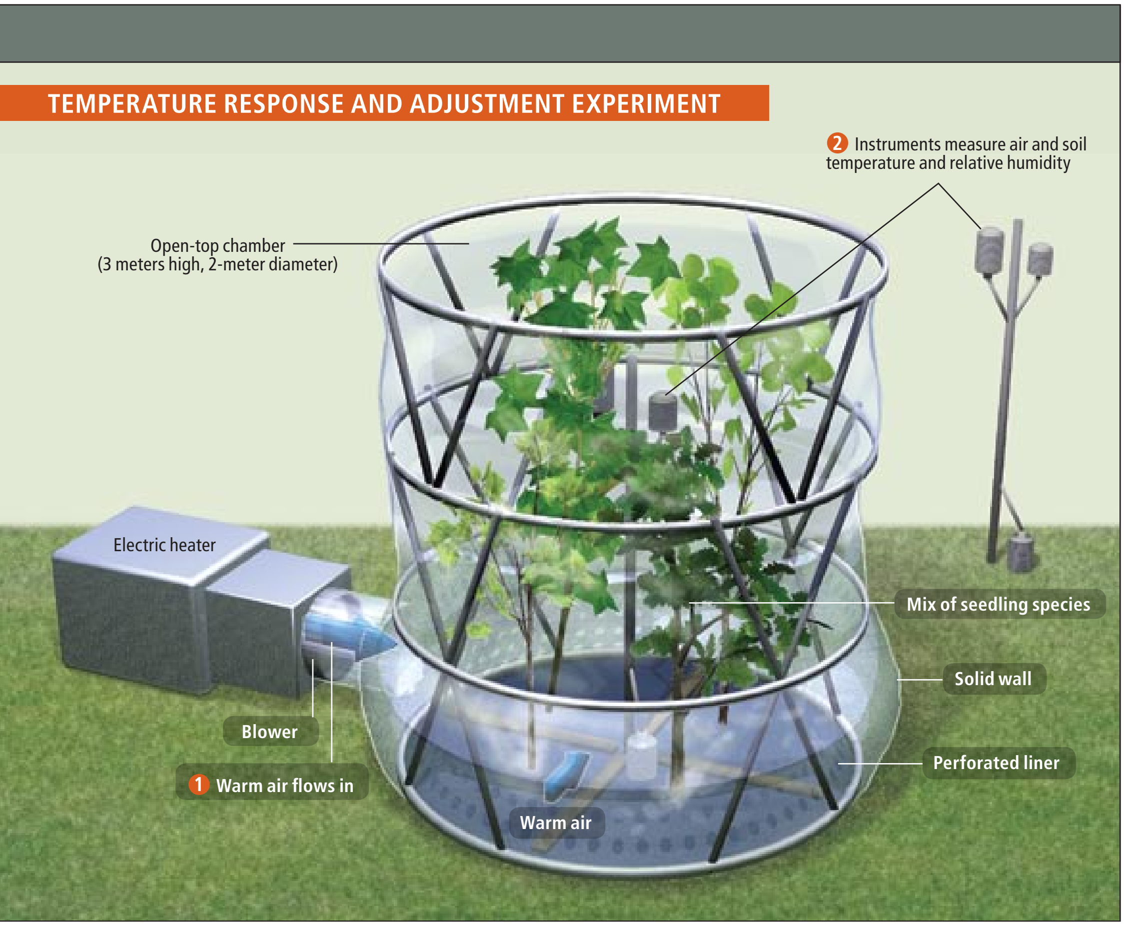
Continued from page 78

Findings around the Globe

Experiments conducted worldwide show that plants and ecosystems possess a remarkable capacity to adjust to new conditions. But scientists expect that thresholds exist beyond which significant and potentially catastrophic responses will occur. As we explore these boundaries, we will find surprises, yet some conclusions informed by field experiment data can already be drawn:

- Higher CO_2 concentrations can enhance yields for commodities such as wheat, rice, barley, soybeans and cotton, but simultaneous warming, and in some locations ozone pollution, may well reduce or negate the "CO_2 fertilization" effect. Climate changes will also alter interactions among crops, weeds, pathogens and insects, with the pests winning out as often as not.
- Deciduous forests in the eastern U.S.—the kind that lose their leaves seasonally—are relatively insensitive to drought. Deep soils hold plenty of water to support the growth of large trees throughout much of the year. But surface soils hold little water and dry out quickly, causing high rates of mortality in young seedlings and small saplings—the forests of the future.
- In a CO_2-enriched atmosphere, greater root growth could provide more nutrients, enhancing the productivity of developing forests. Greater rooting with depth might also benefit plants in arid and dryland ecosystems by increasing access to soil water.
- Global warming and rising CO_2 concentrations could promote the invasiveness of many agricultural weeds, including Canadian thistle, lowering crop yields or demanding more herbicides. Exotic species may also pose problems. For example, recent experiments in the Mojave Desert by Stan Smith of the University of Nevada, Las Vegas, showed that in a year with unusually high rainfall, elevated CO_2 concentration stimulated the spread of *Bromus tectorum*, or cheatgrass, which reduced plant species diversity, modified the food chain and raised the potential for fire.

COURTESY OF OAK RIDGE NATIONAL LABORATORY (*experiment and author photographs*); DAVID FIERSTEIN (*illustration*)



HOW SOYBEANS FARE

SITE: Soybean Free-Air CO_2 Enrichment Facility, University of Illinois at Urbana-Champaign
ELEVATED CO_2: 550 ppm
ELEVATED OZONE: 1.2 times ambient
PLOTS: 20-meter-diameter rings
OUTLOOK: Higher levels of CO_2 and ozone are anticipated by midcentury
RESULTS: Soybean plants grew larger than normal but were more ravaged by Japanese beetles (*below*)

COURTESY OF BRIDGET O'NEILL *Trinity College Dublin (beetles)*

- Although the invasion of woody plants in world grasslands over the past 200 years has resulted mainly from overgrazing and from fire suppression, rising atmospheric CO_2 concentrations may be contributing to the encroachment of trees and shrubs across the western U.S.
- Future CO_2 concentrations will affect plants in ways that could impact public health, including greater production of pollens that trigger allergies and greater growth and toxicity of poison ivy and other invasive species.

Complex Questions

The results of large outdoor experiments are telling, but most investigations have been conducted at middle latitudes and mostly in the U.S. and Europe. New experiments at a wider range of latitudes are needed to clearly predict the response of boreal, tundra and tropical plants and ecosystems. Several years will be needed to prepare such experiments because they are likely to be scientifically complicated and located in remote regions. They will require significant engineering to ensure that altered conditions are imposed uniformly and that the infrastructure is robust enough to last for years.

Biologists must also build installations that not only alter CO_2 concentration, temperature or precipitation patterns, but all three factors in combination. We have so far only scratched the surface. A new experiment near Cheyenne, Wyo., is evaluating how plants in a northern mixed-grass prairie will fare given simultaneous changes in CO_2 concentration and temperature. In the first year of the Prairie Heating and CO_2 Enrichment experiment, Jack Morgan of the U.S. Department of Agriculture's Agricultural Research Service has found indications that warming in combination with higher CO_2 concentration may enhance the abundance of warm-season grasses in the Great Plains, at the expense of cool-season grasses.

How best to manipulate multiple factors and how to account for such combinations, as well as possible feedbacks, in models are complex questions. We will need experimentally derived data very soon if we are to help society anticipate, plan and adapt to a climate that is already changing rapidly. ■

MORE TO EXPLORE

Next Generation of Elevated [CO_2] Experiments with Crops: A Critical Investment for Feeding the Future World. Elizabeth A. Ainsworth et al. in *Plant, Cell and Environment,* Vol. 31, pages 1317–1324; 2008.

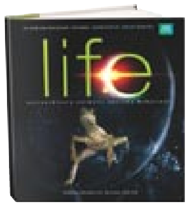
Consequences of More Extreme Precipitation Regimes for Terrestrial Ecosystems. Alan K. Knapp et al. in *BioScience,* Vol. 58, No. 9, pages 811–821; October 2008.

Rising CO_2, Climate Change, and Public Health: Exploring the Links to Plant Biology. Lewis H. Ziska et al. in *Environmental Health Perspectives,* Vol. 117, No. 2, pages 155–158; February 2009.

Amazing Animals ▪ Genghis Khan's Daughters ▪ Immortality

BY KATE WONG

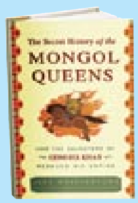
LIFE: EXTRAORDINARY ANIMALS, EXTREME BEHAVIOUR
by Martha Holmes and Michael Gunton. University of California Press, 2010 ($39.95)



From cuttlefish seduction to hyena cooperation, the earth's creatures come to life in the pages of this companion volume to the Discovery Channel/BBC series, premiering in the U.S. in March. Here gelada baboons forage and socialize in the Ethiopian highlands.

EXCERPT

THE SECRET HISTORY OF THE MONGOL QUEENS: HOW THE DAUGHTERS OF GENGHIS KHAN RESCUED HIS EMPIRE
by Jack Weatherford. Crown, 2010 ($26)



Anthropologist Jack Weatherford pieces together the lost history of the ruling women of the Mongol Empire, painting a rich picture of life among the nomadic tribes of the Mongolian Plateau. Here he describes how Genghis Khan's daughters came to power.

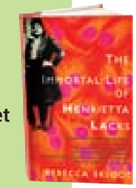
"Genghis Khan was certainly ambitious and had much larger desires in the world than merely uniting the warring tribes of the steppe. Yet, in order to expand his empire, he needed someone to rule the newly conquered people. He had to leave someone in charge. Ideally, he would have had a stable of talented sons and given each one of them a newly conquered country to govern, but his sons were simply not capable. Without competent sons, he could leave a general in charge, but Genghis Khan had been betrayed too many times by men inside and outside his family. He probably knew well the result of Alexander the Great's overreliance on his generals, who subsequently divided the empire among themselves as soon as their leader died. . . .

"Genghis Khan's mother and wives were too old to take command of these new nations and to enjoy the full benefits of what he had to offer, but he had a new generation of women who seemed as capable as the previous one. After uniting the steppe, Genghis Khan turned his attention to foreign nations, and now women assumed a far more important role in building the empire abroad. At least three daughters had been married to closely related clans, and those marriages had helped to solidify bonds within the newly formed Mongol nation; however, now four other daughters faced a far more challenging task beyond the Mongol world, in the lands of neighboring countries. . . ."

ALSO NOTABLE

BOOKS

- **The Science of Liberty: Democracy, Reason, and the Laws of Nature**
  by Timothy Ferris. HarperCollins, 2010 ($26.99)
- **The Edge of Physics: A Journey to Earth's Extremes to Unlock the Secrets of the Universe**
  by Anil Ananthaswamy. Houghton Mifflin Harcourt, 2010 ($25)
- **Piracy: The Intellectual Property Wars from Gutenberg to Gates**
  by Adrian Johns. University of Chicago Press, 2010 ($35)
- **The Immortal Life of Henrietta Lacks**
  by Rebecca Skloot. Crown, 2010 ($26)



- **Manufacturing Depression: The Secret History of a Modern Disease**
  by Gary Greenberg. Simon & Schuster, 2010 ($27)
- **How to Defeat Your Own Clone: And Other Tips for Surviving the Biotech Revolution**
  by Kyle Kurpinski and Terry D. Johnson. Bantam Books, 2010 ($14)
- **March of the Microbes: Sighting the Unseen**
  by John L. Ingraham. Belknap Press, 2010 ($28.95)
- **The Whale: In Search of the Giants of the Sea**
  by Philip Hoare. Ecco Books, 2010 ($27.99)
- **The Double Helix and the Law of Evidence**
  by David H. Kaye. Harvard University Press, 2010 ($45)
- **How to Find a Habitable Planet**
  by James Kasting. Princeton University Press, 2010 ($29.95)

EXHIBITS

- **Mammoths and Mastodons: Titans of the Ice Age**
  March 5 to September 6 at the Field Museum in Chicago.
- **Deeper Than Light**
  February 20 to May 23 at the National Museum of Natural History in Washington, D.C.

MASTODON SKELETON

CHADDEN HUNTER IN *LIFE: EXTRAORDINARY ANIMALS, EXTREME BEHAVIOUR* (*baboons*); JOHN WEINSTEIN, © 2009 THE FIELD MUSEUM (*skeleton*)

Scooting toward Oblivion

People with no actual circus experience still try amazing stunts on our roads

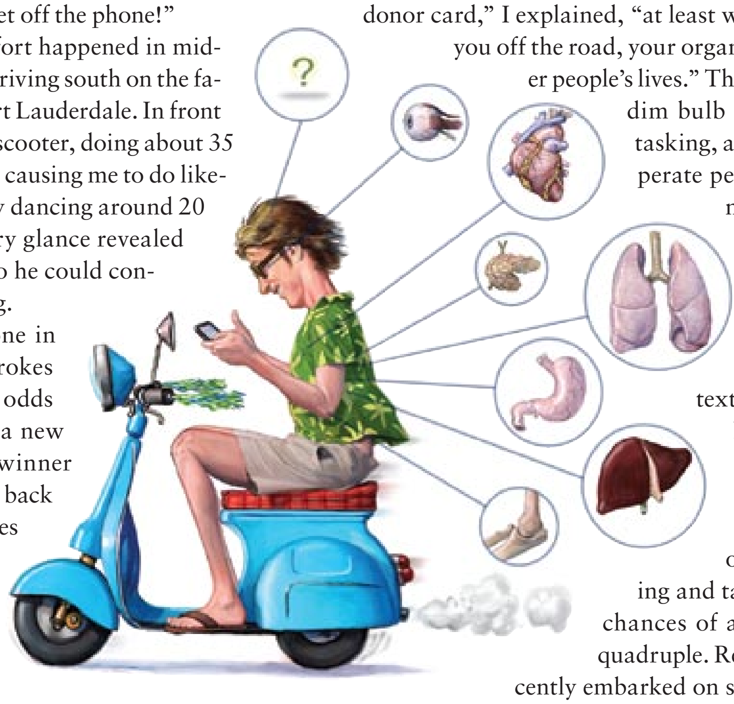
BY STEVE MIRSKY

There's a story about a truck driver who passed the long, lonely hours in his big rig knitting sweaters. His hands thus otherwise occupied, he steered with his knees. A highway patrol officer noted this behavior and set out after the truck driver. As the cop got close, he commanded via his vehicle's loudspeaker, "Pull over." To which the trucker shouted back, "No, it's a cardigan."

Though not a bona fide law-enforcement officer myself, I sometimes act *in loco centurion* while on the road. I do this by sharing safety tips with distracted motorists, such as "Slow down!" or "Pick a lane!" or, my go-to line, "Get off the phone!"

My most recent public safety effort happened in mid-December, in sunny Florida. I was driving south on the fabled A1A, just up the coast from Fort Lauderdale. In front of me was a young man on a motor scooter, doing about 35 miles per hour. Suddenly he slowed, causing me to do likewise. With his speed now erratically dancing around 20 mph, I swung left to pass. A cursory glance revealed that the scooter rider had slowed so he could concentrate on the task at hand: texting.

Scooter boy held his smartphone in both hands and banged out keystrokes with his thumbs, which against all odds were opposable. Wow, I thought, a new champion. My previous all-time winner was a woman in Boston a few years back who had no choice but to use her knees and elbows to more or less guide her vehicle's trajectory along Storrow Drive, because her hands were busy holding the phone and writing notes recording key aspects of the conversation. I had an excellent view of her activities when she got close enough to the car in which I was a passenger for me to gently bang on her window.



But the guy on the scooter couldn't even knee-steer. True, the gyroscopic effect of the scooter's spinning wheels might keep him upright temporarily as he tooled along the roadway, hair flowing in the wind—did I mention that he wore no helmet?—perhaps tweeting to his followers about his derring-do.

As fate would have it, about half a mile later I had to stop for a red light and the scooter, with rider still somehow perched atop it, pulled up to my left. Feeling the necessity to share important public health information with him, I lowered my window and shouted a friendly, "Hey." Seeing that I sought collegial banter, he said, "Huh?" I started to tell him the literally vital news I had, when he said, "Wait." At which point he removed the earbuds that were conveying selections from his smartphone's music library directly to the interior of his helmetless head and drowning out ambient sounds, such as engine noises, car horns and other useful clues to the environment.

"Listen," I began, in vain hope of getting through to a brain that clearly held itself in low regard, "just please sign your organ donor card." He looked at me quizzically. "If you sign your donor card," I explained, "at least when they come to wipe you off the road, your organs might save some other people's lives." The light turned green, the dim bulb returned to his multitasking, and I thought of the desperate people waiting for a kidney, a liver, a heart and sundry other body parts whose prayers might soon be answered, all thanks to me. And, of course, to texting while scootering.

Numerous studies have shown that a sober driver becomes as erratic as an intoxicated one when merely holding and talking on a phone—the chances of an accident more than quadruple. Researchers have only recently embarked on studies of texting's degradation of driving skills, presumably because it never occurred to them that people would be that amazingly daft. Early results indicate that texting is even worse than handheld phone talking. So remember, don't phone and drive, don't fool with the MP3 player and drive, don't drink and text—seriously, your ex really doesn't want to hear from you—and definitely don't text and drive. But if for some unfathomable reason, you absolutely cannot resist the urge to compose short and banal messages instead of paying attention to the road, at least sign your organ donor card. Then upon receiving your remains, transplant surgeons can echo the trucker and say, "It's a card again." ■

PHOTOGRAPH BY FLYNN LARSEN; ILLUSTRATION BY MATT COLLINS