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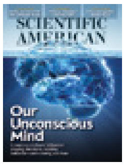
JANUARY 2014

Our Unconscious Mind

It exerts a profound influence: shaping decisions, molding behavior—and running our lives

ON THE COVER



You may think you know why you behave as you do. But, more than you probably realize, the thoughts and emotions that shape your opinions and actions take place below the surface of conscious awareness.

Image by André Kutscherauer.

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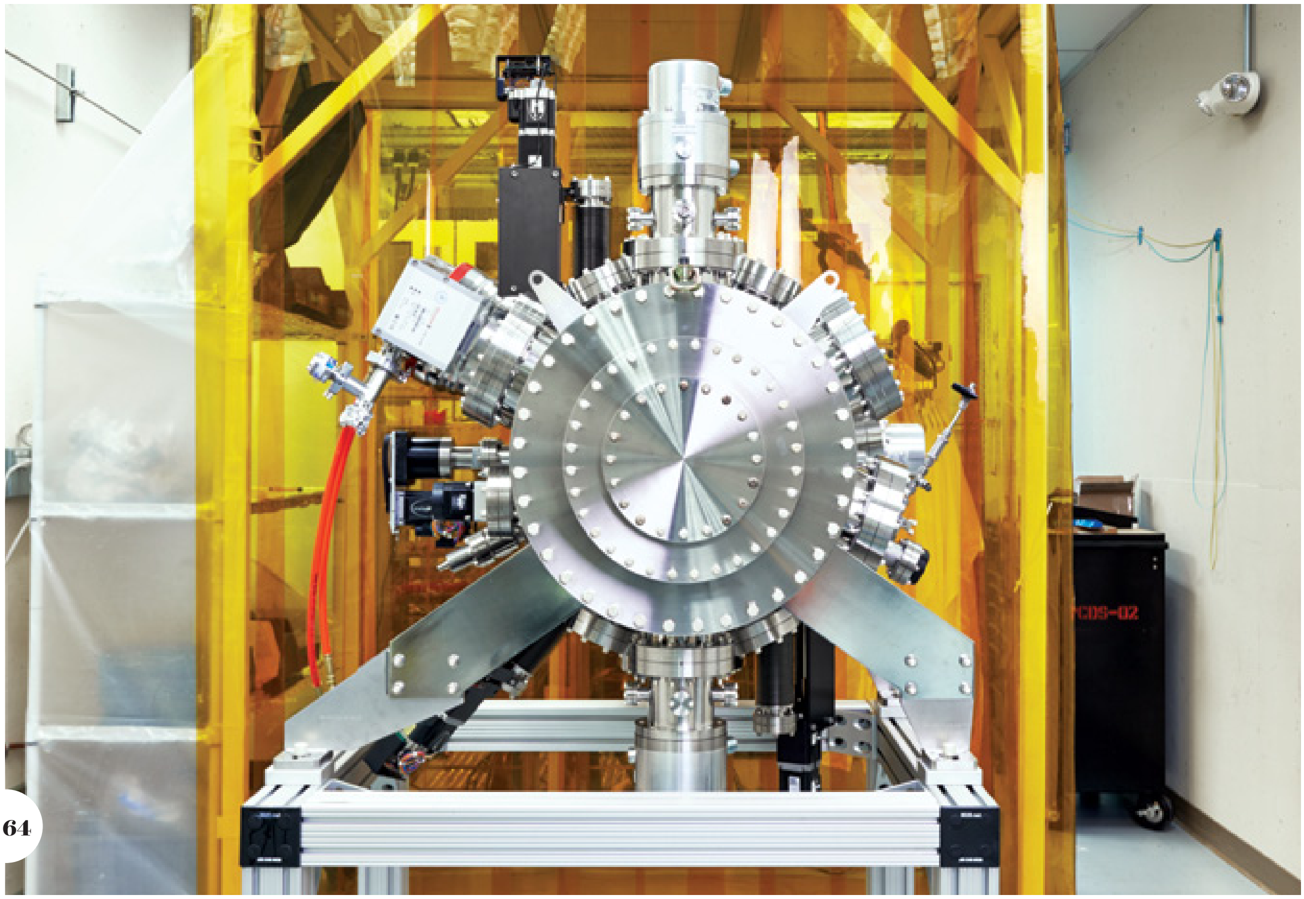

FEATURES

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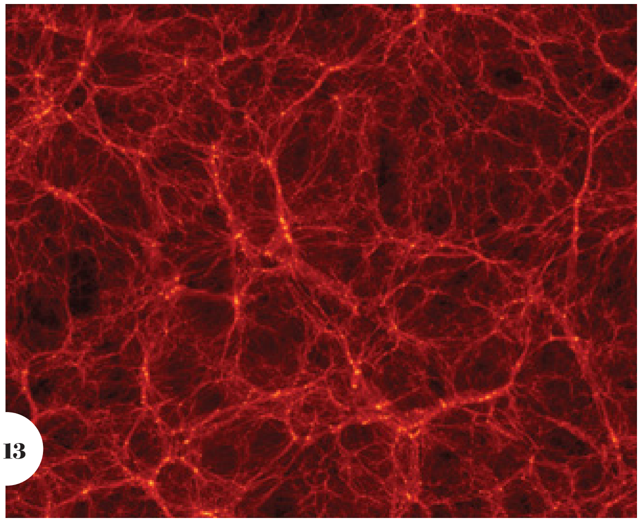

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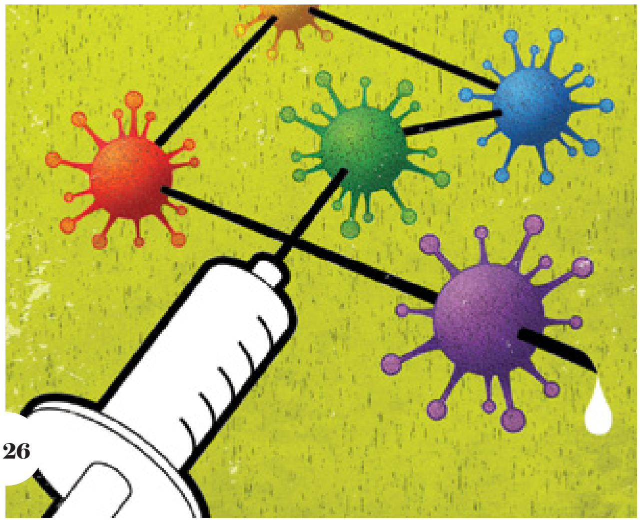

26

78

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DEPARTMENTS

ON THE WEB

How Many Neuroscientists Does It Take…?
At Neuroscience 2013, the latest annual meeting of the Society for Neuroscience, some 30,000 attendees explored the latest research into the mysteries of the mind and brain. Read up on the highlights in our report.
Go to www.ScientificAmerican.com/jan2014/neuro

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Mariette DiChristina is editor in chief of *Scientific American.* Follow her on Twitter @mdichristina

Below the Surface

DRIVING HOME AFTER A VISIT WITH A RELATIVE, YOU suddenly realize you have no specific memory of how you got there. Well, you've taken that trip so many times, you tell yourself, that you could just about do in your sleep. Tying a shoe later, you reflect again on how often you accomplish things while your conscious mind is barely paying attention. Of course, you're not wrong. We all have those moments.

At around three pounds, the gelatinlike tissue in your skull accounts for only a couple of percent of your total body mass, but it consumes a lot of energy—some 20 percent of the calories you eat every day. Conscious thought is "expensive" in energy terms. Is it any wonder the brain tends to shift its more costly processing tasks toward becoming more automated, "cheaper" routines?

That thought struck me during one of our weekly editorial meetings some months ago while we were discussing story ideas. How much of our lives is actually decided for us by our brain without our active awareness, I wondered? Naturally, when I asked that question out loud, longtime *Scientific American* senior editor Gary Stix was only too happy to explore the answer. The outcome is the cover story by Yale University psychologist John A. Bargh, "Our Unconscious Mind," starting on page 30.

Bargh explains how decision making about such tasks as voting, making purchases or even planning vacations often occurs without our giving things much conscious thought. In matters small and large, we routinely arrive at automatic judgments, our behaviors shaped by embedded attitudes. Put another way, awareness about our relative lack of awareness gives us a new appreciation for how profoundly our unconscious mind steers our lives.

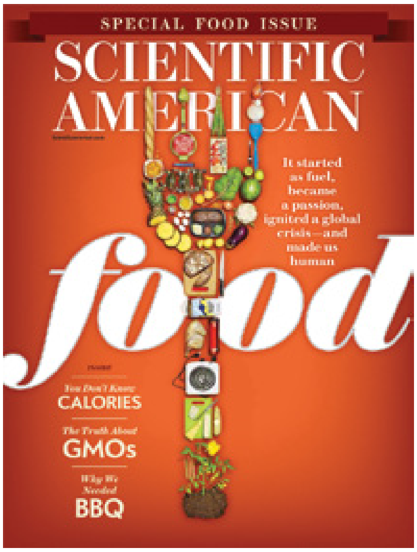
Two other articles take a look below the surface, from different perspectives. "The Ultimate X-ray Machine," by physicists Nora Berrah and Philip H. Bucksbaum, describes a microscope of unprecedented power, which can create exotic forms of matter found nowhere else in the universe. The x-ray laser, powered by the world's longest linear accelerator, subjects atoms, molecules and solids to high-intensity x-ray pulses. The resulting exotic states of matter last only a few femtoseconds—but nonetheless give us useful glimpses of an extreme environment that has no parallels on earth. Turn to page 64.

Beginning on page 58, in "Life under the Lens," by *Scientific American* associate editor Ferris Jabr, we take a microscopic look at the surprisingly intricate minuscule creatures that inhabit our planet, as well as the tiniest features of larger organisms. The photography reveals startling details, from the internal symmetry of a lily bud to a dinosaur bone that has transformed into sparkling crystal. We hope you will enjoy using some of your conscious mind's bandwidth to contemplate the many wonders brought to light by the process of science. SA

Illustration by Nick Higgins

editors@sciam.com

> **“A tentative start in GMO labeling is better than keeping more than 300 million consumers in the dark.”**
>
> ASHOK VASUDEVAN
> *PREFERRED BRANDS INTERNATIONAL*



September 2013

HEALTH AND FOOD

In “Which One Will Make You Fat?” Gary Taubes argues that avoiding carbohydrates, rather than an excess of calories, will lead to weight loss. The right nutrition question instead should be “What should we eat to have the longest, healthiest life?”

There are many ways to lose weight and still become sick and die. I know this firsthand after losing 25 pounds and then suffering a cardiac arrest. And many dieters die of heart disease after losing weight with a high-fat, low-carbohydrate diet.

My reading of the research leads me to conclude that a whole-food, plant-based diet low in fat and high in carbs reduces disease and, as a nice side effect, weight.

John Tanner
Monrovia, Calif.

GENETICALLY UNMOLLIFED

In “Fight the GM Food Scare” [Science Agenda], the editors tell readers not to be alarmed by the unproved dangers of genetically modified foods and argue that labels identifying such food should not be required by law because such labeling would increase fears and lead to an elimination of such foods in the marketplace.

Although genetically modified foods have not been proved to be dangerous, that is not the same as being proved safe. The drug thalidomide (which was later found to cause birth defects) was not proved to be dangerous when it was released. Neither was partially hydrogenated oil (which raises “bad cholesterol”) or high fructose corn syrup (a major component of the obesity epidemic in the U.S.).

Genetically modified foods represent a long-term experiment. Should you wish to partake in that study, I have no quarrel. But to say that *everyone* should become unwilling participants is disingenuous.

Eric Armstrong
Mountain View, Calif.

The editors make a weak argument against labeling genetically modified organisms (GMOs) and a strong one in support of genetic crops. The premise that if you support genetic research, you must oppose labeling is simplistic. Supporting GMO labeling need not mean opposing genetic research. This is akin to opposing traffic lights because you believe in safe driving! Eventually both sides will win. Genetic manipulation seems embedded in our evolutionary gene, and the future will likely be filled with GMOs as science improves and corporations become more responsible. Equally, GMO labeling will evolve as consumers become more aware and governments more responsive.

For now, a tentative start in GMO labeling is better than keeping more than 300 million consumers in the dark. We should embrace knowledge sharing and not shun it based on unfounded fears.

Ashok Vasudevan
CEO, Preferred Brands International

The GMO path is not as clear-cut as “Are Engineered Foods Evil?” by David H. Freedman, suggests in arguing for expanded GMO deployment and safety testing. GMO seeds have been used commercially only since 1994, perhaps not long enough to determine any lasting effects. There is reason to suspect that GMOs *may* be responsible for the sharp increase in the past two decades of celiac disease, irritable bowel syndrome and inflammatory bowel diseases such as Crohn’s.

Holly Bittinger
Chicago

Both the editors and Freedman focus on safety but omit the issues of genetic diversity and control of intellectual property.

We need to restore the genetic diversity that we had prior to the pervasive industrial monoculture farming we h≈ave now. This standardization has made our food system more dependent on energy sources and more vulnerable to disease and climate change. The one-size-fits-all GM crops we have seen so far continue the low-diversity approach.

GM techniques can in theory help with increasing crop diversity. But the objective so far seems to be corporate ownership of genetic codes and reducing the options that farmers and consumers have.

We should write laws to govern the genetic engineering of organisms that benefit everyone, not just vested interests.

Mark Mezger
via e-mail

GMOs often contain trans-species genes that code for proteins no other food plants contain. There have been very few actual studies of the toxicity of these proteins in humans. Bt is a bacterium, and the protein its gene codes for has been linked to an increase of certain antibodies and cytokines in rodents.

Bruce Hlodnicki
via e-mail

THE EDITORS REPLY: Regarding Hlodnicki’s letter, Bt toxins are, in fact, some of the safest pesticides ever used. Many studies—including experiments by researchers with no ties to the biotech industry and at least two long-term studies—have concluded that Bt toxins rarely harm insects other than targeted pests and do not hurt fish or people and other mammals. In one study from the 1950s, people ate large amounts of Bt with no ill effects. To learn

more, see www.ScientificAmerican.com/article.cfm?id=farming-a-toxin.

MAMMOTH UNDERTAKING

George Church neglects the most important reason to clone the woolly mammoth in his arguments in favor of doing so in "Please Reanimate" [Forum]: it would be an incredibly inspirational scientific moment; our generation's moon landing.

In the 1950s and 1960s physics was the premier science; today it is biology, and this would be its pinnacle achievement. Furthermore, unlike the moon landing, it would surely be an international achievement and so would have an even stronger unifying effect.

Carter Edman
via e-mail

The mammoths and other megafauna of the late Pleistocene made the Arctic a far more productive ecosystem than it has been since the time of their extinction. Those who object to the idea of reanimation seem not to be aware that North America has had a drastically impoverished fauna in the past 13,000 years and that impoverished fauna are less productive and resilient.

Unlike Church, I would like to see mammoths re-created as close as possible to the way they were, and I want the rest of the megafauna as well—the glyptodonts, the ground sloths, the extinct great cats.

Tim Cliffe
Emmitsburg, Md.

BACTERIA BOOSTER

I agree that "enlisting bacteria and fungi from the soil to support crop plants is a promising alternative to the heavy use of fertilizer and pesticides," as reported by Richard Coniff in "Super Dirt."

Those of us who are proposing the use of biochar, a carbon-rich soil additive that is created by decomposing biomass with heat and limited air, find that it can increase the effectiveness of this approach. Biochar serves as a host for bacteria and fungi and increases their availability to plants. This technique was practiced several centuries ago by the natives of the Amazon, leading to a thriving economy.

Richard S. Stein
Amherst, Mass.

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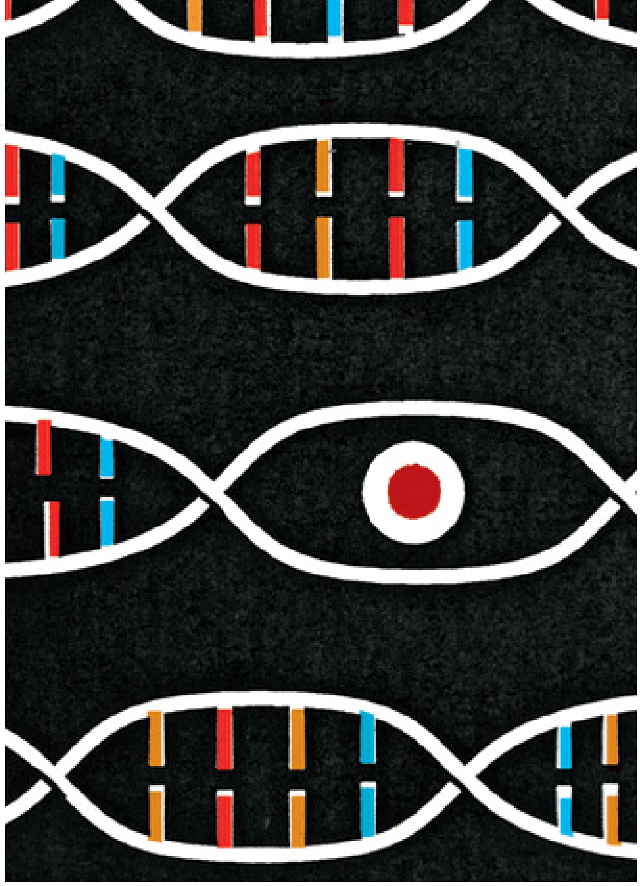

Beware the Eye Spies

Without explicit safeguards, your personal biometric data are destined for a government database

Security through biology is an enticing idea. Since 2011, police departments across the U.S. have been scanning biometric data in the field using devices such as the Mobile Offender Recognition and Information System (MORIS), an iPhone attachment that checks fingerprints and iris scans. The FBI is currently building its Next Generation Identification database, which will contain fingerprints, palm prints, iris scans, voice data and photographs of faces. Before long, even your cell phone will be secured by information that resides in a distant biometric database.

Unfortunately, this shift to biometric-enabled security creates profound threats to commonly accepted notions of privacy and security. It makes possible privacy violations that would make the National Security Agency's data sweeps seem superficial by comparison.

Biometrics could turn existing surveillance systems into something categorically new—something more powerful and much more invasive. Consider the so-called Domain Awareness System, a network of 3,000 surveillance cameras in New York City. Currently if someone commits a crime, cops can go back and review sections of video. Equip the system with facial-recognition technology, however, and the people behind the controls can actively track you throughout your daily life. "A person who lives and works in lower Manhattan would be under constant surveillance," says Jennifer Lynch, an attorney at the Electronic Frontier Foundation, a nonprofit group. Face-in-a-crowd detection is a formidable technical problem, but researchers working on projects such as the Department of Homeland Security's Biometric Optical Surveillance System (BOSS) are making rapid progress.

In addition, once your face, iris or DNA profile becomes a digital file, that file will be difficult to protect. As the recent NSA revelations have made clear, the boundary between commercial and government data is porous at best. Biometric identifiers could also be stolen. It's easy to replace a swiped credit card, but good luck changing the patterns on your iris.

These days gathering biometric data generally requires the cooperation (or coercion) of the subject: for your iris to get into a database, you have to let someone take a close-up photograph of your eyeball. That will not be the case for long. Department of Defense–funded researchers at Carnegie Mellon University are perfecting a camera that can take rapid-fire, database-quality iris scans of every person in a crowd from a distance of 10 meters.

New technologies will also make it possible to extract far more information from the biometrics we are already collecting. While most law-enforcement DNA databases contain only snippets of the genome, agencies can keep the physical DNA samples in perpetuity, raising the question of what future genetic-analysis tools will be able to discern. "Once you have somebody's DNA, you have all sorts of very personal info," Lynch says. "There is a lot of fear that people are going to start testing samples to look for a link between genes and propensity for crime."

Current law is not even remotely prepared to handle these developments. The legal status of most types of biometric data is unclear. No court has addressed whether law enforcement can collect biometric data without a person's knowledge, and case law says nothing about facial recognition.

It is unfortunate that the only body capable of enacting broad and lasting protections against the misuse of biometric data is the U.S. Congress. Yet perhaps legislators can agree that the law needs to catch up with technology. If so, they should start with principles that Lynch and the Electronic Frontier Foundation have proposed. Among other things, such legislation should limit the amount and type of data that the government can store and where they can be stored. It should restrict the collation of different types of biometric data into a single database. And it should certainly require that all biometric data be stored in the most secure manner possible.

Identity theft, fraud and terrorism are real problems. Used properly, biometrics could help protect against them. But the potential for misuse is glaringly obvious. We must begin setting rules to govern the use of these technologies now. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/jan2014

Illustration by Oliver Munday

Commentary on science in the news from the experts

Saleem H. Ali is director of the Center for Social Responsibility in Mining at the University of Queensland in Australia and founding director of the Institute for Environmental Diplomacy and Security at the University of Vermont. He can be followed on Twitter @saleem_ali

Magic Metals

A supply of clean, affordable energy depends on little-known substances

There's one problem with the silicon age: its magic depends on elements that are far scarcer than beach sand. Some aren't merely in limited supply: many people have never even heard of them. And yet those elements have become essential to the green economy. Alien-sounding elements such as yttrium, neodymium, europium, terbium and dysprosium are key components of energy-saving lights, powerful permanent magnets and other technologies. And then there are gallium, indium and tellurium, which create the thin-film photovoltaics needed in solar panels. The U.S. Department of Energy now counts those first five elements as "critical materials" crucial to new technology but whose supply is at risk of disruption. The department's experts are closely monitoring global production of the last three and likewise the lithium that provides batteries for pocket flashlights and hybrid cars.

Earlier this year the DOE took a major step by launching the Critical Materials Institute, a $120-million program to avert a supply shortage. Led by the Ames Laboratory in Iowa, with backing from 17 other government laboratories, universities and industry partners, the institute represents a welcome investment in new research. Unfortunately—like the original Manhattan Project—the program is driven more by the threat of international conflict than by ideals of scientific cooperation. The appropriation made it through Congress almost certainly because of legislators' fear of China's dominance in many critical elements and Bolivia's ambition to become "the Saudi Arabia of lithium."

The worries are probably inevitable. China—historically a prickly partner at best to the U.S.—effectively has much of the world's critical-materials market at its mercy. Take the rare earth elements neodymium, europium, terbium and dysprosium. Despite their name, rare earths are many times more common than gold or platinum and can be found in deposits around the world. In recent years, however, cheap labor and lax environmental regulation have enabled China to corner the global market, mining and refining well over 90 percent of rare earths.

At the same time, China has consistently fallen short of its own production quotas. In 2012 the U.S., the European Union and Japan, suspecting China was manipulating the market, filed a formal complaint with the World Trade Organization (WTO). China argues that production cutbacks were necessary for environmental cleanup. At press time, a preliminary ruling in October 2013 against China will likely be appealed. Meanwhile Japan has announced discovery of vast undersea deposits of rare earths, and the Americans, among others, are working to restart their own disused facilities. The shortages won't last.

Bolivia's lithium is a different story. The impoverished, landlocked country needs no artificial shortages to boost the market. As the lightest metal, lithium has unmatched ability to form compounds that can store electricity in a minimal weight and volume. At least half the world's known reserves are located in a relatively small stretch of the Andes Mountains, where Bolivia and Argentina share a border with Chile.

There's more at stake here than fancy gadgets for the rich. The point of critical materials is to use energy more efficiently. One fifth of the world still lives without access to clean, affordable electricity, a problem that unimpeded supplies of rare earths and lithium could eventually remedy. The hard part will be to prevent old international feuds from getting in the way of that goal. The U.S. can help by embracing the spirit of international development and cooperation. A start could be with the U.S. National Science Foundation, which already maintains an active office in Beijing. We need more such channels to encourage collaborative research on rare earths. Similarly, the strained relations between Washington and La Paz could benefit from signs of sincere U.S. willingness to assist Bolivia in developing the Uyuni salt flats, where a pilot processing plant began operating early in 2013.

Similar modest gestures could bring the world closer to a full-scale treaty on global mineral-supply security. A foundation of sorts has already been laid by efforts such as the Minamata Convention on Mercury, the recently adopted international pact to reduce emissions and use of the toxic metal. Humanity's health and prosperity depend on the wise harnessing of natural resources. Narrow national interests and rivalries can only obstruct that process, ultimately leaving us all just that much poorer. The need for critical materials should catalyze international cooperation. After all, those materials can enlighten the world—literally. SA

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Illustration by Ross MacDonald

PHYSICS

Cosmic Dragnet

The search for dark matter is starting to go cold

Since the 1980s physicists have deployed a string of increasingly advanced detectors in pursuit of something that ought to be ubiquitous but has proved devilishly hard to capture. Dark matter, the invisible stuff thought to make up a quarter of the universe, has yet to show in even the most sophisticated experiments.

Another blow befell the search last October, when the world's most sensitive detector of WIMPs (weakly interacting massive particles) came up empty. Dark matter may well be a WIMP, a ghostly particle that would interact with normal matter very infrequently, which is why at least 15 experiments around the globe are looking for the particles. But if those campaigns fail to hit particle pay dirt in the next few years, scientists may have to refocus the search and embrace alternative explanations for dark matter—some of which are less than appealing.

South Dakota's Large Underground Xenon (LUX) detector was the latest to take an unsuccessful swipe at WIMPs. Although WIMPs are elusive, occasionally one of the particles should collide with an atom inside LUX's 370-kilogram vat of liquid xenon, producing a detectable light signature. The researchers have seen nothing of the kind after three months, ruling out some possible characteristics for WIMPs, such as certain masses for the particles. By now more than half of the possible kinds of WIMPs that had been predicted have been eliminated, says LUX co-spokesperson Richard Gaitskell of Brown University.

The hopes of detecting dark matter are clouded by the possibility that it might not be a WIMP. Another candidate particle, the axion, would be much lighter than a WIMP and therefore more difficult to spot. "You don't hear about axions as much because it has proved somewhat harder to detect them," says Stanford University physicist Peter Graham. Only one large-scale project is currently on the case.

An even thornier possibility is that dark matter only interacts with normal matter via gravity, meaning that snagging dark matter in a particle detector may be forever beyond our grasp. "That's the most pessimistic possibility, which we all hope it isn't," Graham says. —*Clara Moskowitz*

DARK MATTER filaments form the backbone of cosmic structure in a computer simulation of the universe's evolution.

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NEUROSCIENCE

Taking the Hit

The humble fruit fly may help unravel the neural underpinnings of brain injuries

Forty years ago geneticist Barry Ganetzky accidentally knocked out a batch of laboratory fruit flies by snapping a vial against his hand. “All the flies were on the bottom of the vial, not walking, totally uncoordinated, just lying on their sides,” he recalls.

He did not give it much thought at the time, but as the devastating effects of head injuries in professional athletes have come to light, Ganetzky has realized that concussed *Drosophila* fruit flies might be scientifically useful. He and his colleagues at the University of Wisconsin–Madison have begun to explore how fruit flies could help uncover the cellular mechanisms behind traumatic brain injury (TBI) in humans.

Despite decades of study, TBI remains poorly understood. What is known is that injuries are caused by a rapid acceleration or deceleration—such as a car crash or a hard football hit—that sloshes the brain against the inner wall of the skull. The impact can trigger a cascade of cellular reactions that further damage the brain and neurons, potentially leading to long-term cognitive impairments.

Fruit flies may enable larger, more robust studies of TBI. Besides being inexpensive to maintain, *Drosophila* flies have short lives, which allows researchers to track health outcomes over an animal’s entire life span. The insects have already found use in investigations of Alzheimer’s and Parkinson’s. “A neuron inside a fly head is, in principle, the same as a neuron inside a human head,” Ganetzky says. Similar to the human brain, the fly brain, which is about the size of a grain of sand, is encased in the hard shell of its exoskeleton and cushioned by a layer of fluid that allows the brain to slosh around on impact.

In a recent investigation, Ganetzky and his colleagues loaded fruit flies into a vial, then smacked the vial against a padded surface. The researchers later performed autopsies on the concussed insects. The results of the study, published last October in the *Proceedings of the National Academy of Sciences USA,* showed that the flies suffered brain damage and developed many of the same symptoms seen in humans with TBI, including loss of consciousness and coordination and an increased risk of death. As in humans, the ill effects of TBI appeared to depend on the severity of impact, as well as the individual’s age and genetic makeup.

Ganetzky’s team hopes that fly studies will one day lead to a test that diagnoses TBI via biomarkers in the blood and, potentially, a treatment that prevents the deterioration of brain cells.

“Flies are a simple, fast way of getting at the pathways that are involved in TBI,” says Leo Pallanck, who studies neurodegenerative diseases in fruit flies at the University of Washington. “We hope that will lead to treatments and preventive therapies.” —*Sarah Fecht*

DARWIN DALE *Science Source*

FURTHER READINGS AND CITATIONS ScientificAmerican.com/jan2014/advances

IMPORTANT FACTS

VIAGRA® (vi-AG-rah)
(sildenafil citrate) tablets

IMPORTANT SAFETY INFORMATION ABOUT VIAGRA

Never take VIAGRA if you take any medicines with nitrates. This includes nitroglycerin. Your blood pressure could drop quickly. It could fall to an unsafe or life-threatening level.

ABOUT ERECTILE DYSFUNCTION (ED)

Erectile dysfunction means a man cannot get or keep an erection. Health problems, injury, or side effects of drugs may cause ED. The cause may not be known.

ABOUT VIAGRA

VIAGRA is used to treat ED in men. When you want to have sex, VIAGRA can help you get and keep an erection when you are sexually excited. You cannot get an erection just by taking the pill. Only your doctor can prescribe VIAGRA.

VIAGRA does not cure ED.

VIAGRA does not protect you or your partner from STDs (sexually transmitted diseases) or HIV. You will need to use a condom.

VIAGRA is not a hormone or an aphrodisiac.

WHO IS VIAGRA FOR?

Who should take VIAGRA?

Men who have ED and whose heart is healthy enough for sex.

Who should NOT take VIAGRA?

- If you ever take medicines with nitrates:
  - Medicines that treat chest pain (angina), such as nitroglycerin or isosorbide mononitrate or dinitrate
- If you use some street drugs, such as "poppers" (amyl nitrate or nitrite)
- If you are allergic to anything in the VIAGRA tablet

BEFORE YOU START VIAGRA

Tell your doctor if you have or ever had:

- Heart attack, abnormal heartbeats, or stroke
- Heart problems, such as heart failure, chest pain, angina, or aortic valve narrowing
- Low or high blood pressure
- Severe vision loss
- An eye condition called retinitis pigmentosa
- Kidney or liver problems
- Blood problems, such as sickle cell anemia or leukemia
- A deformed penis, Peyronie's disease, or an erection that lasted more than 4 hours
- Stomach ulcers or any kind of bleeding problems

Tell your doctor about all your medicines. Include over-the-counter medicines, vitamins, and herbal products. Tell your doctor if you take or use:

- Medicines called alpha-blockers to treat high blood pressure or prostate problems. Your blood pressure could suddenly get too low. You could get dizzy or faint. Your doctor may start you on a lower dose of VIAGRA.
- Medicines called protease inhibitors for HIV. Your doctor may prescribe a 25 mg dose. Your doctor may limit VIAGRA to 25 mg in a 48-hour period.
- Other methods to cause erections. These include pills, injections, implants, or pumps.
- A medicine called REVATIO. VIAGRA should not be used with REVATIO as REVATIO contains sildenafil, the same medicine found in VIAGRA.

POSSIBLE SIDE EFFECTS OF VIAGRA

Side effects are mostly mild to moderate. They usually go away after a few hours. Some of these are more likely to happen with higher doses.

The most common side effects are:

- Headache
- Feeling flushed
- Upset stomach

Less common side effects are:

- Trouble telling blue and green apart or seeing a blue tinge on things
- Eyes being more sensitive to light
- Blurred vision

Rarely, a small number of men taking VIAGRA have reported these serious events:

- Having an erection that lasts more than 4 hours. If the erection is not treated right away, long-term loss of potency could occur.
- Sudden decrease or loss of sight in one or both eyes. We do not know if these events are caused by VIAGRA and medicines like it or caused by other factors. They may be caused by conditions like high blood pressure or diabetes. If you have sudden vision changes, stop using VIAGRA and all medicines like it. Call your doctor right away.
- Sudden decrease or loss of hearing. We do not know if these events are caused by VIAGRA and medicines like it or caused by other factors. If you have sudden hearing changes, stop using VIAGRA and all medicines like it. Call your doctor right away.
- Heart attack, stroke, irregular heartbeats, and death. We do not know whether these events are caused by VIAGRA or caused by other factors. Most of these happened in men who already had heart problems.

If you have any of these problems, stop VIAGRA. Call your doctor right away.

HOW TO TAKE VIAGRA

Do:

- Take VIAGRA only the way your doctor tells you. VIAGRA comes in 25 mg, 50 mg, and 100 mg tablets. Your doctor will tell you how much to take.
- If you are over 65 or have serious liver or kidney problems, your doctor may start you at the lowest dose (25 mg).
- Take VIAGRA about 1 hour before you want to have sex. VIAGRA starts to work in about 30 minutes when you are sexually excited. VIAGRA lasts up to 4 hours.

Don't:

- Do not take VIAGRA more than once a day.
- Do not take more VIAGRA than your doctor tells you. If you think you need more VIAGRA, talk with your doctor.
- Do not start or stop any other medicines before checking with your doctor.

NEED MORE INFORMATION?

- This is only a summary of important information. Ask your doctor or pharmacist for complete product information OR
- Go to **www.viagra.com or call (888) 4-VIAGRA (484-2472).**

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ASTRONOMY

Drinking from the Cool Cosmic Stream

A glimpse of the ancient universe hints at how galaxies grew so rapidly

How did youthful galaxies in the early universe fatten up to become the behemoths we see today? One explanation, put forth more than a decade ago, is that galaxies in the early universe supped on cold gas to fuel their prodigious star formation. Theoretical astrophysicist Avishai Dekel of the Hebrew University of Jerusalem found that narrow streams of intergalactic gas could act as supply lines, penetrating a budding galaxy's hot halo of gas and feeding that galaxy's growth. Yet the faint streams of cold gas have proved difficult to detect.

A chance cosmic alignment has now brought a galactic gas line to light. Neil Crighton of the Max Planck Institute for Astronomy in Heidelberg and his colleagues examined a brilliant, distant quasar whose light, en route to Earth, pierced an intervening galaxy when the universe was only about three billion years old. The chemical constituents of the galaxy absorbed specific wavelengths of the quasar's light, imprinting a signature of the gas supplying the galaxy.

The gas surrounding the young galaxy "has all the characteristics we'd expect of a cold accretion stream," says Crighton, lead author of a recent study in *Astrophysical Journal Letters.* The telltale traits include low temperature, high density, and a low abundance of elements other than hydrogen and helium forged in the big bang.

Dekel is not ready to claim victory from a single detection, however. "We will have to see many of those to make it compelling," he says. —*Ron Cowen*

PALEONTOLOGY

The Real Bigfoot

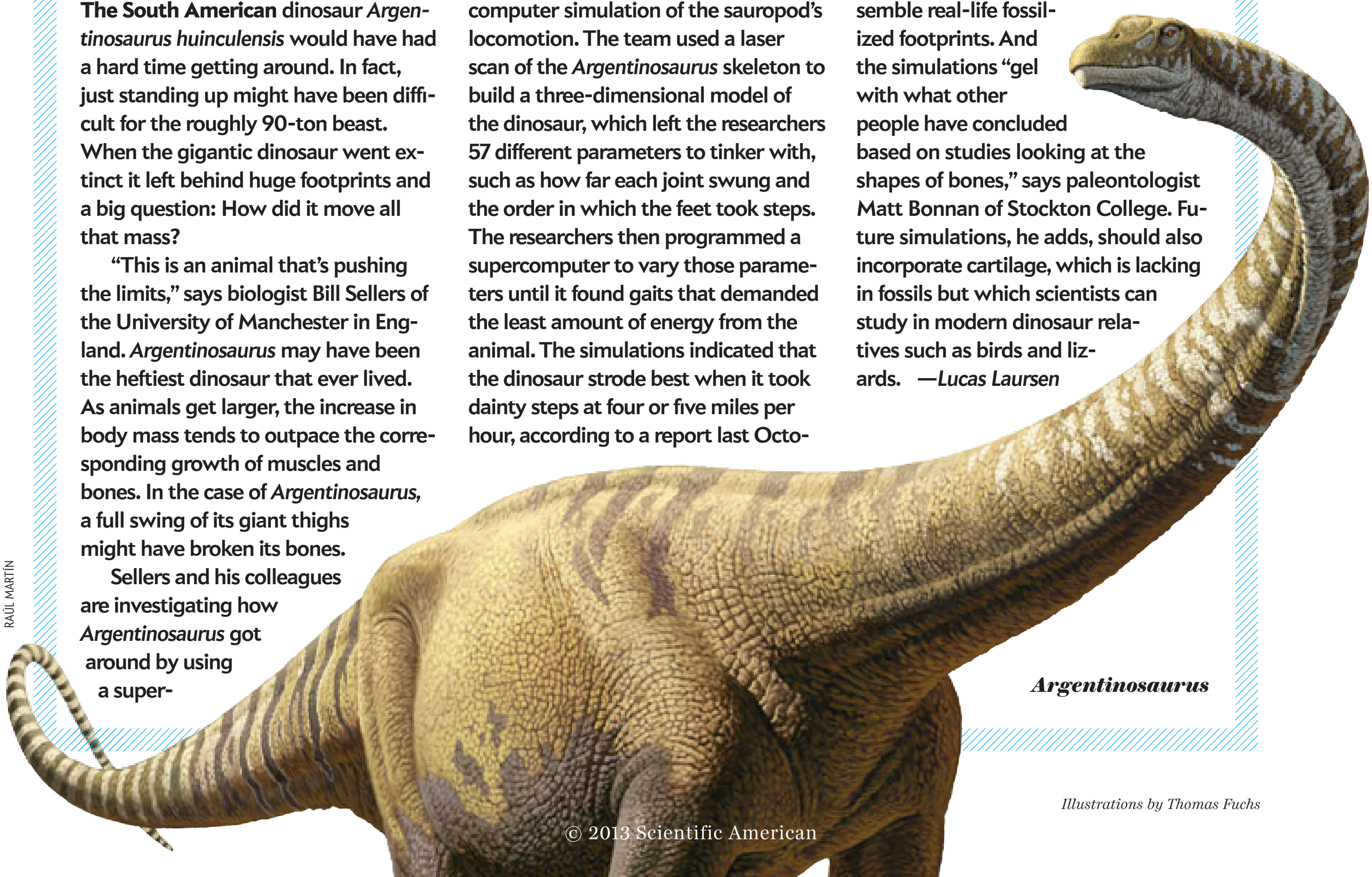
A giant dinosaur probably had to plod along to keep its body from breaking down

The South American dinosaur *Argentinosaurus huinculensis* would have had a hard time getting around. In fact, just standing up might have been difficult for the roughly 90-ton beast. When the gigantic dinosaur went extinct it left behind huge footprints and a big question: How did it move all that mass?

"This is an animal that's pushing the limits," says biologist Bill Sellers of the University of Manchester in England. *Argentinosaurus* may have been the heftiest dinosaur that ever lived. As animals get larger, the increase in body mass tends to outpace the corresponding growth of muscles and bones. In the case of *Argentinosaurus,* a full swing of its giant thighs might have broken its bones.

Sellers and his colleagues are investigating how *Argentinosaurus* got around by using a supercomputer simulation of the sauropod's locomotion. The team used a laser scan of the *Argentinosaurus* skeleton to build a three-dimensional model of the dinosaur, which left the researchers 57 different parameters to tinker with, such as how far each joint swung and the order in which the feet took steps. The researchers then programmed a supercomputer to vary those parameters until it found gaits that demanded the least amount of energy from the animal. The simulations indicated that the dinosaur strode best when it took dainty steps at four or five miles per hour, according to a report last October in *PLOS One.* By staying well within the range of motion of its joints, *Argentinosaurus* may have avoided the pitfalls of its gigantism.

The new study's predictions agree with other lines of evidence. The simulated animal's tracks, for instance, resemble real-life fossilized footprints. And the simulations "gel with what other people have concluded based on studies looking at the shapes of bones," says paleontologist Matt Bonnan of Stockton College. Future simulations, he adds, should also incorporate cartilage, which is lacking in fossils but which scientists can study in modern dinosaur relatives such as birds and lizards. —*Lucas Laursen*



RAÚL MARTÍN

Argentinosaurus

Illustrations by Thomas Fuchs

HEALTH

Under Obamacare, A Rollback of Abortion Coverage

Many of the new online insurance exchanges have banished plans that cover the procedure

Since the passage of the Affordable Care Act (ACA) in 2010, officials across all levels of government have been preparing for the law's sweeping changes to the health care system. For many state legislators, those preparations have included enacting new restrictions on the availability of insurance coverage for legal abortions.

When the online insurance marketplaces erected under the ACA become operational, shoppers in only about half of U.S. states will have access to health plans that cover abortions. The federal law permits states to decide whether or not plans offered through the online exchanges can fund those procedures. According to data compiled by the Guttmacher Institute, a research organization focused on sexual and reproductive health and rights, 23 states have banned abortion coverage from insurance plans sold via the health care exchanges—usually making exemptions only in cases of rape or incest or when the woman's life is at risk.

Under previous laws, only eight states explicitly prevented private health insurance plans from covering abortions. The shift, says Elizabeth Nash, state issues manager at the Guttmacher Institute, "means that more women will be paying out of pocket for abortion care." In the long run, Nash says, the new restrictions may have ripple effects, potentially affecting those who do not purchase an online plan, such as women who receive health insurance through their employers. "The concern is that with so many states limiting abortion coverage, insurance plans will simply stop offering abortion coverage," she says. The National Association of Insurance Commissioners and trade group America's Health Insurance Plans both declined to comment on the possibility.

In several states, such as Arizona, North Carolina, Ohio, Oklahoma and Wisconsin, the new restrictions follow recent squeezes to family-planning funds that could help fuel clinic closures. A handful of the 23 states are expected to offer separate insurance riders that would allow women to shell out extra money for abortion coverage, but it remains to be seen how many buyers will invest in that option or even how they would find out about it.

The average cost of a first-trimester abortion is just under $500. Without insurance coverage, more women could find themselves weighing difficult financial trade-offs or seeking help from nonprofits to foot the bill. —*Dina Fine Maron*

BIOLOGY

Making Dolfriends

Marine mammals forge strong social bonds with other species

In the waters off the northern coast of New Zealand swims a group of one of the world's most poorly understood cetaceans. Named for their resemblance to their better-known cousins, false killer whales dwell in warm tropical and temperate seas across the globe. But humans usually find them only when they become stranded.

Because false killer whales are so elusive, scientists have only a basic understanding of their social lives. Past studies of individuals near Hawaii and Costa Rica have found that false killer whales are social animals that can maintain friendships—swimming, hunting and cavorting—for years.

They also form relationships that cross species boundaries. In a new study researchers tracked the movements and interactions of New Zealand's false killer whales from a few dozen sightings spread over 17 years. On the rare occasions that the animals were spotted, they were often accompanied by common bottlenose dolphins. Using photographs to identify individuals by their distinctively notched dorsal fins, the researchers found that social pairings between individuals of the two species span both time and space. Some of the interspecies pairings lasted more than five years, with pairs spotted together at locations up to 650 kilometers apart. The study was published online in *Marine Mammal Science.*

Some benefits of interspecies groupings may be purely practical. For starters, the fish that both mammals eat tend to be found together, "with the dolphins preying on kahawai and the whales preying on the much larger kingfish," says lead study author Jochen Zaeschmar, a graduate student at Massey University in New Zealand. The two species probably also benefit from working together to detect and avoid predators.

But Zaeschmar also found evidence of social contact between the two species, such as two animals touching as they swam side by side. "The fact that interactions between individual members of each species were observed regularly over the course of five years is an important finding," says Justin Gregg, a research associate at the Dolphin Communication Project. It means that false killer whales and bottlenose dolphins choose to spend time with specific members of the other species rather than randomly mixing or engaging in brief opportunistic encounters.

False killer whales are not the only creatures with diverse friends. "We observe giant moray eels and coral groupers—two distantly related species—foraging in a truly mutualistic and cooperative fashion," Gregg says. So perhaps it should come as no surprise that the marine mammals, "with their complex social behavior, are capable of engaging in equally as sophisticated mixed-species interactions," he adds. *—Jason G. Goldman*

BY THE NUMBERS

33

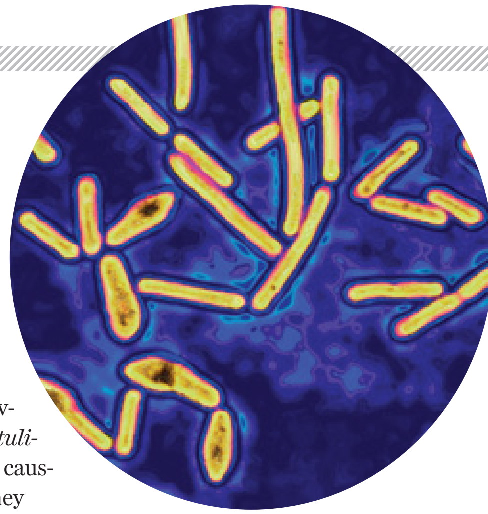
Speed, in miles per hour, at which a cork pops out of a bottle of champagne that is stored at 64 degrees Fahrenheit, or roughly room temperature.

COURTESY OF MAZDAK RADJAINIA *(top)*; SOURCE: "CHAMPAGNE CORK POPPING REVISITED THROUGH HIGH-SPEED INFRARED IMAGING: THE ROLE OF TEMPERATURE," BY GÉRARD LIGER-BELAIR ET AL., IN *JOURNAL OF FOOD ENGINEERING*, VOL. 116, NO. 1; MAY 2013 *(bottom)*

MICROBIOLOGY

A Botulism Bind

Bioterror worries keep key details out of new studies



When scientists in California discovered a new strain of *Clostridium botulinum,* the bacterium responsible for causing the paralytic illness botulism, they duly reported their findings in a scientific journal. The resulting studies were noteworthy for at least two reasons: the new strain of *C. botulinum* was the first to be identified in 40 years, and, perhaps more extraordinary, the researchers purposefully withheld key details of their discovery.

The scientists are keeping the information secret because of bioterror concerns. The toxins made by *C. botulinum,* which inhibit muscle movement by blocking the release of the neurotransmitter acetylcholine, are the most dangerous known to humankind. A single gram of crystalline toxin, "evenly dispersed and inhaled, would kill more than one million people," according to a 2001 assessment published in the *Journal of the American Medical Association.* Botulinum toxin is known or suspected to have been part of bioweapon programs in the former Soviet Union, Iran, Iraq, North Korea and Syria.

Each of the seven previously known strains of the bacterium produces its own toxin, labeled A through G, and each has a corresponding antidote. Until an antidote can be developed for the new strain's toxin, dubbed H, the scientists at the California Department of Public Health who discovered the strain have decided not to release any genetic blueprints. The new strain was isolated from a patient who had contracted botulism but did not die.

The situation harks back to a debate that began in late 2011, when leading influenza scientists attempted to publish details of how they had genetically engineered the deadly H5N1 "bird flu" virus to spread among mammals. They initially faced objections from an expert panel that advises the U.S. government, which argued that the research could become a recipe for a pandemic virus. Yet eventually the advisory board reconsidered, and the researchers published their work.

The botulinum investigators could have held off on publishing their findings until the H antitoxin was made, says Ron Fouchier, a virologist at Erasmus Medical Center in Rotterdam and one of the scientists who led the H5N1 research. "Why rush now?" Fouchier says.

The journal editors weighed the consequences of publishing redacted research but felt an obligation to print the two botulinum studies promptly. "We decided it was important enough to let the scientific community know," asserts David Hooper, deputy editor of the *Journal of Infectious Diseases.* The journal plans to add the genetic sequence to the scientific record once an H antitoxin is developed.

—Helen Branswell

BY THE NUMBERS

45

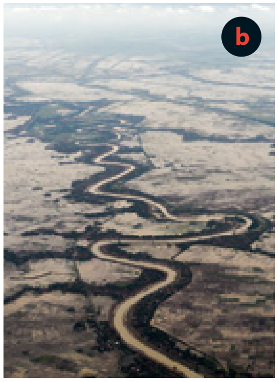
Maximum temperature, in degrees Fahrenheit, for a bottle of bubbly, recommended by the American Academy of Ophthalmology for revelers to avoid blinding eye injuries.

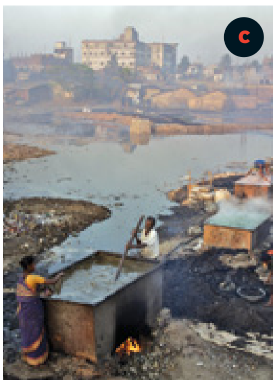
JAMES CAVALLINI *Science Source (top);* SOURCE: AMERICAN ACADEMY OF OPHTHALMOLOGY *www.aao.org/newsroom/release/20121219.cfm (bottom)*

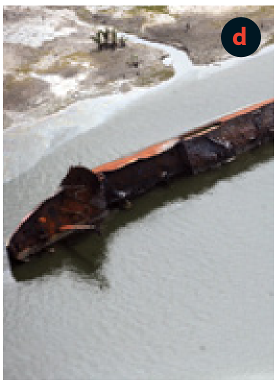
ENVIRONMENT

Pick Your Poison

A list of the 10 most polluted places on earth ranges from nuclear sites to e-waste dumps







JANE HAHN *Corbis* (a); DIDIER MARTI *Getty Images* (b); GETTY IMAGES (c); PIUS UTOMI EKPEI *Getty Images* (d)

Agbogbloshie, a neighborhood of Accra, Ghana, is where European gadgets go to die. Ghana imports some 237,000 tons of computers, cell phones, televisions and other electronics annually, mostly from Europe, making Agbogbloshie one of the largest e-waste dumps in Africa. It may already be the dirtiest. The site has earned the dubious distinction of joining Chernobyl and the industrial hub of Noril'sk, Russia, on the Blacksmith Institute's list of the world's 10 most polluted places. Workers at Agbogbloshie burn insulated electrical cables to recover the valuable copper inside, releasing lead and other heavy metals in the process.

"Everybody wants a laptop, wants the modern devices," Jack Caravanos, a professor at the City University of New York School of Public Health and a Blacksmith technical adviser, said during a press conference last November. "Stopping e-waste is proving very complicated and difficult."

The Blacksmith Institute, along with Green Cross Switzerland, compiled the new rankings after surveying more than 2,000 sites in 49 countries. The organizations estimate that toxic pollution threatens the health of more than 200 million people in the developing world.

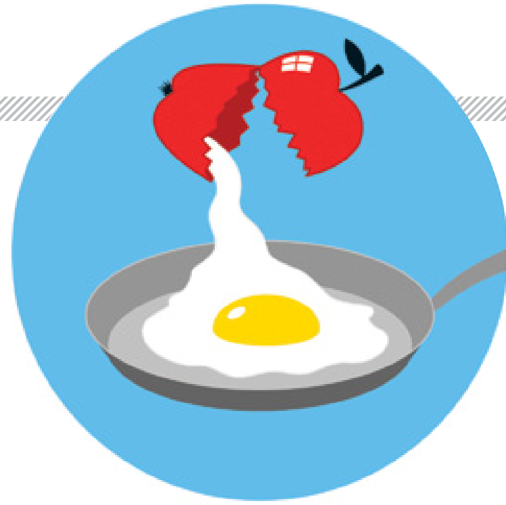
Several places that appeared on an earlier list, compiled in 2006, have now dropped off, thanks to cleanup efforts. In Haina, Dominican Republic, heavily lead-contaminated soil at a battery recycling center has been buried in a specialized landfill, which Blacksmith hailed as the greatest "success story" among the sites flagged in 2006. China and India have also disappeared from the top 10. The Chinese government shut down about 1,800 polluting factories in Linfen, and India has implemented a program to assess and remediate contaminated sites across the country.

Although none of the sites now listed are in the U.S., Japan or western Europe, much of the pollution stems from the lifestyles of wealthy countries, noted Stephan Robinson of Green Cross Switzerland. Some pollution comes from producing the raw materials for consumer goods. Tanneries in Bangladesh, for example, provide leather for Italian-made shoes sold in New York City or Zurich. And some pollution, as is the case in Agbogbloshie, comes from things that affluent nations no longer want. —*David Biello*

THE TOP 10 TOXIC THREATS

Agbogbloshie, Ghana (a) E-waste	**Kabwe, Zambia** Lead mining
Chernobyl, Ukraine Nuclear accident	**Kalimantan, Indonesia** Gold mining
Citarum River Basin, Indonesia (b) Industrial and domestic pollution	**Matanza Riachuelo, Argentina** Industrial pollution
Dzerzhinsk, Russia Chemical manufacturing	**Niger River Delta, Nigeria** (d) Oil spills
Hazaribagh, Bangladesh (c) Tanneries	**Noril'sk, Russia** Mining and smelting

SITES ON THE UNRANKED LIST APPEAR IN ALPHABETICAL ORDER.



FOOD SCIENCE

Over Easy, Hold the Eggs

A West Coast start-up wants to make the staple ingredient obsolete

Josh Klein used to work on vaccine development for HIV, but these days he focuses on a different biochemical conundrum: making cakes moist and fluffy. He insists he's still making a difference. As director of biochemistry research at Hampton Creek Foods in San Francisco, Klein is on a mission to systematically identify and replicate every single culinary function of chicken eggs—using plant proteins.

Although Hampton Creek's founder, Josh Tetrick, is a vegan, his goal is not to convert others. Instead Tetrick hopes that Hampton Creek's products will outcompete eggs on price and thereby "sneak sustainability" into a variety of diets. The company, which is backed by tech-centric venture capital firms, recently launched a mayonnaise alternative, Just Mayo, and an egg substitute, Beyond Eggs, for making cookies.

As targets for ecological overhaul go, the egg industry is a good one. The world's hens lay more than one trillion eggs a year, and they do so with startling inefficiency. Egg farming requires 39 kilocalories of energy to produce one kilocalorie of protein—on par with raising cattle for beef—according to a 2003 study in the *American Journal of Clinical Nutrition*. The energy-to-protein ratio for plants is 2.2 to one.

Whereas there are other egg substitutes on the market for allergy sufferers and conscientious objectors alike, Klein says he is taking a more scientific approach. His team has scanned more than 1,500 plants, identifying 11 as strong candidates for egg stand-ins. "The egg is more than just a nutrient," he says. "It reacts to things like temperature, pH and salt content." By identifying proteins that perform specific functions—emulsion, coagulation, aeration, and so on—Klein and Tetrick say that Hampton Creek's products, taken as a whole, will be the first to totally replace eggs without sacrificing taste.

TECHNOLOGY

Big Data, Big Energy

Electricity-hogging data centers could soon power themselves

The data centers of the future might do more than crunch and store information. In addition to serving Web pages, streaming Netflix videos and hosting social networks, they might soon produce their own power.

Data centers consume a tremendous amount of energy—they account for roughly 2 percent of total electricity use in the U.S., by one estimate. But Microsoft researchers may have found a way for tech companies to reduce their energy usage without sacrificing the dependability of their infrastructure. The solution, they say, lies in fuel cells, devices that convert chemical energy from fuel into electricity. By integrating fuel cells directly into server racks, data centers could double their efficiency, the researchers predict.

Fuel cells work by stripping electrons from a fuel molecule (often hydrogen). The electrons are routed through an external circuit, producing electricity.

Placing fuel cells as close to data servers as possible would curb many of the efficiency losses that come from transmitting electricity over long distances. And underground gas lines supplying fuel cells would be more resilient during storms than overhead power lines.

In one scenario, fuel-cell assemblies would dot the data center, each powering a few racks of servers. The challenge is finding the optimal balance among reliability, cost and efficiency. "It's the classic Goldilocks issue: not too hot, not too cold," says Sean James, senior research program manager for Microsoft's Global Foundation Services. Hooking up too many servers to one fuel cell means more problems if that cell malfunctions, but hooking up too few servers increases the number and cost of the fuel cells needed. Another hurdle: data move fast, and fuel cells react rather slowly. Demand on a given server can spike in milliseconds, but fuel cells take several seconds to adjust to the increased load.

A full-scale data center powered by fuel cells is still several years out. In the meantime, as more information and services move into the cloud, it does not appear that data centers—or their huge energy footprint—are going away. *—David Wogan*

Adapted from Plugged In blog at ***blogs.ScientificAmerican.com/plugged-in***

Next up for Hampton Creek are a premixed cookie dough—which can be eaten raw without fear of salmonella—and a replacement for scrambled eggs. The powdered egg replacers already on the market generally cannot be scrambled, and many liquid products are actually egg-based.

Having tackled breakfast, Hampton Creek will attempt to fill the egg's role in airy baked goods. It will take "very hard work" to replace the egg yolk's structure-building lipoproteins, predicts Marc Anton of the French National Institute for Agricultural Research. In a typical batter, egg proteins surround air bubbles trapped in the mixture by sugar and fat, and the heat of baking seals the bubbles shut. The complexities of the process leave plenty of room for error. Even still, Klein and his team think they may already have found a plant candidate that can hold up a pound cake with egglike panache. —*Rachel Feltman*

EXTINCTION COUNTDOWN
LA HOTTE BUSH FROG

ROBIN MOORE

Good Dads Help Rare Haitian Frogs Thrive in Captivity

Out on the fingerlike peninsula of southwestern Haiti is the remote forest realm of the La Hotte bush frog—or what is left of it. "It's a very beautiful forest," says Carlos Martinez Rivera, a conservation biologist at the Philadelphia Zoo. "It feels like going to any other tropical rain forest. But it's a very tiny patch of forest." In recent decades Haiti has desperately cut down trees to grow crops or make charcoal. So, in 2010, the Philadelphia Zoo captured 154 frogs from nine species in those fading forests for breeding back in the U.S.

Now the zoo hosts more than 1,500 Haitian frogs, including more than 1,200 La Hotte bush frogs. "If you do have a doomsday scenario where the forest is gone, the species will still be preserved," Martinez Rivera says.

Biology and behavior have helped the frog thrive in captivity. The females lay large clutches of eggs, which the males then guard until they hatch, freeing up the females to mate again and lay more eggs. "They're very prolific in that sense," Martinez Rivera says. —*John R. Platt*

Read more at blogs.ScientificAmerican.com/extinction-countdown

ECOLOGY

Mercury Lockdown

Activated carbon traps pollution in place

Good for more than barbecuing, charcoal may be the key to improving the health of mercury-laden soils and sediments. In the most polluted areas—Superfund sites and other contaminated hotspots—mercury cleanup has traditionally meant dredging, a disruptive and costly endeavor. But activated carbon, a granulated form of charcoal, can trap mercury in place, which may allow for cheaper, simpler remediation efforts.

"Instead of digging up contaminated sediments or soil, we hoped to add something to the sediments that will keep the mercury from getting into the food web," says Cynthia Gilmour of the Smithsonian Environmental Research Center. In a recent study, she and her colleagues tested how well activated carbon locked up methylmercury, the form of mercury that tends to rise up the food chain and that can cause neurological problems, to prevent it from accumulating in living tissue.

Using sediments from four mercury hotspots, the scientists measured the amount of the toxic substance taken up by sediment-dwelling worms. Activated carbon reduced the bioaccumulation of methylmercury by 30 to 90 percent, the researchers reported last October in a study published online in *Environmental Science & Technology*.

The charcoal idea came from study co-author Upal Ghosh of the University of Maryland, Baltimore County, who had been using activated carbon as a remediation tool for polychlorinated biphenyls (PCBs), another pollutant that lingers stubbornly in sediments and then climbs the food chain. Ghosh suggested trying the same approach to deal with methylmercury. "These two chemicals have probably the highest bioaccumulation rates that we know of," Gilmour notes.

—Carrie Madren

SPACE

Put Up the Earth Shield

The U.N. is taking first steps to curb the risk of wayward asteroids

When a meteor exploded over Chelyabinsk, Russia, last February, the world's space agencies found out along with the rest of us, on Twitter and YouTube. That, former astronaut Ed Lu says, is unacceptable—and the United Nations agrees.

In October the U.N. General Assembly approved a set of measures to limit the dangers of rogue asteroids. The U.N. plans to set up an International Asteroid Warning Group for member nations to share information about potentially hazardous space rocks. If astronomers detect a threatening asteroid, the U.N.'s Committee on the Peaceful Uses of Outer Space will help coordinate a mission to deflect it.

Lu and other members of the Association of Space Explorers (ASE) had recommended that the U.N. take those first steps toward addressing the problem of wayward asteroids. The ASE has also asked the U.N. to coordinate a practice asteroid-deflection mission to test the technologies for pushing a rock off course before such tactics become necessary.

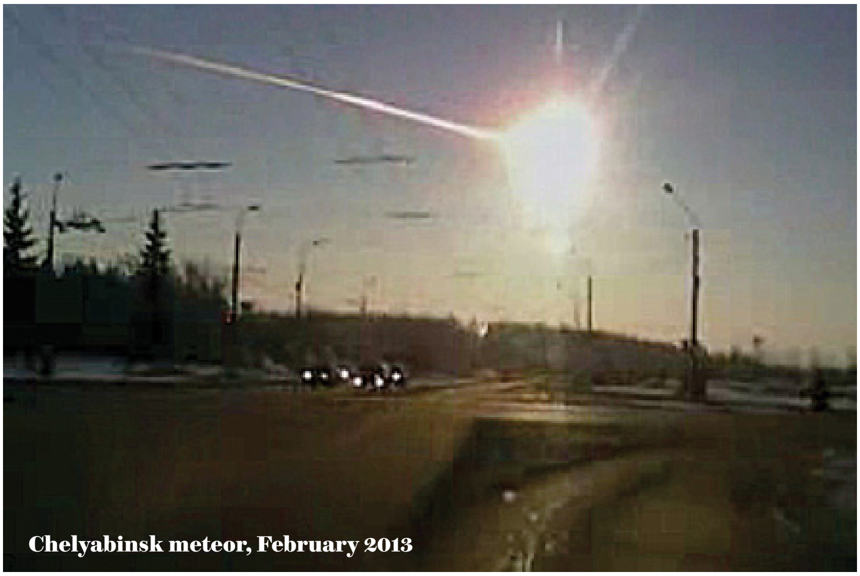
The ASE urges that each country delegate asteroid duties to a specific internal agency. "No government in the world today has explicitly assigned the responsibility for planetary protection to any of its agencies," said ASE member and *Apollo 9* astronaut Rusty Schweickart during a public discussion in October at the American Museum of Natural History in New York City.

The next key step in defending Earth is to identify the menacing objects. "There are about one million asteroids large enough to destroy New York," Lu said at the meeting. "Our challenge is to find these asteroids first, before they find us."

The B612 Foundation, a nonprofit Lu created to tackle the problem of asteroid impacts, is developing a privately funded space telescope called Sentinel. The telescope's sensitivity to infrared light—the heat given off by objects warmed by the sun—should enable it to spot a large number of truly menacing asteroids, but smaller bodies, such as the one that hit over Chelyabinsk, will remain mostly unseen.

Early detection is important because it increases the chance of being able to deflect a giant asteroid before impact. If a spacecraft were rammed into an asteroid five or 10 years before the rock was due to hit Earth, the slight orbital alteration should be enough to ensure a miss.

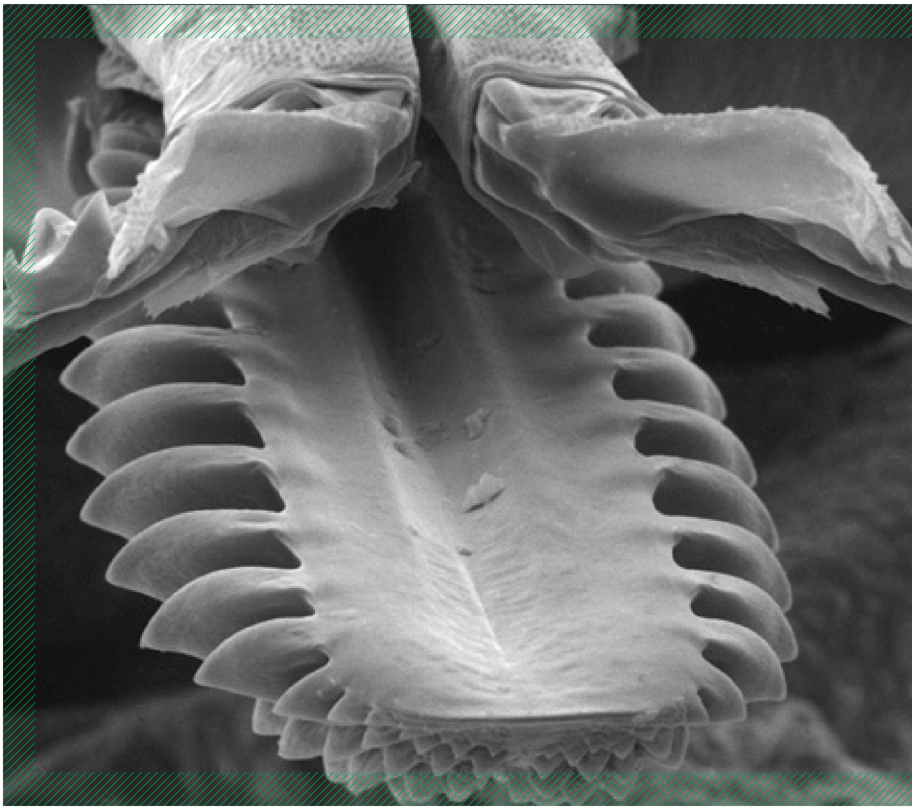
The impact over Chelyabinsk, which injured 1,000 people, was a warning shot, American Museum of Natural History astronomer Neil deGrasse Tyson said at the discussion. Now it's time for Earth's citizens to take action. *—Clara Moskowitz*



Chelyabinsk meteor, February 2013

AP PHOTO

COMMENT AT ScientificAmerican.com/jan2014



COURTESY OF DANIA RICHTER

WHAT IS IT?

For ticks, mealtime is an extended affair. The arachnid parasites latch on to hosts for days at a time. To find out exactly how ticks penetrate and anchor into the skin of their hosts, researchers examined tick mouthparts under microscopes and watched as the parasites attached themselves to the ears of mice.

As they report in the journal *Proceedings of the Royal Society B,* ticks first burrow into the host's skin with two telescoping, barbed structures called chelicerae. They then perform a breaststroke maneuver with the chelicerae, spreading them like arms and pulling them back. That motion sinks a spiky, swordlike appendage into the host. Positioned alongside the chelicerae, the shaft, called a hypostome, forms a tube for withdrawing blood.

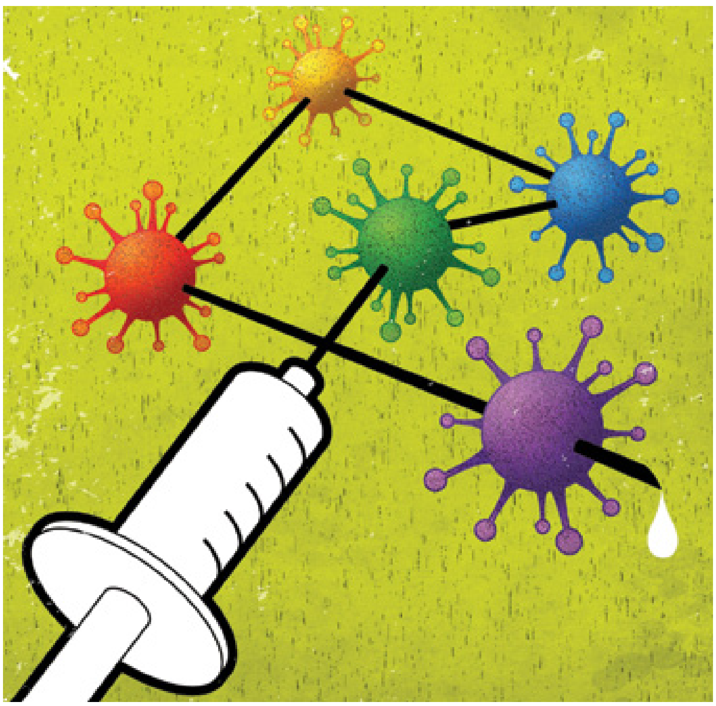
Peering at a tick with a scanning electron microscope, "you can almost fly into its mouth and right into its midgut, like one of those red blood cells they're sucking up," says lead study author Dania Richter, who conducted the research at Charité University Hospital in Berlin.

—Rachel Nuwer

Maryn McKenna is a journalist, a blogger and author of two books about public health. She writes about infectious diseases, global health and food policy.

A Flu Vaccine That's Always in Season

A single shot to thwart all flu viruses may be within reach



In the spring of 2013 a strain of influenza virus that had never infected humans before began to make people in China extremely ill. Although the virus, known as H7N9, had evolved among birds, it had mutated in a way that allowed it to spread to men, women and children. Within several months H7N9 sickened 135 individuals, of whom 44 died, before subsiding with the advance of summer weather.

We got lucky with H7N9. Had it triggered a pandemic—an explosion of infectious disease across a large geographical area—we would have been woefully unprepared, and millions might have died. The trouble is that every new virus requires a new vaccine, and making new vaccines takes time. Even a typical flu season is brimming with slightly mutated versions of familiar viruses. In most cases, manufacturers anticipate these changes and tweak existing formulas so that they will still work against the new strains. When a virus like H7N9 makes a surprise appearance in people, however, manufacturers must scramble to concoct an entirely new vaccine from scratch, which takes too long to prevent a large number of people from becoming sick and dying.

Public health officials have longed for years to turn the tables, envisioning a "universal" flu vaccine that would be ready and waiting on the shelves to defeat either a marginally mutated strain or a completely unexpected virus. After numerous disappointments, a handful of recent studies indicate that a universal vaccine may at last be close at hand. In an interview last summer National Institutes of Health director Francis Collins suggested that one might be achieved in the laboratory in just five years. Before such a vaccine can reach the general public, however, researchers will have to convince either manufacturers or the government to pay for more studies and demonstrate to the U.S. Food and Drug Administration that the new vaccines are just as safe as those we already use.

STALKING A KILLER

FLU VACCINES HAVE WORKED on the same principles since investigators first made them in the 1940s. Each vaccine contains flu antigens—bits of viral molecules that can trigger an immune response. The antigens used in routine flu vaccines are fragments of a mushroom-shaped protein, called a hemagglutinin, that protrudes from a flu virus's surface and helps the pathogen cling to cells inside an infected individual. Once exposed to those bits of protein, a person's immune system produces sentinel molecules called antibodies that will recognize any flu virus possessing the same hemagglutinin and direct an attack against it.

Flu is a rapidly evolving virus, however, and the structure of hemagglutinin in a given strain changes in small ways every season. Even a minor alteration can make it much more difficult for the immune system to identify and eliminate a flu virus that is nearly identical to its earlier version. This is why we have to get new flu shots every year.

Scientists have searched for decades for a way to outsmart the flu virus rather than always hurrying to outpace it. The first glimpse of more efficient vaccines appeared in 1993, when Japanese researchers discovered that mice sometimes generate a single antibody that blocks infection by two flu strains with different hemagglutinins. Fifteen years later several different teams demonstrated that humans occasionally make these cross-protective, or broadly neutralizing, antibodies as well. Most of these

Illustration by Thomas Fuchs

antibodies bind not to a hemagglutinin's mushroom cap but rather to its slender stem—a region of the molecule where, as it turns out, less structural mutation takes place. Because the stem's makeup is similar across many strains of flu, the researchers reasoned, an antibody that recognizes it could potentially protect against a range of viral strains with distinct caps.

Building on this discovery, several groups have altered the structure of hemagglutinins, creating a cap to which the immune system does not react. Animals exposed to these tweaked proteins produce cross-protective antibodies that bind to the stalk rather than strain-specific antibodies that home in on the cap. Other scientists are trying to get animals and people to make antibodies against a different viral protein, M2, which is embedded in the flu virus's membrane and helps it enter cells. Like the hemagglutinin stalk, M2 changes little.

Additional teams are focusing on completely different strategies, such as designing a vaccine that encourages the production of T cells, the attack dogs of the immune system. T cells produce broader, longer-lasting immunity than antibodies, but classic flu vaccine formulas do not encourage their activity. Others are administering a sequence of vaccines against different flu strains so that the immune system assembles a diverse antibody artillery.

Much of this research has happened only in the past five years. In fact, for 15 years after the earliest studies in Japan, work on a universal flu vaccine accumulated in mere dribs and drabs—until a pandemic, which killed more young and middle-aged adults than usual, jolted scientists into a higher gear. In April 2009 a highly infectious new strain of swine virus dubbed H1N1 jumped suddenly from pigs to people. Manufacturers had already spent months preparing the vaccine for the 2009–2010 season, which was still a ways away—and that vaccine was useless against the new strain. They had to go back to square one.

For 15 years research on a universal vaccine accumulated in mere dribs and drabs until a pandemic jolted scientists into a higher gear.

Beginning work on the H1N1 vaccine so late in the manufacturing cycle, combined with some peculiarities of the virus—it was not easy to replicate en masse in the lab, which slowed down production—resulted in millions of doses arriving on the market months after planners hoped. By the next spring, H1N1 killed as many as 18,000 people in the U.S. These delays spurred some incremental changes in flu vaccine manufacturing. Yet they also underscored the fact that better techniques cannot solve the root problem of having to rapidly fabricate a new vaccine every time a completely new virus appears.

"We realized that despite all the technology we have, it is very hard to manufacture and deliver a [brand-new] vaccine in time to actually have an impact," says Kanta Subbarao, chief of the emerging respiratory viruses section at the NIH.

FINAL HURDLES

EVEN IF RESEARCHERS who are working on a universal flu vaccine finally overcome all their remaining technical challenges, the real hurdle may be securing both funding for future studies and federal approval for a new product. Asked what he needs to begin trials with people, Peter Palese, who is a professor and chair of microbiology at Mount Sinai Hospital in New York City, laughs and replies, "Money." Federal or private money? "Any money," he says.

His answer captures the paradox of research into new flu vaccines. Although current vaccines are flawed and require a lot of time to tweak, they confer some protection most of the time. "Why expend the effort to invest hundreds of millions of dollars to get to something new?" says Michael Osterholm, director of the Center for Infectious Disease Research and Policy at the University of Minnesota, which published a lengthy 2012 report scrutinizing the lack of private and government funding for "game-changing" flu vaccines.

Certain unique properties of the most promising universal flu vaccines in production may be a source of additional obstacles. Studies have suggested that the experimental universal flu shots do not trigger as strong an immune response as older vaccines do. Guaranteeing that the new vaccines are as effective as the old ones may mean adding more ingredients or finding new ways to administer them.

Any new flu vaccine is practically guaranteed lengthy FDA examination. Current seasonal vaccines change so little from year to year that they move through FDA review quickly. But a universal vaccine—using new antigens and a new delivery system—would undergo extensive inspection for both efficacy and safety. For comparison, approval of the vaccine Prevnar, the first to confer protection against pneumonia in infants and young children, took 15 years and required very large clinical trials. "There are 60, 70 years" of FDA approvals and clinical experience behind existing flu vaccines, Palese points out. "But if you go in with a new approach, then the FDA will be starting from zero as well."

Given legally mandated caution on the FDA's side and a natural inclination on the part of manufacturers to stick with a "good enough" product, many have wondered whether a universal flu vaccine will ever reach the market. The emerging consensus seems to be that novel partnerships—in which, perhaps, industry brings the innovation, but government provides the funding—may be able to mitigate the weaknesses on each side. A joint government-industry conference, hosted in 2012 by the FDA and the NIH, concluded that such collaborations offer the best way forward.

"The science is coming along very fast, but we need to figure out how to get to the next step of development," Subbarao says. Given how quickly the flu virus can mutate—and how suddenly a new lethal virus can leap from animals to people—they had better figure it out fast. SA

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David Pogue is the anchor columnist for Yahoo Tech and host of several *NOVA* miniseries on PBS.

In Tech We Don't Trust

Tech companies promise the world, but how do we know that we're not the ones being sold out?

Last October, T-Mobile made an astonishing announcement: from now on, when you travel internationally with a T-Mobile phone, you get free unlimited text messages and Internet use. Phone calls to any country are 20 cents a minute.

T-Mobile's plan changes everything. It ends the age of putting your phone in airplane mode overseas, terrified by tales of $6,000 overage charges. I figured my readers would be jubilant. But a surprising number had a very different reaction. "Why should I believe them?" they wrote. "Cell carriers have lied to us for years."

That's not the first time that promises from a tech company have been greeted not with joy but with skepticism. When Apple introduced a fingerprint scanner into the Home button of the iPhone 5S, you might have expected the public's reaction to be, "Wow, that's much faster than having to type in a password 50 times a day!" But instead a common reaction was: "Oh, great. So now Apple can give my fingerprints to the NSA."

Really? That's your reaction to the first cell phone with a finger scanner that actually works?

And it's not so unreasonable.

Technology used to be admired in America. We marveled at the first radio, the laptop computer, the flat TV. Tech companies were our blue-chip companies. An IBM man was a good catch—respected, impressive. We were proud of our technological prowess and of the companies that were at the forefront.

Today it's not so simple. Our tech companies have a trust problem.

Over the years they've brought it on themselves. Google tested privacy tolerance when it introduced Gmail—with ads relating to the content of your messages. (It doesn't seem to matter that software algorithms, not people, scan your mail.)

Then a team of researchers discovered that when you synced your iPhone, your computer downloaded a log of your geographical movements, in a form accessible with simple commands. (Apple quickly revised its software.) When Barnes & Noble understated the weight of its Nook e-reader in 2010 or overstated the resolution of the Nook in 2011, suddenly even product specs could no longer be trusted.

Next came news about the National Security Agency and its collection of e-mail correspondence, chat transcripts and other data from Microsoft, Google, Facebook, Apple and others. Those companies admit to complying with the occasional warrant for individuals' data, but they strenuously deny providing the NSA with bigger sets of data. Do you think that makes the news any easier to take?

Of course not. We're human. We look for patterns. Each new headline further shakes our trust in the whole system.

These days tech companies make efforts to respect, or at least to humor, the public's alarm. In the latest iPhone software, for example, Apple has provided an almost hilariously complete set of on/off switches, one for every app that might want access to your location information.

But it may be too late for that. These companies' products are impossibly complex. There's no way for an individual to verify that software does exactly what we think it does. How do we know those iOS 7 switches do anything at all?

Every time a company slips up, we can only assume that it is just the tip of the iceberg. It may take years for these companies to regain our trust.

But this "I don't trust them anymore" thing sounds distinctly familiar. And it isn't specific to tech companies. At one time or another, haven't we also learned not to trust our government? Our police? Our hospitals? Our newspapers? Our medicines? And, goodness knows, our phone companies?

It's too bad. Mistrust means a life of wariness. It means constant psychic energy, insecurity, less happiness. And then, when we finally get what should be terrific news from a tech company, we're deprived of that little burst of unalloyed pleasure. SA

SCIENTIFIC AMERICAN ONLINE
A short history of tech snoopings: ScientificAmerican.com/jan2014/pogue

Illustration by Scott Brundage

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PSYCHOLOGY

Our Unconscious Mind

Unconscious impulses and desires impel what we think and do in ways Freud never dreamed of

By John A. Bargh

Illustrations by Tim Bower

John A. Bargh is a professor of psychology at Yale University. His Automaticity in Cognition, Motivation, and Evaluation Lab at Yale investigates unconscious influences on behavior and questions such as the extent to which free will exists.

WHEN PSYCHOLOGISTS TRY TO UNDERSTAND the way our mind works, they frequently come to a conclusion that may seem startling: people often make decisions without having given them much thought—or, more precisely, before they have thought about them *consciously*. When we decide how to vote, what to buy, where to go on vacation and myriad other things, unconscious thoughts that we are not even aware of typically play a big role. Research has recently brought to light just how profoundly our unconscious mind shapes our day-to-day interactions.

One of the best-known studies to illustrate the power of the unconscious focused on the process of deciding whether a candidate was fit to hold public office. A group of mock voters were given a split second to inspect portrait photographs from the Internet of U.S. gubernatorial and senatorial candidates from states other than where the voters lived. Then, based on their fleeting glimpses of each portrait, they were asked to judge the candidates. Remarkably, the straw poll served as an accurate proxy for the later choices of actual voters in those states. Competency ratings based on seeing the candidates' faces for less time than it takes to blink an eye predicted the outcome of two out of three elections.

For more than 100 years the role of unconscious influences on our thoughts and actions has preoccupied scientists who study the mind. Sigmund Freud's massive body of work emphasized the conscious as the locus of rational thought and emotion and the unconscious as the lair of the irrational, but contemporary cognitive psychologists have recast the Freudian worldview into a less polarized psychological dynamic. Both types of thought processes, it turns out, help us adapt to the protean demands of a species that survives by marshaling the mental firepower to hunt a Stone Age mastodon, face off in a Middle Ages joust or, in the new millennium, sell Apple's stock short.

IN BRIEF

Decision making often occurs without people giving much conscious thought to how they vote, what they buy, where they go on vacation or the way they negotiate a myriad of other life choices.

Unconscious processes underlie the way we deliberate and plan our lives—and for good reason. Automatic judgments, for one, are essential for dodging an oncoming car or bus.

Behaviors governed by the unconscious go beyond looking both ways at the corner. Embedded attitudes below the level of awareness shape many of our attitudes toward others.

Sigmund Freud meditated on the meaning of the unconscious throughout his career. These newer studies provide a more pragmatic perspective on how we relate to a boss or spouse.

Post-Freudian psychology has set aside the id and ego for a more pragmatic take on what defines our unconscious self. Nobel laureate Daniel Kahneman has described the modern distinction between the automatic and the controlled. In his bestselling book *Thinking Fast and Slow,* Kahneman characterized automatic thought processes as fast, efficient and typically outside the realm of conscious awareness, making them devoid of deliberation or planning. They require only a simple stimulus: the words on this page, for instance, connect effortlessly in your mind with their meaning. Controlled processes are the opposite. They require purposeful and relatively slow engagement of conscious thought—picture the labored effort that goes into doing your tax returns.

Similar to Freud's primal id and controlling ego, the automatic and controlled systems complement each other yet also, at times, conflict. You need to react without reflection to dodge an oncoming bus but also need to check yourself from throwing a punch at the reckless bus driver.

Snap judgments—relatively automatic thought processes—abound in our daily life—and for good reason. Outside of the relatively small number of individuals any one of us knows really well, most people we interact with are strangers we might never see again—while standing in line at the bank, say—or others we come across in the course of their jobs—cashiers, taxi drivers, waiters, insurance agents, teachers, and so on. The default unconscious perception generates expectations about behavior and personalities based on minimal information. We expect waitresses to act a certain way, which is different from what we expect of librarians or truck drivers. These expectations come to us immediately and without our thinking about them, based only on a person's social place.

The unconscious way we perceive people during the course of the day is a reflexive reaction. We must exert willful, conscious effort to put aside the unexplained and sometimes unwarranted negative feelings that we may harbor toward others. The stronger the unconscious influence, the harder we have to work consciously to overcome it. In particular, this holds true for habitual behaviors. An alcoholic might come home in the evening and pour a drink; a person with a weight problem might reach for the potato chips—both easily casting aside the countervailing urge toward restraint.

Understanding the tug the unconscious exerts on us is essential so that we do not become overwhelmed by impulses that are hard to understand and control. The ability to regulate our own behavior—whether making friends, getting up to speed at a new job or overcoming a drinking problem—depends on more than genes, temperament and social support networks. It also hinges, in no small measure, on our capacity to identify and try to overcome the automatic impulses and emotions that influence every aspect of our waking life. To make our way in the world, we need to learn to come to terms with our unconscious self.

GUT REACTIONS

WHEN WE MEET SOMEONE NEW, we form a first impression even before striking up a conversation. We may observe the person's race, sex or age—features that, once perceived, automatically connect to our internalized stereotypes about how members of a particular group are apt to behave. These assumptions about the social group in question—hostile, lazy, pleasant, resourceful, and so on—are often incorrect for the particular individual from that group standing in front of us, someone who usually has done nothing to merit any of these impressions, bad or good.

DISCONNECT: Slowness in naming the colors of words that indicate a different color can test for unconscious distractions.

SOURCE: "STUDIES OF INTERFERENCE IN SERIAL VERBAL REACTIONS," BY J. R. STROOP, IN *JOURNAL OF EXPERIMENTAL PSYCHOLOGY,* VOL. 18, NO. 6; DECEMBER 1935

These reflexive reactions often persist, even if they run counter to our conscious beliefs. Many people who say they have a positive attitude toward minority groups are astonished when social scientists reveal contradictions using a simple test. The Implicit Association Test calls on test subjects to characterize objects on a computer screen according to qualities they possess—a puppy may be good, a spider bad. Afterward, the test taker sees a series of faces of people of different races and is asked to classify them as white, black, and so forth.

Here's the trick: the same buttons are used for the initial evaluation and the group classification tasks. The left button might be for making both *good* and *white* responses and the right one for both *bad* and *black*. In a later trial, the button labels are reversed so that the left button records good objects and black faces and the right corresponds to bad and white. A white respondent would reveal underlying prejudice if the task is easier—measured by a faster response—when the buttons are configured for *bad/black* than for the *good/black* condition. Many people who hold positive conscious attitudes toward minority groups and who think of themselves as being motivated to treat all people fairly and equally are nonetheless surprised by the greater difficulty indicated by a slower pressing of the *good/black* buttons.

Why Some Social Science Studies Fail

Reports have recently documented that some of the original studies demonstrating unconscious effects on social behavior—research, for instance, that showed that people walk more slowly after hearing words associated with the elderly ("Florida" and "bingo")—could not be replicated when the procedures were repeated in new studies. The accounts, however, have generally neglected to mention that many other studies published over the past decade or so have successfully reproduced original findings on unconscious thought and behavior and have also extended this line of investigation in new directions.

These studies have confirmed that an unconscious gesture or a casual word for which a strong association has previously been formed—"priming" to a social psychologist—can change a person's behavior. They provide evidence that subliminal motivations make use of the same mental processes—working memory and executive function—as used in conscious acts of self-control and that people often misunderstand the actual underlying reasons for their behavior when influenced by unconscious impulses.

Studies with replication failures have generally neglected to incorporate procedures, learned through earlier trials, that increase the likelihood of pinpointing an unconscious influence on a person's behavior. In many of the original studies, words and verbal material were used to prime a behavior. Studies that have avoided the use of verbal cues and have instead brought to bear more natural and realistic stimuli that trigger a behavior, such as photographs of victorious athletes, have met with more success. These stimuli are the kinds that matter most for unconscious priming effects in our daily lives.

Further support for this area of social psychology has come from imaging studies examining the workings of brain regions activated by the unconscious cues that affect our behaviors and judgments. This work provides some understanding of the physiological basis for priming effects. Brain scans show that areas typically activated by the perception of whether a surface is "rough" or "smooth" also light up when a person does or does not have difficulty—in essence, has a rough or smooth time—interacting with someone else, and the same midbrain regions that respond to physical warmth have been shown to respond to the friendliness and generosity that characterize social warmth.

The question is not whether various unconscious effects on judgments and behaviors are real and can be replicated—because they are and often have been—but rather why some researchers reproduce these effects and others do not. This question is important to advancing our knowledge of how unconscious social influences operate, and it draws needed attention to the precise contexts and conditions required to produce thoughts and behaviors from unconscious priming cues. More work remains. Still, the overall body of evidence collected so far clearly shows that unconscious influences on judgment, emotion, behavior and motivation are of practical importance both to society as a whole and to the everyday lives of its members. *—J.A.B.*

These types of reactions complicate interpersonal relationships and fair treatment in the courts, the workplace and schools precisely because they originate in the unconscious mind. Because we are not aware of them, these feelings tend to get mixed up in whatever we are consciously focusing on at the moment. Instead of recognizing an unacknowledged racial bias, we divert our attention to some negative feature or characteristic about the person in question. A college admissions officer might zero in on a less than stellar grade in an otherwise solid medical school application from a prospective minority student without realizing those same negative features are not weighted so heavily for the other applicants.

Although research on unconscious social perception has often focused on stereotypes and prejudice, in reality the scope of this line of inquiry is much broader. In general, people have a hard time untangling the sources of various positive and negative feelings and are prone to misunderstanding their true causes. In a classic demonstration of this effect, the current day's weather affected how people being interviewed over the telephone rated how well their entire life had gone up to that point—they were more likely to characterize their whole existence as sunny when the weather was nice. Conscious awareness of this effect, moreover, brought about an immediate change. When the interviewers called attention to the weather outside, the feelings colored by the presence of either sun or clouds no longer had an effect.

OUT OF CONTROL

UNCONSCIOUS THOUGHTS and feelings influence not only the way we perceive ourselves and the world around us but also our everyday actions. The effect the unconscious has on behavior has provoked debate among psychologists for decades. For a good part of the 20th century, B. F. Skinner and the behaviorist school of psychology argued forcefully that our actions were entirely under the control of what we saw, heard and touched in our surroundings and that conscious intent played no role. This idea was embodied in the classic experiment in which a rat learns through trial and error that pressing a bar results each time in the animal receiving a food pellet. In the Skinnerian worldview, most of what we do translates into a more sophisticated variation on the theme of pressing the bar with one's snout—we just need to press the equivalent of the correct bar—perhaps sliding the dollar bill in the candy machine—to get what we want.

Research in the 1960s debunked Skinner's behaviorism. Yet the opposite extreme, that behavior is always under intentional control and never directly triggered by environmental cues, is equally false. Merely watching or listening to someone else can make us behave in ways that we do not even realize.

People have a natural tendency to mimic and imitate the physical behavior of others—their emotional expressions, arm and hand gestures, their body postures. These impulses appear throughout the natural world in the fluid way that schools of fish, herds of antelope and flocks of birds coordinate group behavior so that they move almost as if they were a single organism. In humans, the tendency to spontaneously mimic and imitate what others around us are doing has been observed in very young infants and toddlers, and for nearly a century psychologists have argued that being a copycat helps us learn language and other behaviors from our parents.

Imitation, moreover, does not disappear with childhood. In what is known as the chameleon effect, you might find yourself taking on the posture and other physical behaviors of someone you have just engaged in conversation at a party—the crossed legs, the folded arms, the same head scratching. The mimicry carries on until you decide to refresh your drink and seek out a new interlocutor whose stance and gestures you then take up, like a chameleon blending in with its environment. Conforming to the same behaviors of others would seem to make adaptive sense, especially when you do not yet know what is the appropriate thing to do in a given social situation.

The advice "when in Rome, do as the Romans do" makes sense because others are unlikely, in general, to be engaging in unsafe or socially inappropriate behaviors. And as is demonstrated in research by Paula Niedenthal and Robert Zajonc, when both were collaborating at the University of Michigan, a fascinating long-term effect of this propensity toward imitation turns up in couples coming to more closely resemble each other the longer they are together, presumably because on a daily basis they unconsciously assume their partner's facial expressions and postures.

Imitation fosters a social mind-set without the need for providing an explicit road sign that instructs people in what to do next: waiting patiently in a long line encourages others to do the same; holding a door for a neighbor, curbing one's dog and not littering put others in a frame of mind to do the right thing. Unconscious imitation fosters empathetic feelings toward others, a "social glue" that creates a sense of closeness even among total strangers. The strongest form of mimicry results when two or more people engage in the same activity at the same time: armies marching or churchgoers singing a hymn together. Research on behavioral synchrony has shown it has the effect of increasing cooperation even if the individuals involved have never met before.

Unfortunately, the natural tendency toward imitation cuts both ways. As psychologist Kees Keizer of the University of Groningen in the Netherlands and his colleagues found in field research, one misdeed leads to another. The researchers placed graffiti on an alley wall, which led to an increase in littering of pamphlets that were placed around the handlebars of bicycles parked along the alley. Fighting graffiti and other small, nuisance infractions, it turns out, can have a large impact on improving the quality of urban life. This research supports the "broken windows" theory championed most famously by former New York City mayor Rudy Giuliani, who in the mid-1990s promoted the strict enforcement of laws against minor infractions—littering, jaywalking and vandalism; the dramatic drop in crime during this period has been attributed, in part, to this policy.

A tendency to copy others often extends beyond the imitation of mere gestures and facial expressions to taking on facets of someone else's personal identity. When we meet or are reminded of an acquaintance, an unconscious mental process may begin that "primes" us to initiate behaviors characteristic of that individual. Some studies have shown that college students exposed to descriptions associated with the elderly—"Florida," "gray," "bingo," and so on—subsequently walk down the hall more slowly after the experiment is finished, in line with the stereotype of the elderly as slow and weak. Similarly, "priming" words or images related to the stereotypical idea of a nurse leads to greater helping behavior, and cuing stereotypes associated with politicians results in more long-winded speeches. All these effects appear to occur unconsciously, without the participants being aware of how their behavior has been influenced.

Investigations into what social psychologists call stereotype threat have shown that merely bringing to mind a stereotype about, say, race or gender in a member of a group that is the target of such biases may affect performance in school or the workplace. Claude Steele of Stanford University has documented the negative impact on test performance when a minority student, before the exam begins, is asked to check off what racial or ethnic group the student belongs to. The late Nalini Ambady, then at Harvard University, demonstrated that even preschool girls at a Harvard day care do worse on simple math tests if they are first subtly reminded of being female. Widely held positive stereotypes have the opposite effect. In the same study with preschool girls, Asian-Americans did better than average if they were reminded of their ethnic background but faltered if the priming exercise emphasized their gender instead.

Recently controversy has emerged over an inability to reproduce the results of some priming studies. The reasons that the studies could not be repeated are complex and depend, in part, on the methods used to carry them out—subtleties explained further in the accompanying box on the opposite page.

Unconscious influences, in fact, are not always effective in motivating what we do. Many people are familiar with the idea of subliminal advertising in movie theaters—having the words "eat popcorn" flashing imperceptibly on the screen was once thought to cause concession stand sales to boom. Worries about subliminal advertising emerged in the 1950s with Vance Packard's best seller *The Hidden Persuaders*. As it turned out, these reports were mostly bogus, but many people still wonder about the possibility of subliminal messages influencing consumer behavior. Indeed, subsequent research has consistently shown that if a person is already motivated to take some action—quenching thirst, for instance—a subliminal message favoring one brand of beverage over others can be effective.

Regular advertisements, unencumbered by hidden messaging, are powerful influences in their own right. In one new study examining regular television ads, participants watched a five-minute segment of a popular comedy show and were given a bowl of Goldfish crackers. The presence of any food ads during commercial breaks substantially increased consumption of the snack by participants. The food ads primed snacking absent any subliminal subterfuge. The error we often make is to assume

that we can control the effects an ad has on our behavior just because we are fully aware of its content.

EMBODIED COGNITION

SOME OF THE RESEARCH on the unconscious and behavior focuses on the way the surrounding physical environment influences our psychological state of mind. In the 1980s a series of experiments by Fritz Strack, now at the University of Würzburg in Germany, and his colleagues showed that unconscious feedback from their own incidental facial expressions—smiles or frowns—sufficed to cause people to register the value judgment of liking or disliking an object that was in their field of view. Study participants held pencils in either their teeth—activating the smile muscles—or their lips—flexing frown muscles. The physical positioning of the facial muscles produced the corresponding psychological state.

Studies in this area of research, known as embodied cognition, have shown that a host of physical actions and sensations trigger psychological states that are metaphorically related to those behaviors and feelings. Remembering a past incident in which you hurt someone emotionally may cause you to have a stronger desire to help and cooperate with others in a friendly way—a compensation for the bad deed. In one well-known study, after being prompted to recall a guilt-inducing behavior, participants had to wash their hands, ostensibly to help prevent the spread of the flu virus within the room where the experiment took place. The physical act of hand washing seemed to "wash away" guilt. Any lingering friendly or helpful tendencies vanished in the group that had gone through the scrubbing exercises compared with others who had not washed up—a phenomenon dubbed the "Macbeth effect," after Lady Macbeth's compulsive

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hand-washing rituals in the eponymous play by Shakespeare.

In similar fashion, protecting against disease appears to satisfy abstract social or political needs. In one study, politically conservative participants just inoculated against the H1N1 flu virus reported more favorable attitudes toward immigrants compared with those who had not received a shot, as if protection from invasion of the flu virus carried over to a perception that newcomers were well-meaning and not somehow invading and despoiling their adoptive culture.

Metaphors also apply to the way we describe people we routinely encounter. Everyone knows the meaning of a "close" relationship or a "cold" father. One recent theory, conceptual scaffolding, asserts that we use these metaphors so readily because the abstract version of the mental concept is strongly associated with the physical world we inhabit. In experiments, people who clutch a hot coffee cup for a brief time form impressions of others as being "warmer," more friendly and more generous than if they hold, say, an iced coffee. Related studies on the way physical experiences unconsciously influence judgment and behavior in metaphorical ways have revealed that having participants sit on hard chairs during a negotiation causes them to take a "harder" line and compromise less than do those sitting on soft chairs. And when holding something rough, they judge an encounter as more awkward and not having gone smoothly.

We tend to unconsciously evaluate nearly everything we come into contact with in a crude good-or-bad manner. The unconscious, automatic response even translates into our basic movements, our inclination to approach or avoid an object. Clinical psychologist Reinout Wiers of the University of Amsterdam recently developed a successful therapeutic intervention for alcoholism and substance abuse based on this insight. In treatment, patients had to respond to images that represented alcohol abuse in various ways by repeatedly pushing a lever away, without any further instructions about how to evaluate the meaning of the pictures. Compared with a control group of patients, those who responded by pushing away the lever showed markedly lower relapse rates a year later, as well as more reflexively negative attitudes toward alcohol. The unconscious connection between making muscle movements associated with avoidance caused the development both of negative psychological attitudes and of a visceral gut reaction that helped the patients forgo the temptation to imbibe away from the clinic.

FREUD REDUX

THE MOST RECENT EXPERIMENTAL WORK deals with unconscious motivations and goals—the basic question of "What do people want?"—which was, of course, a central theme of Freud's long career. The modern theories about what drives behavior differ from the one put forward by the Austrian neurologist because this thinking derives from studies on groups of average people instead of case studies of abnormal individuals. They also point to a single psychological system that we all possess that can operate in both conscious or unconscious mode, unlike Freud's unconscious, which plays by its owns rules, wholly separate from those that drive conscious activity.

In fact, in the modern psychology of desire, researchers have found that whether or not we are conscious of a particular goal we have set for ourselves, the way we go about pursuing that goal is very similar. In research on this phenomenon by Mathias Pessiglione and Chris Frith, both then at the Wellcome Trust Center for Neuroimaging at University College London, study participants were asked to push a lever as fast as they could when prompted. Before each trial, they received either a conscious or subliminal cue about the reward they would receive. Higher incentives (British pounds versus pence) produced faster pushes, whether they were consciously perceived or not. Moreover, brain imaging revealed the same incentive-sensitive brain regions switch on in both the conscious and the subliminal reward trials. This and other studies suggest that an unconsciously perceived stimulus may suffice to cause someone to actually pursue a goal without any awareness of how it originated—no conscious deliberation or free will required.

Our unconscious mind may not only nudge us to choose a particular option, but it may help muster the necessary motivation to actually achieve it. Psychologists have long known that people given power in a social science experiment often exhibit selfish and corrupt behavior, putting personal interests first. The urge to exert power within a group often reveals itself through a series of subtle, physical cues of which we are unaware. Participants in one study randomly assigned to sit in a professor's desk chair showed less concern with what other people thought of them and had less inhibition about expressing racist and other antisocial sentiments, compared with participants seated instead in a student's chair in front of the desk.

Fortunately, many people's goals are directed toward the welfare of others, as is the case for parents who put their child's interests above their own. If power has the general effect of unconsciously activating important personal goals, these "communally" oriented individuals should react by being more likely to help others and less apt to focus on themselves. Indeed, studies have shown that power causes these individuals to assume more of an altruistic perspective and leave less for others to do, all again without any awareness of their motivations. These individuals also become more preoccupied with what others think of them and display less of a tendency to hold racial biases.

Freud spent countless thousands of words in providing explanations as to why our unfulfilled wishes express themselves in the imagery and stories that populate our nightly dreams. The latest research provides a more pragmatic perspective on how thought and emotion just below the surface of our awareness shape the way we relate to a boss, parent, spouse or child. That means we can set aside antiquated notions of Oedipus complexes and accept the reality that the unconscious asserts its presence in every moment of our lives, when we are fully awake as well as when we are absorbed in the depths of a dream. SA

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ASTRONOMY

The Search for Life on Faraway Moons

Moons orbiting distant exoplanets may account for most of the habitable locales in the galaxy. If only we could find them

By Lee Billings

Illustrations by Ron Miller

Lee Billings is a journalist and author based in New York City. His first book, *Five Billion Years of Solitude,* chronicles the scientific quest to discover Earth-like planets elsewhere in the universe.

We now know of more than 1,000 planets orbiting other stars. In all likelihood, hundreds of billions more call the Milky Way home. Many of the known "exoplanets" are large, gaseous worlds like Jupiter or Neptune— hostile places for life.

But like those giants of our solar system, distant exoplanets may also have large moons. And if they do, moons—not planets—may be the most common home for life in the universe.

The frontier of the search for moons of exoplanets—exomoons—lies deep in the basement of the Harvard-Smithsonian Center for Astrophysics, inside a gloomy room lined with computers in wire-mesh cages. Raising his voice over the mechanical whine of the cooling fans, British astronomer David Kipping remarks that nearly all of this computing power is currently devoted to analyzing a single planet, Kepler-22b, which orbits a sunlike star some 600 light-years away from Earth. The distant world is named for NASA's planet-hunting Kepler space telescope, which first spotted it. Kipping's hope is that on closer inspection, the data that first revealed Kepler-22b's presence may also divulge the subtler signals of lunar companions. He calls his project the Hunt for Exomoons with Kepler, or HEK.

Kipping's project is the most advanced exomoon hunt today. The intense computing power is necessary, Kipping says, because even the largest conceivable exomoon would leave a vanishingly faint signal in the data. Because of this, he intensively searches for evidence of exomoons around just a few carefully selected targets. He may not find as many exomoons as he would with a quick search of lots of targets, but "I'm not sure I'd believe those results," he says. "Our goal is nice, clean, solid detections that everyone can agree on."

He has reason to be circumspect. Any claim of an exomoon discovery would be controversial, not only because the work is difficult but also because the find potentially has profound implications. For instance, Kipping explains, Kepler-22b resides in its star's habitable zone, the region where liquid water could exist. The planet is so large it is likely to be an inhospitable, gas-shrouded orb rather than a rocky, terrestrial world like Earth. If, however, Kepler-22b has a massive lunar companion, that moon might be a pleasant place to live and a possible target for future astronomical searches for extraterrestrial life and intelligence.

"Moons could be habitable," he says. "And if that's true, there's a hell of a lot more opportunities for life out there than anyone has previously appreciated."

MAKING MOONS

MANY ASTRONOMERS (as well as science-fiction authors) had long assumed that other planetary systems would mirror our own, with bountiful icy moons orbiting cold, giant worlds, similar to the arrangements we see around Jupiter and Saturn. With the first exoplanet discoveries of the 1990s, however, new possibilities arose; planet hunters began finding gas-giant planets that, after forming in the outer dark, somehow migrated in to closer, hotter orbits around stars. Some even occupied their stars' habitable zones. Such positioning raised the question: Might some moons around those warm giants have rocky compositions, protective atmospheres and oceans like on Earth?

Three researchers at Pennsylvania State University—Darren Williams, Jim Kasting and Richard Wade—were the first to study in detail how feasible it would be for an exomoon to possess an Earth-like environment. Their study, published in 1997 in *Nature* (*Scientific American* is part of Nature Publishing Group), asked how large a habitable-zone moon must be to maintain a substantial atmosphere and liquid water on its surface. "We found that moons smaller than Mars, about a tenth the mass of Earth, couldn't

IN BRIEF

Astronomers are searching for rocky moons that may circle distant exoplanets.

Such exomoons could be a haven for life, provided that the moon is large enough to hold on to an atmosphere.

These moons might be detectable using existing data sets, but their presence would impart such a subtle signal to the data that massive amounts of processing power would be required to find them.

hold on to an atmosphere for more than a few million years," Williams says. Below that threshold, a moon would not generate enough gravitational force to retain a substantial atmosphere. The atmosphere of such a too tiny moon would boil off in radiation from the nearby star.

The trouble is that moons as big as a terrestrial planet do not seem very easy to build. Astronomers believe that most moons form in much the same way that planets do—gradually coalescing out of a spinning disk of gas, ice and dust [*see box on next page*]. Most computer simulations of this piece-by-piece lunar assembly struggle to produce anything much bigger than Jupiter's Ganymede, the largest moon our solar system managed to make. According to the 1997 study, such a moon would need to bulk up fourfold or fivefold to hang on to a permanent atmosphere.

Fortunately, nature has devised other ways to make massive moons. Earth's moon, for example, is too large to have quiescently formed alongside our planet from a shared disk of gas and dust. Many astronomers think, instead, that our Earth-moon system was forged out of a cataclysmic collision early in our solar system's history. Pluto and its largest moon, Charon, are thought to be another collision-forged duo, albeit on a much smaller scale. These pairs could account for other types of moons. In so-called binary-exchange reactions, a giant planet encountering a binary pair captures one member as a moon while the other member gets ejected into space. This kind of exchange has happened at least once before in our solar system: Neptune's biggest moon, Triton, has a bizarre orbit that moves in the opposite direction of the giant planet's rotation. Astronomers believe that Triton is the captured remnant of a binary pair that Neptune tore apart long ago.

These large moons could potentially support liquid water—and thus life—even if they orbit a planet located outside of a star's habitable zone. Extra warmth could come from the reflected light and emitted heat of a host planet, as well as the planet's gravitational pull. Just as the moon raises tides in Earth's oceans, the gravitational tug of a gas giant could send tidal energy rippling through a nearby moon, flexing the lunar interior and pumping it full of frictional heat. The effect is akin to heating up a metal paper clip by bending it back and forth in your hand. Indeed, if a moon orbits too close to its gas-giant planet, it could experience so much tidal heating that it boils off its atmosphere or melts into a glowing ball of slag, according to recent work by René Heller of McMaster University and Rory Barnes of the University of Washington. In wider lunar orbits, just the right amount of tidal heating could keep moons comfortably toasty, even if the planet is far from its star's warming rays.

Tidal forces could also change a moon's orbit so that it would eternally present only one hemisphere toward its host planet, just as the moon does to Earth. Envisioning the night skies of such tidally locked worlds, Heller says, yields a deeply strange picture. "Imagine, for example, standing on the planet-facing hemisphere of a tidally locked moon," he says. "The planet would be huge and would not move in the sky. At 'noon' on the moon, which corresponds to the point in its orbit where the star would be highest in the sky, the star would pass behind the planet, and there would be no reflected light from the planet. You would see stars all around but only a black disk directly overhead. At 'midnight,' when the moon's orbit would be taking the star beneath your feet, the planet's illuminated face would shift from a crescent to converge on a full circle, and you'd get all that reflected light. So at midnight, your sky would be much brighter than at noon."

SEARCH STRATEGY

MOONS LARGE ENOUGH to hold on to an atmosphere should, in theory, be visible in data from the Kepler satellite. Since its launch in 2009 until gyroscope problems cut short the mission last year, Kepler gazed unceasingly at a single patch of sky, continuously monitoring the brightness of more than 150,000 target stars. It searched for planets by detecting transits: shadows cast toward our solar system as planets crossed the faces of their suns. Each transit manifests as a distinct, recurring dip in a star's "light curve," its brightness plotted over time.

The smallest planet Kepler has found so far, Kepler-37b, is exceedingly small—only slightly larger than Earth's moon. According to Kipping, if Kepler can find moon-size planets, it should also be able to find planet-size moons.

Yet even though Kipping is combing through Kepler's data for signs of them, he is not a member of the Kepler team, nor is his project affiliated with the NASA mission. In fact, anyone could do what he is doing: the Kepler data are publicly available. Astronomers and hobbyists alike have already discovered new planets by sifting through the voluminous data set. Kipping's everyman approach extends to fund-raising as well—he raised $12,000 on a crowdfunding Web site to buy CPUs, which are now part of the Michael Dodds Computing Facility, named for the most generous donor.

Kipping's search strategy is founded on a counterintuitive quirk of gravitational interactions: in a sense, moons orbit planets, but planets also orbit moons. More strictly, a planet and a moon actually orbit a shared center of mass, so that as a moon whips around a planet, the planet wobbles back and forth.

Imagine that you are looking out at a distant moon-planet system. If the moon swings around to the right of the planet, the planet, orbiting the same center of mass, will shift a little bit to the left. Now imagine that moon-planet system transiting left to right across the face of the star. The planet will be left of where it would be if it did not have a lunar companion. This leftward shift, in a left-to-right-moving planet, will delay the onset of the transit by perhaps a few minutes. On the same system's next transit, the moon may be on the other side of its orbit, slightly shifting the position of the planet to the right and advancing the planet's transit a few minutes early.

In addition to these shifts in the onsets of transits, a circling moon can alter the transit's total duration. Unfolding over multiple orbits, this to-and-fro temporal waltz of fluctuating transit properties is an exomoon's expected calling card.

In addition to these timing effects, a sufficiently large moon could block a star's light, adding its own minuscule dip to a transiting planet's signal. The combined planet-moon dip would look much like the signal from an ordinary planet, except for the fact that occasionally the moon would pass directly in front of or behind the planet. The eclipsed moon-planet system would not block quite as much light. Astronomers could use this variation to infer the presence of the hidden moon.

Yet searching for any of these subtle effects has its challenges. A small dip in starlight from a transiting exomoon could just as plausibly be caused by more prosaic phenomena. Every modulation of the light curves so far has been best explained by simple things such as star spots, stellar fluctuations and instrumental errors.

Worse, a single timing signature could be produced by a wide range of possible planet-moon arrangements that varied in details such as the size of the moon and the period and inclination of its

How to Make a Moon

Scientists don't expect gaseous Jupiter-like planets to harbor much life, but if such a planet is home to a sufficiently large moon, the moon just might. A fertile moon would have to be massive enough to gravitationally hold on to a thin atmosphere, however. Different methods of moon formation can lead to moons of vastly different sizes.

Lumps from a Disk

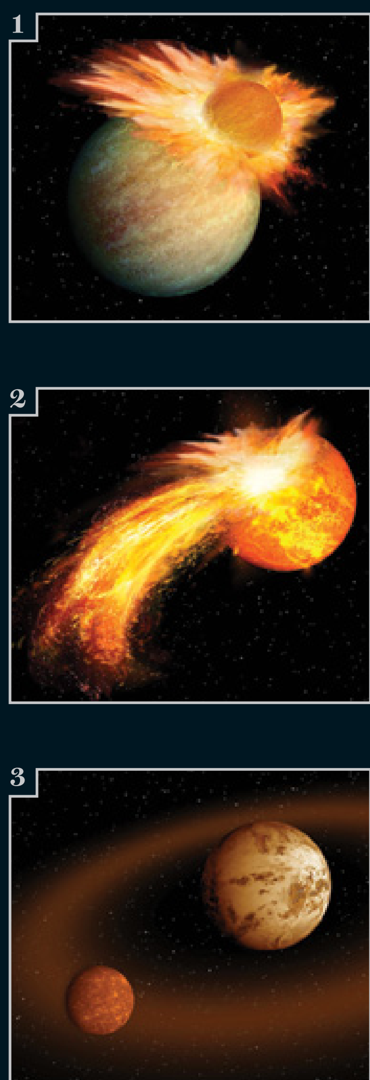
Example: Jupiter's moons

Planets are thought to form out of a disk of dust, gas and ice spinning around a star. Around these young planets additional disks might form, like eddies in a current (*1*). Over millions of years these secondary disks of matter clump into rings and moons (*2* and *3*). Yet these processes can build moons only as big as Jupiter's Ganymede—not large enough to hold on to an atmosphere.

Massive Collision

Example: Earth's moon

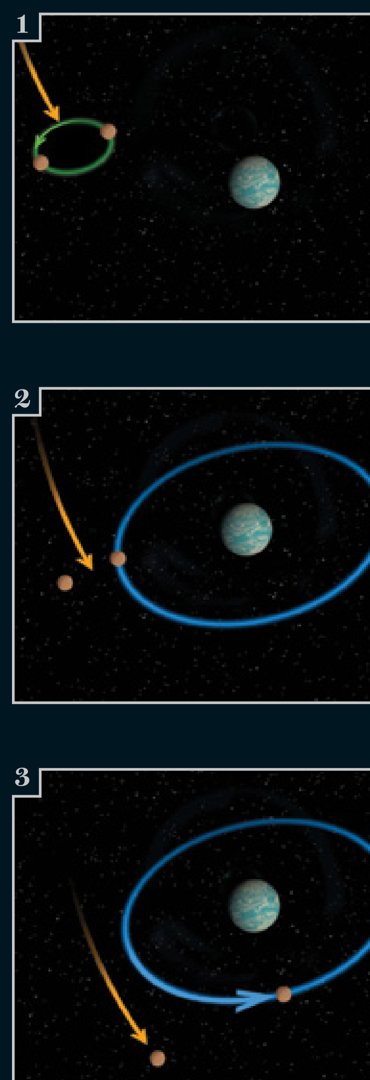
Soon after Earth formed, astronomers believe it was struck by a Mars-size object (*1*). The resulting cataclysm spit out a shower of rock and iron (*2*) that, over time, cooled and turned into the moon (*3*). In theory, such collisions could result in two objects that are nearly equal in size. In this double-planet scenario, the "moon" would be just as big as its "planet."



Binary Capture

Example: Neptune's moon Triton

Once a double-planet system forms—perhaps by collision—the pair could encounter another, larger planet (*1*). As the pair flies by (*2*), the larger planet could pull in one of the objects and fling the other off into space (*3*). Captured moons that come from binary planet systems could also be relatively large.



SCIENTIFIC AMERICAN ONLINE Watch how an exomoon would affect the light from a star at ScientificAmerican.com/jan2014/exomoons orbit. This inherent uncertainty makes it quite difficult to characterize any given exomoon through timing alone.

Yet if astronomers manage to pin down a planet-moon system's orbital configuration through timing effects, as well as the moon's dip in a light curve, they can establish masses for the system's moon, the planet and the star. By pairing those masses with size estimates based on how much starlight a planet or moon blocks, astronomers can infer each object's density, creating a window into the composition, formational history, and potential habitability of planets and their moons. With careful scrutiny of transit after transit for any given system, even more faint details can coalesce from those fluctuations of starlight.

"It's amazing how much can be packed into a light curve," Kipping muses in his office, several floors above the subterranean computer room. "What happens if a transiting planet or moon is slightly oblate or if it has rings? What happens if a world's atmosphere refracts and bends the starlight passing through? These sorts of effects can be salient in the data. It's incredibly satisfying to look up at the stars, these twinkling pinpricks of light in the sky at night, and know that we're able to take this simple measurement of brightness and turn it into all this more complex information."

To tease out the presence of a moon orbiting any particular transiting planet, Kipping's HEK project first makes a guess. What would the light curve look like if a moon were orbiting this particular planet? The HEK algorithm generates a very large number of artificial light curves from hypothetical, virtual planet-moon systems that possess a wide variance of masses, radii and orbits. Next it sifts through the Kepler data for matches, gradually homing in on any statistically plausible lunar signals. This exhaustive trial-and-error process is why HEK requires so much computing power. It is also why Kipping prefers to carefully select just the very best targets from Kepler's gargantuan hoard of planets and candidates. Most of those targets are low-mass, Neptune-size worlds that orbit fairly close to a sunlike host star, completing an orbital lap in six months or less. Such planets would manifest the clearest signals of an accompanying large moon.

The project also plans to examine transiting planets around red dwarf stars, which are far smaller, dimmer and more numerous than stars like our sun. The small sizes mean that a transiting planet will block a higher percentage of the star's total light. The relatively dim output moves the habitable zone close to the star; any planet orbiting at that radius would have to whip around quickly, giving astronomers more transits to work with. "For us, everything gets better with these stars," Kipping says. "In the very best cases, we could probably detect a moon only a tenth or a fifth of an Earth-mass."

In perhaps the very worst case, HEK will detect no exomoons at all, a prospect that would at least allow Kipping and his colleagues to set upper limits on how many planets harbor large moons. Already we know something about what is not there. "If there were lots of really big moons, like a two-Earth-radius moon around a Jupiter-size transiting planet, you could just look by eye at the light curve and see the moon's effect," says University of Florida astronomer Eric Ford. "So there's a good chance if that was in the Kepler field, someone would've found it by now or be hot on its trail." After further analysis, Kipping's team has ruled out the possibility that Kepler-22b, one target of the early investigations, has a moon larger than about half the size of Earth.

Other astronomers, such as Eric Agol of the University of Washington, remain skeptical that Kepler's current data set can deliver verifiable exomoons, particularly via temporal effects alone. "My opinion is that a believable detection is going to require actually seeing the transit of a moon," Agol says. "But that's at the very hairy edge of what Kepler can do. Of course, nature can always surprise us."

Despite his doubts, Agol acknowledges that he and a few other collaborators are pursuing an unofficial search of their own, one that, in comparison to HEK, uses less intensive computation to seek more obvious effects in a larger number of Kepler light curves. "My feeling is our search should be around every planet that's been detected, within reason," Agol says.

LUNAR LENSES

KIPPING POINTS OUT that moons can increase the chance for life in more than one way. For example, he says, without the moon, Earth's climate and seasons could be quite different because on astronomical timescales the moon helps to stabilize our planet's tilt. What is more, before the moon spiraled out to its present orbital distance from our world, its enormous tidal effects on the early Earth could have played a vital role in the origin and flourishing of life.

"When we find an Earth-size planet in the habitable zone, one of the first questions will be, 'Well, does it have a moon?'" Kipping says. The answer to that question will help determine whether a planet is a true Earth twin or merely a cousin with a vague family resemblance. "I wonder if our own is a fluke or if things like it are really common," he adds. "With a sample size of one, we can't really know the answer. If we find some outside our solar system, we'll get a better idea."

Through the right kind of telescopic eyes, ones well beyond Kepler's capabilities, an exomoon could do far more than simply signpost a promising mirror Earth orbiting a nearby star. Whether observing an Earth-size transiting planet or an Earth-size transiting moon, Kipping says, a sufficiently large telescope on the ground or in space could investigate that distant world's atmosphere, looking for markers of life, such as the oxygen that fills our own planet's skies.

Kipping also thinks some exomoons could be used to map the surfaces of their host planets. Astronomers already use transiting planets to map the surfaces of stars by carefully monitoring the star's brightness as the planet crosses its face. "When a moon passes in front of a planet as seen from Earth, you're getting the same opportunity, but now you're looking at the surface brightness of the planet," he explains. "So, potentially, using something very sophisticated, you could begin mapping an Earth twin's continents, its water distribution, all from how the light curve changes shape as the moon passes over. Sometimes I think that's the most likely way we'll ever get anything like a photograph of one of these potentially habitable planets. This could be the first, smallest slice of a very big pie." SA

MORE TO EXPLORE

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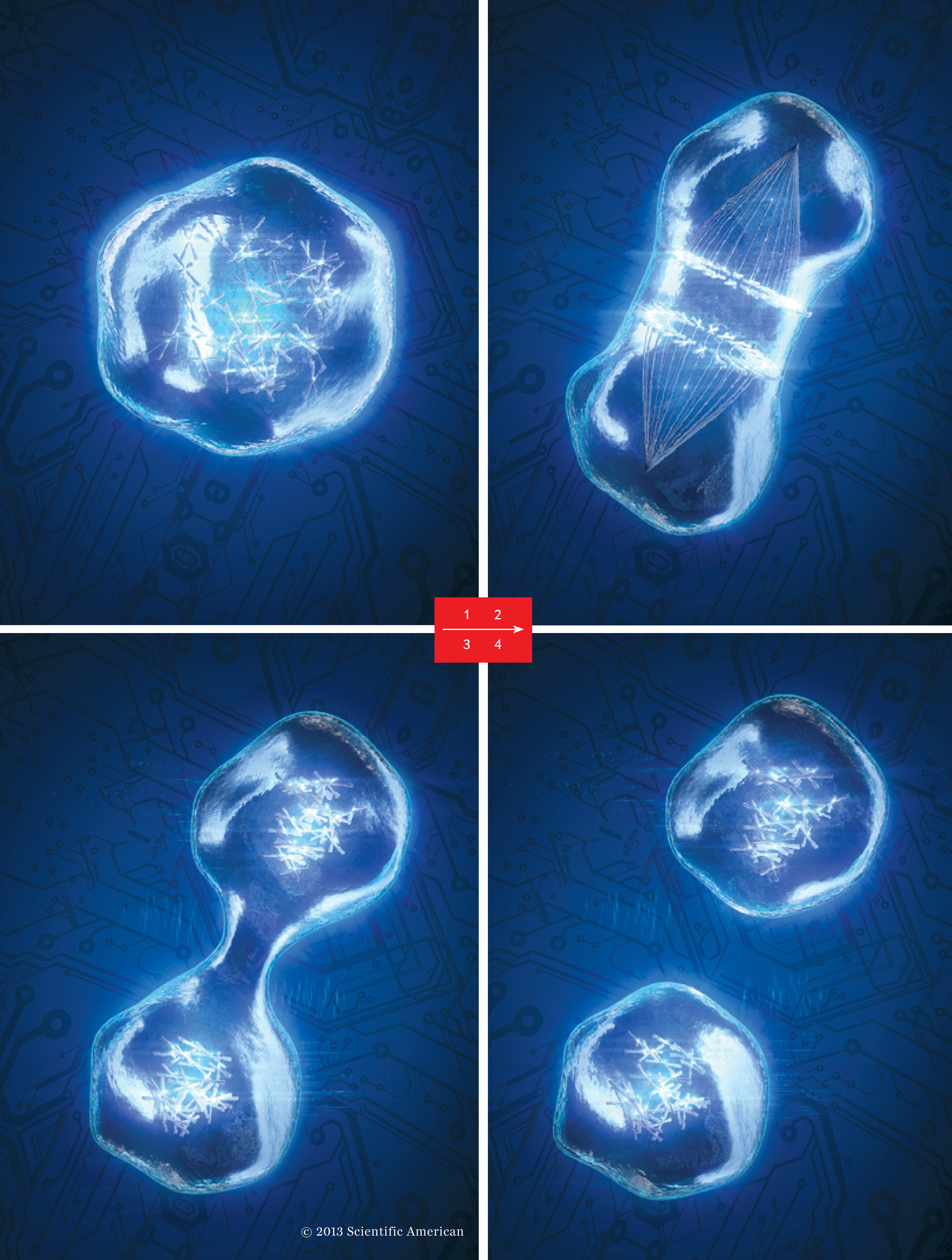
BIOENGINEERING

SIM(U)²LATING A + LIVING → CELL

In creating the first complete computer model of an entire single-celled organism, biologists are forging a powerful new kind of tool for illuminating how life works

By Markus W. Covert

Illustration by André Kutscherauer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Markus W. Covert is an assistant professor of bioengineering at Stanford University, where he directs a laboratory devoted to systems biology.

THE CRUCIAL INSIGHT CAME TO ME AS I LEISURELY RODE MY BIKE HOME FROM WORK. It was Valentine's Day, 2008. While I cruised along, my mind mulled over a problem that had been preoccupying me and others in my field for more than a decade. Was there some way to simulate life—including all the marvelous, mysterious and maddeningly complex biochemistry that makes it work—in software?

A working computer model of living cells, even if it were somewhat sketchy and not quite accurate, would be a fantastically useful tool. Research biologists could try out ideas for experiments before committing time and money to actually do them in the laboratory. Drug developers, for example, could accelerate their search for new antibiotics by homing in on molecules whose inhibition would most disrupt a bacterium. Bioengineers like myself could transplant and rewire the genes of virtual microorganisms to design modified strains having special traits—the ability to fluoresce when infected by a certain virus, say, or perhaps the power to extract hydrogen gas from petroleum—without the risks involved in altering real microbes. Eventually, if we can learn to make models sophisticated enough to simulate human cells, these tools could transform medical research by giving investigators a way to conduct studies that are currently impractical because many kinds of human cells cannot be cultured.

But all that seemed like a pipe dream without a practical way to untangle the web of interlinked chemical reactions and physical connections that make living cells tick. Many previous attempts, by my lab at Stanford University as well as others, had run into roadblocks; some had failed outright.

But as I pedaled slowly through the campus that winter evening, I thought about the work I had been doing recently to record images and video of single living cells. That's when it hit me—a way to make a realistic, functional simulator: choose one of the simplest single-celled microbes out there, a bacterium called *Mycoplasma genitalium,* and build a model of an individual germ. Limiting the simulation to just one cell would simplify the problem enough that we could, in principle, include every bit of biology known to occur in that cell—the unwinding of every rung of its twisted DNA ladder, the transcription of every message in that DNA into an RNA copy, the manufacture of every enzyme and other protein made from those RNA instructions, and the interactions among every one of those actors and many others, all building to cause the cell to grow and eventually divide into two "daughters." The simula-

IN BRIEF

Computer models that can account for the function of every gene and molecule in a cell could revolutionize how we study, understand and design biological systems.

A comprehensive simulation of a common infectious bacterium was completed last year and, while still imperfect, is already generating new discoveries.

Scientists are now building models of more complex organisms. Their long-term goal is to simulate human cells and organs in comparable detail.

tion would generate, nearly from first principles, the entire drama of single-celled life.

Previous attempts had always tried to simulate a whole colony of cells because that is how almost all the data we have on cell behavior were collected: from populations, not individuals. Advances in both biotechnology and computing, however, had started to make single-cell studies much easier to do. Now, I realized, the tools were at hand to try a different approach.

Ideas whirred around in my head. The minute I reached home, I started sketching out plans for a simulator. The next morning, I began writing software code for just a couple of the many, many distinct processes that go on in a living microorganism. Within a week, I had completed several prototype modules, each one a software representation of a particular cellular process. The modules were producing output that looked fairly realistic.

I showed the work to a handful of other biologists. Most of them thought I was nuts. But I felt I was on to something, and two exceptional and daring graduate students, Jonathan R. Karr and Jayodita C. Sanghvi, saw enough potential in the approach that they agreed to work with me on the project.

Completing this model would mean creating dozens of such modules, combing through nearly 1,000 scientific articles for biochemical data, and then using those values to constrain and tweak thousands of parameters, such as how tightly enzymes bind to their target molecules and how often DNA-reading proteins bump one another off the double helix. I suspected that, even with the diligent help of collaborators and graduate students, the project would take years—but I also had a hunch that, at the end, it would work. There was no way to know for sure, except to try.

A GRAND CHALLENGE

AS WE SET OUR SIGHTS on summiting this mountain, we took inspiration from the researchers who first dreamed of modeling life. In 1984 Harold Morowitz, then at Yale University, laid out the general route. He observed at the time that the simplest bacteria that biologists had been able to culture, the mycoplasmas, were a logical place to start. In addition to being very small and relatively simple, two species of *Mycoplasma* cause disease in humans: the sexually transmitted, parasitic germ *M. genitalium,* which thrives in the vaginal and urinary tracts, and *M. pneumoniae,* which can cause walking pneumonia. A model of either species could be quite medically useful, as well as a source of insight into basic biology.

The first step, Morowitz proposed, should be to sequence the genome of the selected microbe. J. Craig Venter and his colleagues at The Institute for Genome Research (TIGR) completed that task for *M. genitalium* in 1995; it has just 525 genes. (Human cells, in contrast, have more than 20,000.)

I was a graduate student in San Diego when, four years later, the TIGR team concluded that only 400 or so of those genes are essential to sustain life (as long as the microbes are grown in a rich culture medium). Venter and his co-workers went on to found Celera and race the federal government to sequence the human genome. They synthesized the essential genes of one *Mycoplasma* species and showed they functioned in a cell.

To me and other young biologists in the late 1990s, this gang was Led Zeppelin: iconoclastic, larger-than-life personalities playing music we had never heard before. Clyde Hutchinson, one of the biologists in Venter's band, said that the ultimate test of our understanding of simple cells would come when someone modeled one in a computer. You can build a functional cell in the lab by combining pieces without understanding every detail of how they fit together. The same is not true of software.

I showed the sample code to a handful of other biologists. Most of them thought I was nuts. But I felt I was on to something.

Morowitz, too, had called for building a cell simulator based on genome data from *Mycoplasma.* He argued that "every experiment that can be carried out in the lab can also be carried out on the computer. The extent to which these [experimental and simulation results] match measures the completeness of the paradigm of molecular biology"—our working theory of how the DNA and other biomolecules in the cell interact to yield life as we know it. As we put the puzzle together, in other words, it becomes more obvious which pieces and which interactions our theory is missing.

Although high-throughput sequencers and robotic lab equipment have greatly accelerated the search for the missing pieces, the floods of DNA sequences and gene activity patterns that they generate do not come with explanations for how the parts all fit together. The pioneering geneticist Sydney Brenner has called such work "low-input, high-throughput, no-output" biology because too often the experiments are not driven by hypotheses and yield disappointingly few insights about the larger systems that make life function—or malfunction.

This situation partly explains why, despite headlines regularly proclaiming the discovery of new genes associated with cancer, obesity or diabetes, cures for these diseases remain frustratingly elusive. It appears that cures will come only when we untangle the dozens or even hundreds of factors that interact, sometimes in unintuitive ways, to cause these illnesses.

The pioneers of cell modeling understood that simulations of whole cells that included all cellular components and their webs of interactions would be powerful tools for making sense of such jumbled, piecemeal data. By its nature, a whole-cell simulator would distill a comprehensive set of hypotheses about what is going on inside a cell into rigorous, mathematical algorithms.

The cartoonlike sketches one often sees in journal articles showing that factor X regulates gene Y … somehow … are not nearly precise enough for software. Programmers express these processes as equations—one of the simpler examples is $Y = aX + b$—even if they have to make educated guesses as to the values of variables such as a and b. This demand for precision ultimately reveals which laboratory experiments must be done to fill holes in knowledge of reaction rates and other quantities.

At the same time, it was clear that once models had been verified as accurate, they would take the place of some experiments, saving the costly "wet" work for questions not answerable by simulations alone. And simulated experiments that generated surprising results would help investigators to prioritize their research and increase the pace of scientific discovery. In fact, models offered such tempting tools for untangling cause and effect that, in 2001, Masaru Tomita of Keio University in Japan called whole-cell simulation "a grand challenge of the 21st century."

When still a graduate student, I was impressed by the early results of the leading cell modelers of the time [*see box on opposite page*], and I became obsessed with this grand challenge. Even as I set up my own lab and focused on developing techniques for imaging single cells, the challenge remained in my thoughts. And then, on that February bicycle ride home, I saw a way to meet it.

As I flipped through the plots and visualizations, my heart began to race. The model was up and running. What would it teach us?

TWO CRUCIAL INSIGHTS

IT WAS CLEAR that before we could simulate the life cycle of a microbial species accurately enough to mimic its complex behaviors and make new discoveries in biology, we would have to solve three problems. First, we needed to encode all the functions that matter—from the flow of energy, nutrients and reaction products through the cell (that is, its metabolism), to the synthesis and decay of DNA, RNA and protein, to the activity of myriad enzymes—into mathematical formulas and software algorithms. Second, we had to come up with an overarching framework to integrate all these functions. The final problem was in many ways the hardest: to set upper and lower limits for each of the 1,700-odd parameters in the model so that they took on values that were biologically accurate—or at least in the right ballpark.

I understood that no matter how exhaustively we scrutinized the literature about *M. genitalium* and its close relations for those parameters (Karr, Sanghvi and I eventually spent two years culling data from some 900 papers), we would have to make do in some cases by making educated guesses or by using results from experiments on very different kinds of bacteria, such as *Escherichia coli,* to obtain certain numbers, such as how long RNA transcripts hang around in the cell, on average, before enzymes rip them apart to recycle their pieces. Without a way to constrain and check those guesses, we had no hope of success.

In that aha! moment in 2008, I had realized that modeling a single cell—rather than a bunch of cells, as almost all previous studies had done—could give us that constraint we needed. Consider growth and reproduction. A large population of cells grows incrementally; the birth or death of an individual cell does not change things much. But for a single cell, division is a very dramatic event. Before it splits in two, the organism has to double its mass—and not just its overall mass. The amounts of DNA, cell membrane and every kind of protein needed for survival must each double. If the scope of the model is constrained to a single cell, the computer can actually count and track every molecule during the entire life cycle. It can check whether all the numbers balance as one cell becomes two.

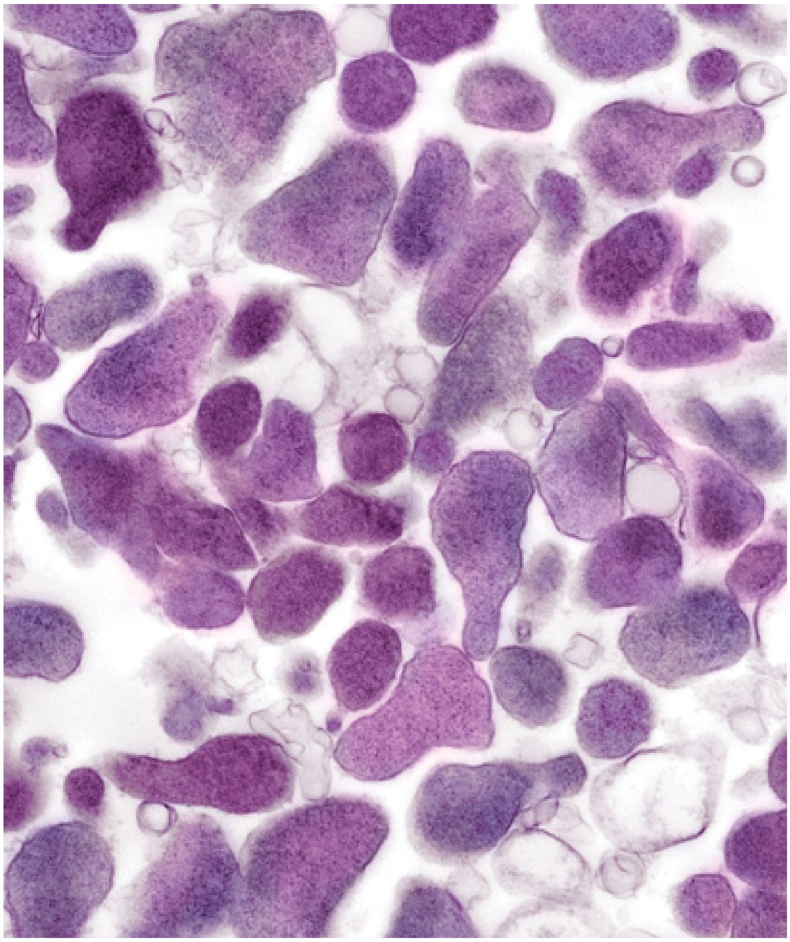
Moreover, a single cell reproduces at essentially a set pace. *M. genitalium,* for example, typically divides every nine to 10 hours in a normal lab environment. It rarely takes fewer than six hours or more than 15. The requirement that the cell must duplicate all of its contents on this strict schedule would allow us to choose plausible ranges for many variables that would otherwise have been indeterminate, such as those that control when replication of the DNA begins.

I put together a team of physicists, biologists, modelers and even a former Google software engineer, and we discussed what mathematical approaches to use. Michael Shuler, a biomedical engineer at Cornell University who was a pioneer in cell simulation, had built impressive models from ordinary differential equations. Bernhard Palsson, under whom I studied in San Diego, had developed a powerful technique, called flux-balance analysis, that worked well for modeling metabolism. But others had shown that random chance is an important element in gene transcription, and cell division obviously involves a change in the geometry of the cell membrane; those other methods would not address these aspects. Even as a grad student, I had realized that no one technique could model all the functions of a cell; indeed, my dissertation had demonstrated a way to link two distinct mathematical approaches into a single simulator.

We decided, therefore, to create the whole-cell model as a collection of 28 distinct modules, each of which uses the algorithm that best suits the biological process and the degree of knowledge we have about it [*see box on page 50*]. This strategy led to a patchwork collection of mathematical procedures, however. We needed to sew them all together somehow into one cohesive whole.

Milestones in Modeling Cells

The long path to the author's first working model of a single cell of a simple bacterium, *Mycoplasma genitalium,* was informed by the theoretical, genetic and modeling efforts of other researchers. Designing a computer model of a human cell is sure to be harder still, given the far greater complexity of mammalian cells. Human cells, for example, contain nearly 40 times as many genes, and those genes are packed into sets of chromosomes that are far more intricate in their physical structure and in the patterns of information they contain. Some critical intermediate steps that need to be accomplished are listed at the bottom right.



SINGLE-CELLED BACTERIUM *Mycoplasma genitalium* (*purple bodies*) is about as simple as life gets. Yet modeling its life cycle was no easy task.

1967

Francis Crick and Sydney Brenner formulate and propose "Project K: 'The Complete Solution of *E. coli,*'" an effort to figure out the "design" of this common gut bacterium, including fine details of its genetics, energy processing and reproduction.

1984

Harold Morowitz, then at Yale University, outlines a plan to sequence and then model a *Mycoplasma* bacterium.

1984

A team led by Michael Shuler of Cornell University presents a computer model that uses differential equations to capture most of the major biological processes involved in the growth of a single cell of *Escherichia coli.* The model was not able to include gene-level activity, because the *E. coli* genome had not yet been sequenced.

1989–1990

Bernhard Palsson of the University of Michigan releases a comprehensive model of the metabolism of the human red blood cell that includes the effects of pH variation and low blood glucose.

1995

J. Craig Venter of TIGR and his colleagues complete the genome sequence of *M. genitalium.*

1999

Masaru Tomita and his teammates at Keio University in Japan construct E-Cell, a cell-modeling system based on differential equations that includes 127 genes, most of them from *M. genitalium.*

2002

The Alliance for Cellular Signaling, a large collaboration of about 50 researchers, launches an ambitious 10-year, $10-million effort to model mouse B cells of the immune system and heart muscle cells. The project generates some exciting data sets but encounters difficulties manipulating B cells in culture.

2002

Palsson, George Church of Harvard University and Covert, along with several others, complete a genome-scale model of the metabolism of *Helicobacter pylori,* a bacterium that infects humans and can cause stomach ulcers and stomach cancer.

2004

Palsson and Covert, along with three others, publish a computational model of all 1,010 genes involved in regulating the metabolism and DNA transcription of *E. coli* and show that the model accurately predicts the results of lab experiments on real bacteria.

2012

Covert and his co-workers publish a whole-cell model of *M. genitalium* that, for the first time, simulates all the genes and known biochemical processes in a self-reproducing organism.

2013

Covert and his colleagues show that the model accurately predicts the activity of several enzymes.

WHAT'S NEXT

- Complete a whole-cell model for a more typical, better-studied bacterium, such as *E. coli.*
- Model a single-celled eukaryote, such as the yeast *Saccharomyces cerevisiae.* In a eukaryote, the DNA is packaged inside a membrane-bound nucleus, not free-floating as it is in a bacterium.
- Build a model of an animal cell that can be easily cultured, such as a macrophage (a kind of immune cell) from a mouse.
- Construct a first-draft model of a human cell—again, probably a macrophage.
- Model other kinds of human cells, especially those that play the most important roles in common diseases.

SCIENCE SOURCE

The Simulator at Work

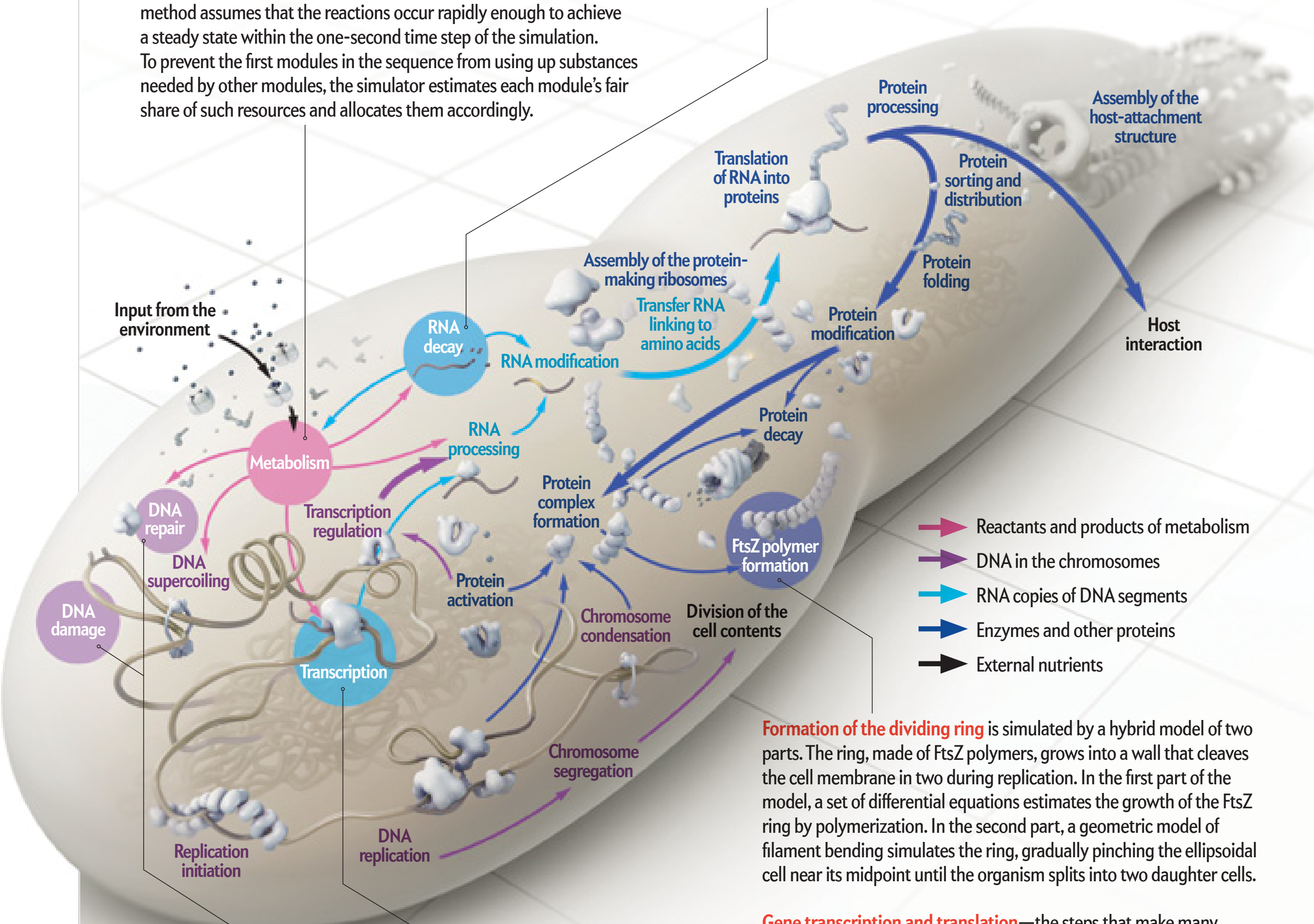
The author's computer model of the infectious bacterium *Mycoplasma genitalium* represents almost every aspect of the life, growth and replication of this microbe. No single mathematical approach can simulate every biological function in the cell, so these functions are divided among 28 distinct modules (*labeled in cell below*), which are involved in the processing of DNA (*purple*), RNA (*light blue*), proteins (*dark blue*), and energy, nutrients and waste (*pink*). For each module, the researchers selected whichever mathematical method worked best—several examples are highlighted below.

The program begins with all modules running in a random sequence to simulate one second of real time. Many input values are drawn from a large table of variables representing their initial states, and some values are selected from ranges or probability functions. Researchers can simulate different scenarios by altering the starting configuration.

After the first time step, the program updates the state table to reflect the outputs of all the modules. The sequence then runs again for another one-second time step, updates the cell-state table, and so on. The loop continues until the cell divides successfully, dies or becomes unrealistically old.

Metabolism of energy, nutrients and waste is modeled by using flux-balance analysis, which exploits linear programming techniques to calculate the reaction rates that produce optimal growth, energy production or some other characteristic the modeler chooses. This method assumes that the reactions occur rapidly enough to achieve a steady state within the one-second time step of the simulation. To prevent the first modules in the sequence from using up substances needed by other modules, the simulator estimates each module's fair share of such resources and allocates them accordingly.

Decay and recycling of RNA and protein are modeled by using Poisson processes, which make use of a random-number generator and probability functions to decide whether a particular piece of RNA or protein decays or survives to the next time step.



Formation of the dividing ring is simulated by a hybrid model of two parts. The ring, made of FtsZ polymers, grows into a wall that cleaves the cell membrane in two during replication. In the first part of the model, a set of differential equations estimates the growth of the FtsZ ring by polymerization. In the second part, a geometric model of filament bending simulates the ring, gradually pinching the ellipsoidal cell near its midpoint until the organism splits into two daughter cells.

Gene transcription and translation—the steps that make many of the proteins needed for cell growth and duplication—are simulated by multipart algorithms that include Markov models (which track over time the states of the enzymes that copy genes from DNA into RNA), probabilistic binding of these enzymes to the DNA, and linear programming to allocate energy and other resources.

DNA damage and repair are also modeled in this nondeterministic way.

SOURCE: "A WHOLE-CELL COMPUTATIONAL MODEL PREDICTS PHENOTYPE FROM GENOTYPE," BY JONATHAN R. KARR ET AL., IN *CELL*, VOL. 150, NO. 2; JULY 20, 2012

SCIENTIFIC AMERICAN ONLINE See examples of the simulator's output at ScientificAmerican.com/jan2014/cell-model

Illustration by AXS Biomedical Animation Studio

I thought back to an undergraduate course I had taken on chemical plant design. For the final class project, we used a powerful simulator package called HYSYS to sketch out a large refinery. HYSYS let us design each principal reaction to occur in a separate vessel. Pipes then connected the output of one vessel to the inputs of others. This framework connected many different kinds of chemical operations into an orderly, predictable system.

It occurred to me that this approach, with some modification, might work for our cell simulator if I was willing to make an important, simplifying assumption: that even though all these biological processes occur simultaneously in a living cell, their actions are effectively independent over periods of less than a second. If that assumption was sound, we could divide the life of the cell into one-second ticks of the clock and run each of the 28 modules, in order, for one tick before updating the pool of cell variables. The model would capture all the interconnectedness of biochemistry—the reliance of gene transcription and DNA synthesis on the energy and nucleotides produced by metabolism, for example—but only on timescales greater than one second.

We had no theoretical proof that this would work. It was a leap of faith.

While constructing our virtual cell, we put in software sensors to measure what was going on inside. Every run of the simulator, covering the entire life cycle of a single cell, churned out 500 megabytes of data. The numerical output flowed into a kind of instrument panel—a collection of dozens of charts and visualizations that, when printed, completely filled a binder.

The results were frustrating at first. For months, as we debugged the code, refined the math, and added more and better lab-derived constraints for the parameters, the cell refused to divide or behaved erratically. For a while it produced huge amounts of the amino acid alanine and very little else.

Then, one day, our cybernetic germ reached the end of its cell cycle and divided successfully. Even more exciting, the doubling time was around nine hours, just like that of living *M. genitalium*. Many other readings were still way off, but we felt then that success was within reach.

Months later I was at a two-day conference in Bethesda, Md., when I was called to the hotel's front desk between sessions.

"Dr. Covert? This package came for you."

Back in my room, I peeled open the box and pulled out a binder. As I spent the next hours flipping through hundreds of pages of plots and complex visualizations, my heart began to race. The great majority of the data looked just like one would expect from an actual growing cell. And the remainder was intriguing—unexpected but biologically plausible. That is when I knew we had reached the summit of that mountain that loomed so large years ago. The first computer model of an entire living organism was up and running. What would it teach us?

A WINDOW INTO THE LIFE OF A CELL

AFTER ABOUT A YEAR of applying our new tool, we still see fascinating things every time we peer inside the workings of the virtual microorganism as it handles the millions of details involved in living and reproducing. We found, to our surprise, that proteins knock one another off the DNA shockingly often—about 30,000 times during every nine-hour life cycle. We also discovered that the microbe's remarkably stable doubling period is actually an emergent property that arises from the complex interplay between two distinct phases of replication, each of which independently varies wildly in duration. And the second-by-second records of the cell's behavior have allowed us to explain why it is that the cell stops dividing immediately when certain genes are disabled but reproduces another 10 times before dying when other essential genes are turned off. Those additional rounds of division can happen whenever the cell stockpiles more copies of the protein made from the gene than it needs in one lifetime—the extra is passed on to its descendants, which perish only when the store at last runs out. These initial results are exciting, but we may need years to understand everything that these simulations are telling us about how these microbes, and cells in general, function.

Our work with *M. genitalium* is only the first of many steps on the way to modeling human cells or tissues at the level of genes and molecules. The model that we have today is far from perfect, and mycoplasmas are about as simple as self-sustaining life-forms get. We have made all our simulations, source code, knowledge base, visualization code and experimental data freely available online, and we and other investigators are already working to improve the simulator and extend it to a variety of organisms, such as *E. coli* and the yeast *Saccharomyces cerevisiae,* both of which are ubiquitous in academic and industrial labs.

In these species, the regulation of genes is much more complex, and the location within the cell at which events occur is far more important. When those issues have been addressed, I anticipate that the next target will be a mouse or human cell: most likely a cell, such as a macrophage (an attack cell in the immune system), that can be readily cultured and employed as a source of measurements to both tune and validate the model.

I cannot guess how far we are today from such technology. Compared with bacteria, human cells have many more compartments and exhibit far greater genetic control, much of which remains mysterious. Moreover, as team players within multicellular tissues, human cells interact more intimately with other cell types than bacteria do.

On February 13, 2008, I would have said that we were at least a decade away from the goal of modeling the simplest cell, and I would not have even considered attempting to model anything more complex. Now we can at least conceive of trying to simulate a human cell—if only to see how the software fails, which will illuminate the many things we still need to learn about our own cells. Even that would be a pretty big step. SA

MORE TO EXPLORE

The Dawn of Virtual Cell Biology. Peter L. Freddolino and Saeed Tavazoie in *Cell,* Vol. 150, No. 2, pages 248–250; July 20, 2012.

A Whole-Cell Computational Model Predicts Phenotype from Genotype. Jonathan R. Karr et al. in *Cell,* Vol. 150, No. 2, pages 389–401; July 20, 2012.

Bridging the Layers: Toward Integration of Signal Transduction, Regulation and Metabolism into Mathematical Models. Emanuel Gonçalves et al. in *Molecular Biosystems,* Vol. 9, No. 7, pages 1576–1583; July 2013.

FROM OUR ARCHIVES

Cybernetic Cells. W. Wayt Gibbs; August 2001.

ENERGY

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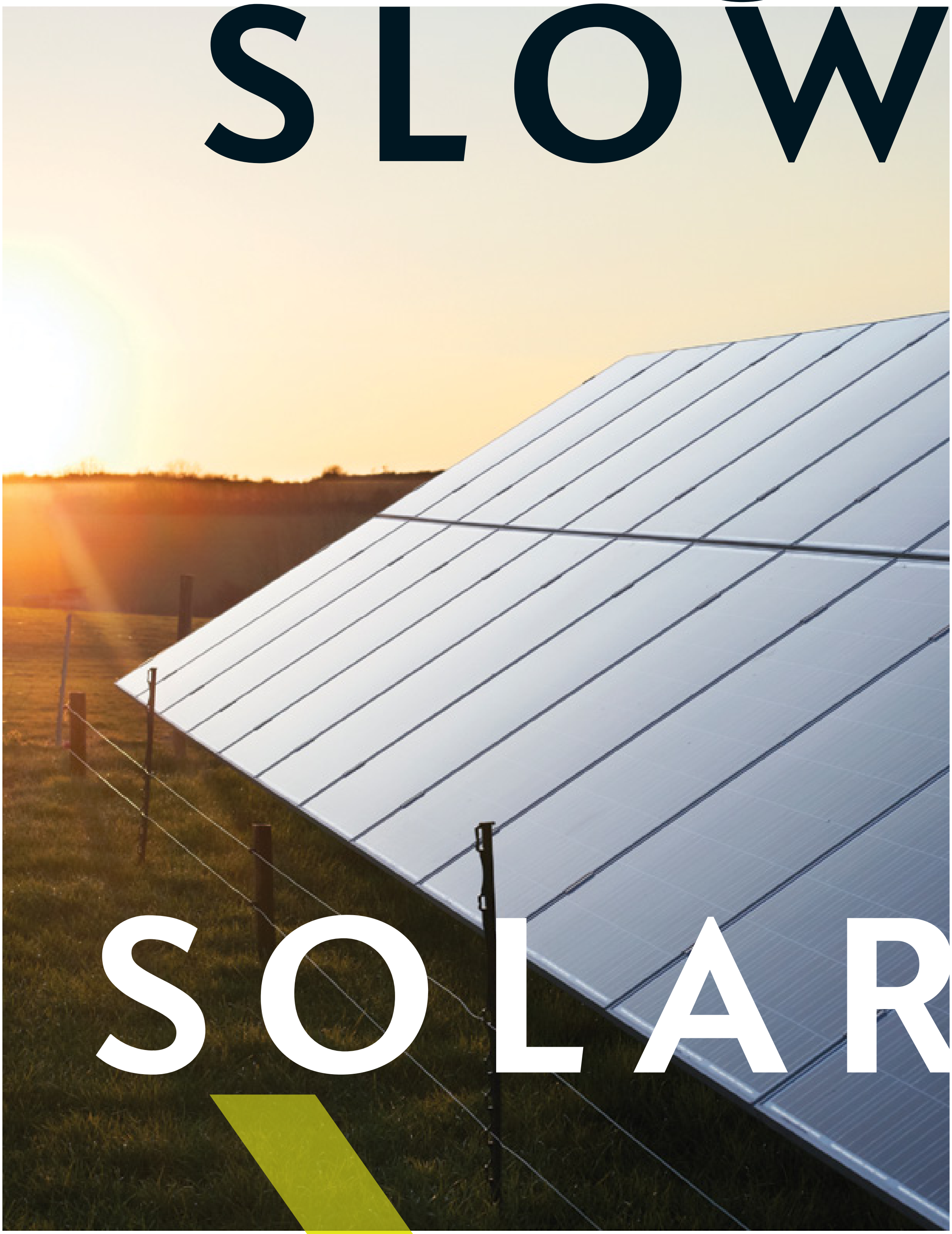

SOLAR

The great hope for a quick and sweeping

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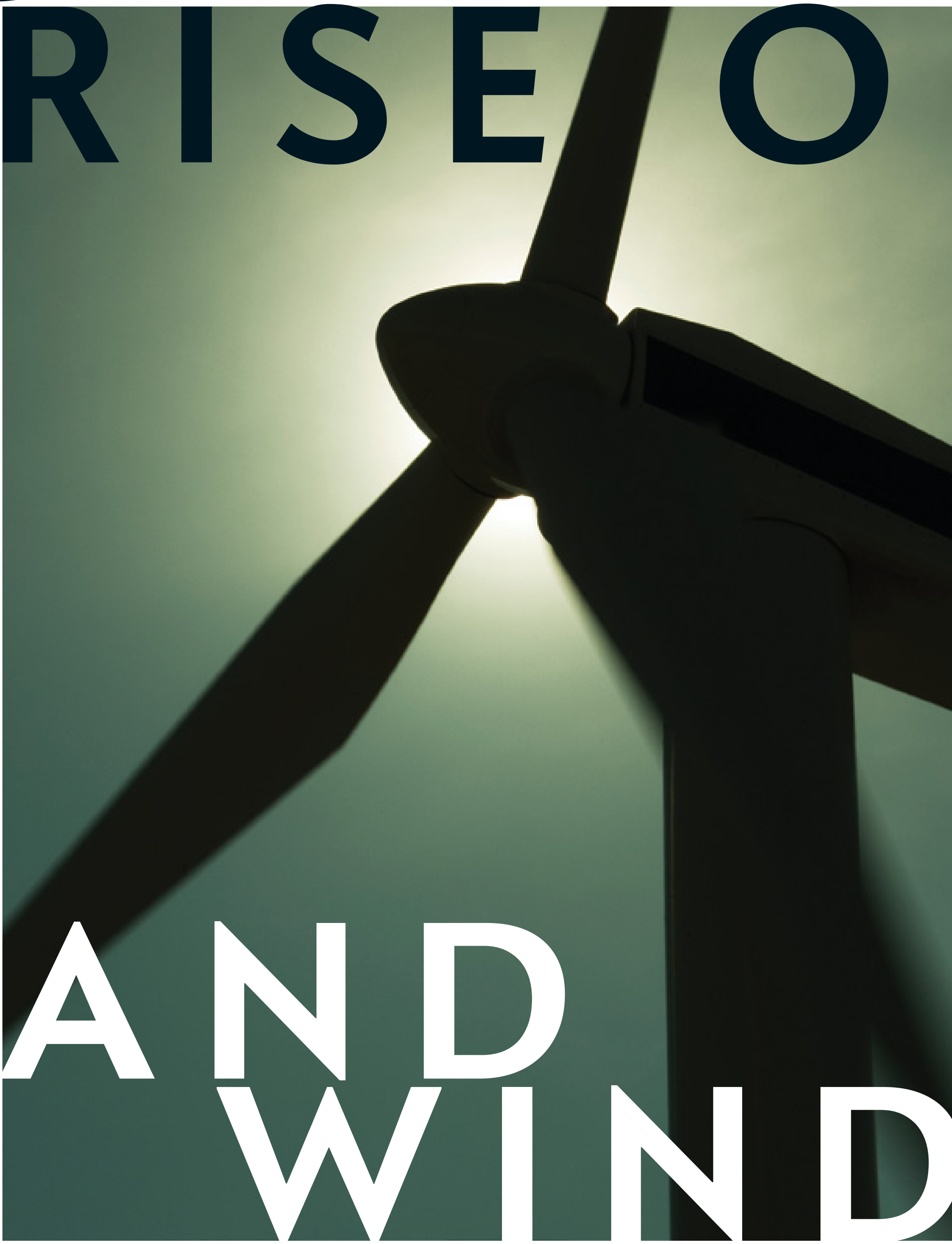
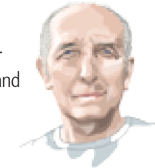


AND
WIND

transition to renewable energy is wishful thinking *By Vaclav Smil*



Vaclav Smil is a distinguished professor emeritus at the University of Manitoba and author of more than 30 books on many aspects of energy and the environment.

RENEWABLE ENERGY SOURCES COULD TAKE THE WORLD BY STORM.

That is what well-known advocate Amory Lovins envisaged in 1976. He claimed that by the year 2000, 33 percent of America's energy would come from many small, decentralized renewable sources. Decades later, in July 2008, environmentalist Al Gore claimed that completely repowering the country's electricity supply in a single decade would be "achievable, affordable and transformative." And in November 2009 Mark Jacobson and Mark Delucchi published "A Path to Sustainable Energy by 2030" in *Scientific American,* presenting a plan for converting the global energy supply entirely to renewables in just two decades.

Yet from 1990 to 2012 the world's energy from fossil fuels barely changed, down from 88 to 87 percent. In 2011 renewables generated less than 10 percent of the U.S. energy supply, and most of that came from "old" renewables, such as hydroelectric plants and burning wood waste from lumbering operations. After more than 20 years of highly subsidized development, new renewables such as wind and solar and modern biofuels such as corn ethanol have claimed only 3.35 percent of the country's energy supply.

The slow pace of this energy transition is not surprising. In fact, it is expected. In the U.S. and around the world, each widespread transition from one dominant fuel to another has taken 50 to 60 years. First came a change from wood to coal. Then from coal to oil. The U.S. is going through a third major energy transition right now, from coal and oil to natural gas. Between 2001 to 2012 America's coal consumption fell by 20 percent, and crude oil was down by 7 percent; at the same time, the consumption of natural gas rose by 14 percent. Yet even though natural gas is abundant, clean and affordable, it will be another decade or two before gas use overwhelms

IN BRIEF

The major global energy transitions—from wood to coal to oil—have each taken 50 to 60 years. The current move to natural gas will also take a long time.

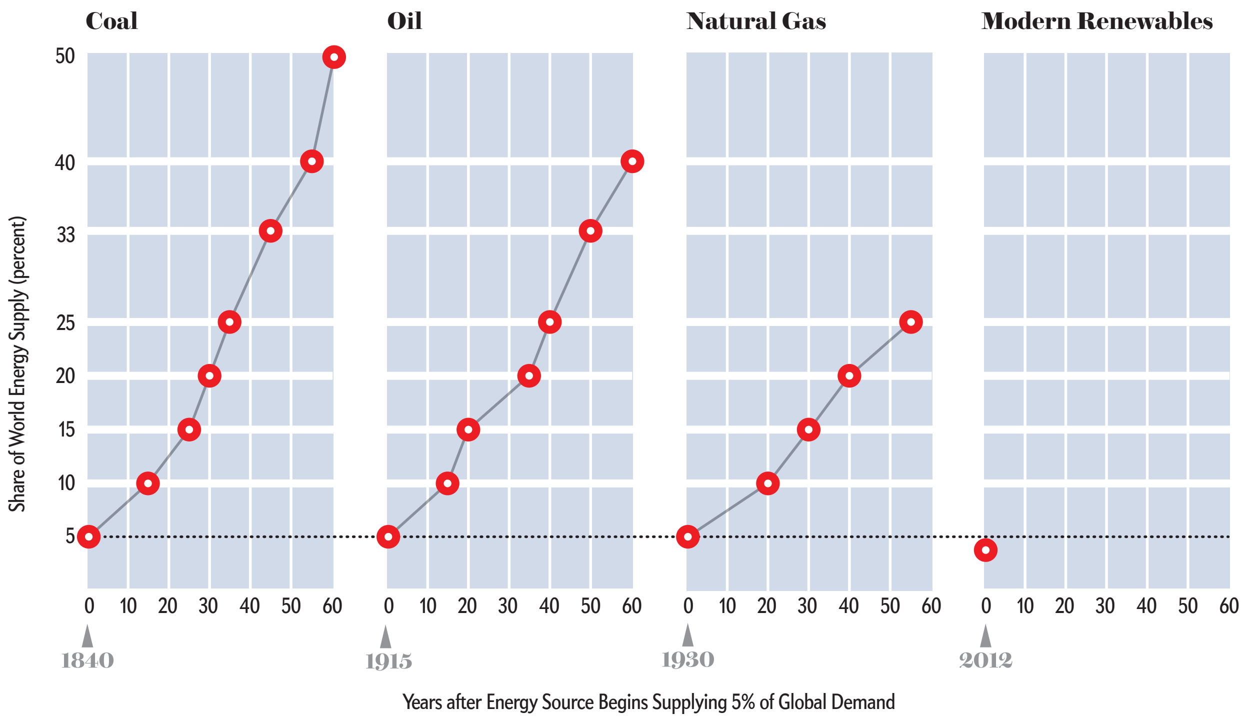
There is no reason to believe that a change to renewable energy sources will be exceptionally fast. In rich countries, "old" renewables such as hydroelectricity are maxed out, so growth will have to come from new renewables such as wind, solar and biofuels, which provided only 3.35 percent of the U.S. supply in 2011.

But, the author argues, certain policies could hasten the rise of renewables. These include funding research into many technologies, ending unneeded subsidies, making sure prices reflect the environmental and health costs imposed by energy sources, and improving energy efficiency worldwide.

PRECEDING PAGES: OLI KELLETT *Getty Images* (*solar panels*); MARTIN SOEBY *Gallery Stock* (*turbine*)

Many Years Needed to Take Over the Energy World

Each major energy source that has dominated world supply has taken 50 to 60 years to rise to the top spot. Coal reached 5 percent of global supply in 1840 (*bottom left*) and gradually took over from wood, reaching 50 percent some 60 years later, around 1900. Subsequent transitions to oil and natural gas have followed a similar pattern in reaching benchmark levels of supply (*vertical axis*), rising steadily after they achieve 5 percent. Oil has not yet reached 50 percent and may never. Natural gas is still partway along the path and is taking longer to ascend. The so-called modern renewable energy sources—wind, solar, geothermal and liquid biofuels—have hit only about 3.4 percent; unless a disruptive technology or revolutionary policy speeds up change, they, too, may be destined for a long transition.



SOURCES: BP STATISTICAL REVIEW OF WORLD ENERGY; UNITED NATION STATISTICS DIVISION

coal consumption, which still generates more than a third of U.S. electricity.

Renewables are not taking off any faster than the other new fuels once did, and there is no technical or financial reason to believe they will rise any quicker, in part because energy demand is soaring globally, making it hard for natural gas, much less renewables, to just keep up.

Change can take place faster in some countries, but the global move to renewables will proceed slowly, particularly as the current shift to natural gas plays out. Of course, it is always possible that a disruptive technology or a revolutionary policy could speed up change. But energy transitions take a long time.

FROM WOOD TO COAL TO OIL

TODAY'S GREAT HOPE for a quick and sweeping transition to renewable energy is fueled mostly by wishful thinking and a misunderstanding of recent history. Most people think that the world's energy consumption during the 19th century—the era of rapid industrialization—was dominated by coal, that the 20th century was the era of oil and that our current century will belong to renewable energy. The first two impressions are wrong; the last one remains questionable.

Even with the rise of industrial machines, the 19th century was not run on coal. It ran on wood, charcoal and crop residues (mostly cereal straw), which provided 85 percent of all energy worldwide—roughly 2.4 yottajoules (YJ, 1×10^{24} joules). Coal began to supply more than 5 percent of all fuel energy around 1840 but by 1900 still supplied only about half of demand. The rise from 5 to 50 percent took 50 to 60 years. Fairly good U.S. statistics point to 1885 as the year when energy supplied by fossil fuels (mostly coal, some crude oil and a very small volume of natural gas) had surpassed energy provided by wood and charcoal. The tipping point occurred in 1875 in France and 1901 in Japan but not until 1930 in the U.S.S.R., 1965 in China and the late 1970s in India.

Likewise, in the 20th century the biggest energy source was not oil but indeed coal. Bituminous coals and lignites reached the highest share of global fuel consumption, at about 55 percent, during the 1910s. But crude oil, already in use then, did not surpass coal until 1964.

Graphic by Jen Christiansen

And yet because coal's declining relative importance was accompanied by a steady increase in global energy demand, in raw terms coal—not crude oil—ended up as the 20th century's most important fuel: coal contributed roughly 5.3 YJ of energy, compared with 4 YJ for oil. Only two major economies have accomplished the third fossil-fuel transition; natural gas surpassed crude oil consumption in the U.S.S.R. in 1984 and in the U.K. in 1999.

One way I have demonstrated that transitions are gradual and prolonged is by plotting the rate of an energy source's ascendance. I begin to count a fuel when it has reached 5 percent of the total supply and then see when it reaches a measure of dominance.

The three successive changeovers have intriguing similarities [*see box on preceding page*]. Coal (replacing wood) reached 5 percent of the global market around 1840, 10 percent by 1855, 15 percent by 1865, 20 percent by 1870, 25 percent by 1875, 33 percent by 1885, 40 percent by 1895 and 50 percent by 1900. The sequence of years needed to reach these milestones was 15-25-30-35-45-55-60. The intervals for oil replacing coal, which began at the 5 percent level in 1915, were virtually identical.

Natural gas reached 5 percent of the global fuel market by about 1930. It has reached 10, 15, 20 and 25 percent of supply over a sequence of 20-30-40-55 years and is now on its way to reaching 33 percent of the total. If we compare the number sequences, we see that natural gas has taken significantly longer to reach 25 percent of the overall market, roughly 55 years compared with 35 years for coal and 40 years for oil.

A mere three sequences do not dictate the tempo of future global energy transitions. And a real breakthrough in safe and inexpensive nuclear power or a truly cheap way to efficiently store massive amounts of energy generated by wind and solar could hasten another change. But the similar pacing of three global transitions over two centuries is remarkable, particularly because the fuels required very different production techniques, distribution channels and machinery to convert them into usable power—whether diesel engines for trains or furnaces for homes. Worldwide the enormous investment and infrastructure needed for any new energy source to capture a large share of the market require two to three generations: 50 to 75 years.

The most important way to speed up the gradual transition to renewables is to lower overall energy use through efficiency gains. The faster global demand rises, the more difficult it is to supply a large fraction of it.

A CHALLENGING SWITCH TO RENEWABLES

THUS FAR renewable energy technologies are on the same slow course. In 2011 renewables generated 9.39 percent of the U.S.'s energy: 9.135 quadrillion BTU of the total 97.301 quadrillion BTU consumed (equivalent to about 103 quintillion joules). Traditional renewables supplied 6.01 percent: hydroelectric plants 3.25 percent, wood (mostly waste from lumbering operations) 2.04 percent, with the small remainder from biomass and geothermal. "New" renewables were still negligible: liquid biofuels at 2.0 percent, wind 1.19 percent and solar 0.16 percent.

The total of 3.35 percent for the new renewables is an important number. Virtually all future growth in the U.S. renewable energy supply will have to come from these sources because the old ones, especially hydro, have very limited potential to grow further.

A transition to renewable energy is particularly challenging for several reasons. The first is scale. In 2012 the global use of fossil energies was about 450 exajoules (1×10^{18} joules), 20 times greater than during the 1890s, when coal was overtaking wood. Simply generating this much energy with any new source is daunting, and a significant share of it will have to come from the U.S., which now consumes close to a fifth of the world's total.

Another factor is the intermittent nature of wind and solar energy. Modern societies need a reliable, uninterrupted supply of electricity, with an increasing share demanded at night to power air conditioning and the electronic infrastructures of megacities, ranging from subways to Internet servers. Coal and nuclear plants provide the "base load" of power in the U.S.—the share of electricity that is produced steadily around the clock. Hydroelectric and natural gas–fired plants, which can be switched on and off quickly, typically supply the added power needed to meet the short but high peaks in demand that arise well above base load during certain hours.

Wind and solar can contribute to the base load, but they alone cannot supply all of it, because the wind does not always blow, the sun is down at night and that supply cannot be predicted reliably. In countries such as Germany, where renewables have already grown substantially, wind and solar may supply anywhere from a negligible amount to roughly half of all demand during certain sunny and windy hours. These large fluctuations require backup from other power plants, typically coal- or gas-fired, or increased electricity imports. In Germany, all this variability can cause serious disruptions in electricity flow for some neighboring countries.

If electric utilities had an inexpensive way to store massive amounts of excess power generated by wind and solar when demand is low, which could later be tapped to meet peak demand, then the new renewables would expand much more quickly. Unfortunately, decades of development have provided only one good, large-scale solution: pumping water up to an elevated reservoir so it can flow back through a turbine to generate electricity. Not many localities have the elevation change or space to make this work, and the process entails net energy loss.

The alternative solution is to build an extensive array of wind and solar plants across a large region—on the scale of a major nation or half of a continent—and connect them with transmission lines, maximizing the chance that a subset of the plants will always be providing power to the grid. Better and longer transmission lines are technically possible, but they are expensive to build and often face stiff local opposition: not surprisingly, the approval of new lines in both the U.S. and Germany is proceeding at a slow pace.

Ultimately mass adoption of renewable energy would require a fundamental reshaping of our modern energy infrastructure. For electricity, it would entail a shift from a relatively small number of very large thermal or hydropower plants to a much greater number of small, distributed wind and solar systems. For liquid fuels, it would require moving from extraction of high-power-density oil to production of lower-power-density biofuels. In many ways, a transition to renewables is more demanding than the prior shifts from coal to oil and then to natural gas.

The final factor leading to a prolonged shift is the size and cost of existing infrastructure. Even if we were given free renewable energy, it would be economically unthinkable for nations, corporations or municipalities to abandon the enormous investments they have made in the fossil-fuel system, from coal mines, oil wells, gas pipelines and refineries to millions of local filling stations—infrastructure that is worth at least $20 trillion across the world. According to my calculations, China alone spent half a trillion dollars to add almost 300 gigawatts of new coal-fired generating capacity between 2001 and 2010—more than the fossil-fuel generating capacity in Germany, France, the U.K., Italy and Spain combined—and it expects those plants to operate for at least 30 years. No country will walk away from such investments.

WHAT TO DO?

LET ME BE CLEAR. There are many environmental reasons to reduce dependence on fossil fuels, even beyond the quest for reduced greenhouse gas emissions. Burning fossil fuels emits sulfur and nitrogen oxides that lead to acid rain and photochemical smog, black carbon that adds to global warming, and heavy metals that harm human health. Reliance on fossil fuels also causes water pollution and ruins land. A switch to nonfossil energy is environmentally desirable, although some of the alternatives also have significant environmental impacts.

How to get there as effectively as possible is the real question. Knowing that the transition will take many decades makes a number of policy choices clear. Energy and environmental policies in the U.S. and the world have been dismal. Instead of short-term fads promoted by wishful thinking, we need long-term policies based on realistic expectations, and we should be making no-regret choices rather than hasty, poorly conceived commitments.

One way to do this is to avoid picking energy winners. Governments cannot foresee which promising research and development activities will make it first to the free market, and hence they should not keep picking apparent winners only to abandon them soon for the next fashionable option (remember fast breeder reactors or fuel-cell cars running on hydrogen?). Spending on a variety of research activities is the best strategy: Who would have guessed in 1980 that during the next three decades the best return on federal investment in energy innovation would come not from work on nuclear reactors or photovoltaic cells but from work on horizontal drilling and hydraulic fracturing ("fracking") of shale deposits?

Governments also should not offer large subsidies or loan guarantees to companies that are jumping onto the latest energy bandwagon, exemplified by Solyndra, a manufacturer of photovoltaic solar systems, which received $535 million from the U.S. government before promptly going bankrupt. Subsidies can accelerate the advance of nascent energy conversions, but they should be guided by realistic appraisals, and they require steady commitment, not flitting from one exaggerated "solution" to another.

At the same time, prices of all forms of energy should reflect, as much as possible, the real costs, which include both the immediate and the long-term environmental and health impacts of creating that energy. The impacts range from greenhouse gases and black carbon from burning fossil fuels, to soil erosion, nitrogen runoff and water depletion caused by growing corn for ethanol, to the cost of a high-voltage supergrid to link far-flung wind and solar farms. This reality check can reveal long-term advantages of energy sources.

The most important way to speed up the gradual transition to renewables is to lower overall energy use. The faster demand rises, the harder it is to supply a large fraction of it. Recent studies have shown that there are no insurmountable technical problems to reducing energy use by a third, both in the affluent world and in rapidly modernizing countries, notably through efficiency gains. As we reduce demand, we can retire the old fossil sources. People and politicians in wealthy nations must also accept the fact that during the past half a century the price of energy, though rising, has been extraordinarily low in historic terms. Rich countries should pay more to properly account for energy's environmental and health consequences.

Energy transitions on a national or global scale are inherently protracted affairs. The unfolding shift from fossil fuels to renewable energy sources will be no exception. It will require generations of perseverance. SA

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BIOLOGY

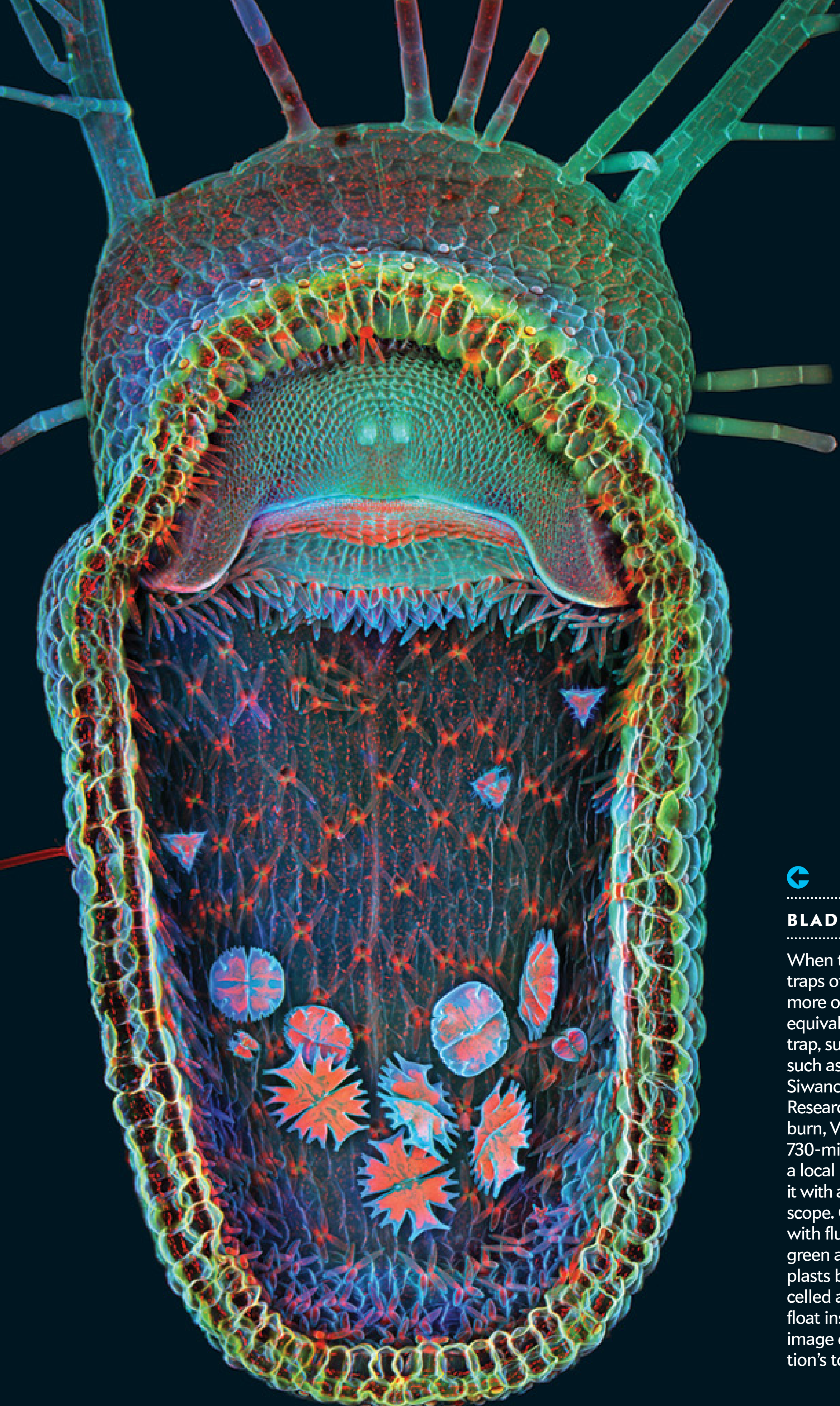
LIFE UNDER THE LENS

Microscopes transform the way we see and understand the creatures on our planet

By Ferris Jabr

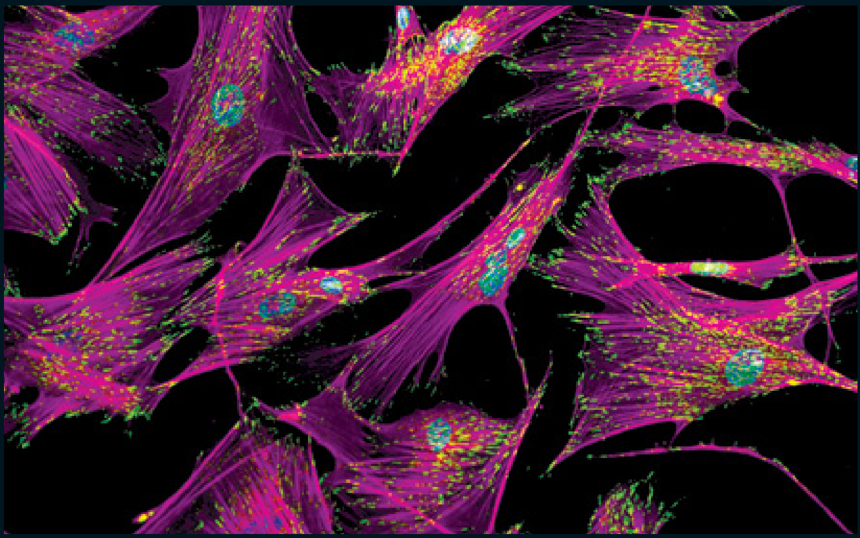
IN THE 1800S ENGLISH POET WILLIAM BLAKE famously challenged his readers to "see a world in a grain of sand." If only he had owned a modern microscope. Thanks to increasingly powerful optical tools, we now know that beneath the skin of every leaf, inside each speck of dirt, and within our own blood and bones is a cosmos of visual delights that usually remains unseen. Stunning pictures of the planet's smallest critters—and of the tiniest features of larger organisms—have inspired some of the greatest shifts in how we think about life on earth.

In the following pages, we present a selection of images that earned scientists, professional photographers and hobbyists awards and honors in the 2013 Olympus BioScapes International Digital Imaging Competition. The photographs will plunge you inside the unique underwater snare of a flesh-eating plant, open a window onto a bat forming in utero, reveal tiny faces hidden in a palm tree's stem and uncover surprising details of a dinosaur bone that has turned into shimmering crystal. SA



BLADDERWORT TRAP

When triggered, the saclike traps of the bladderwort, more or less the aquatic equivalent of the Venus flytrap, suck up minute prey such as water fleas. Igor Siwanowicz of Janelia Farm Research Campus in Ashburn, Va., collected this 730-micron-wide trap from a local pond and magnified it with a laser scanning microscope. Cell walls, covered with fluorescent dyes, glow green and blue, and chloroplasts blush red. Single-celled algae called desmids float inside the pouch. This image earned the competition's top prize.

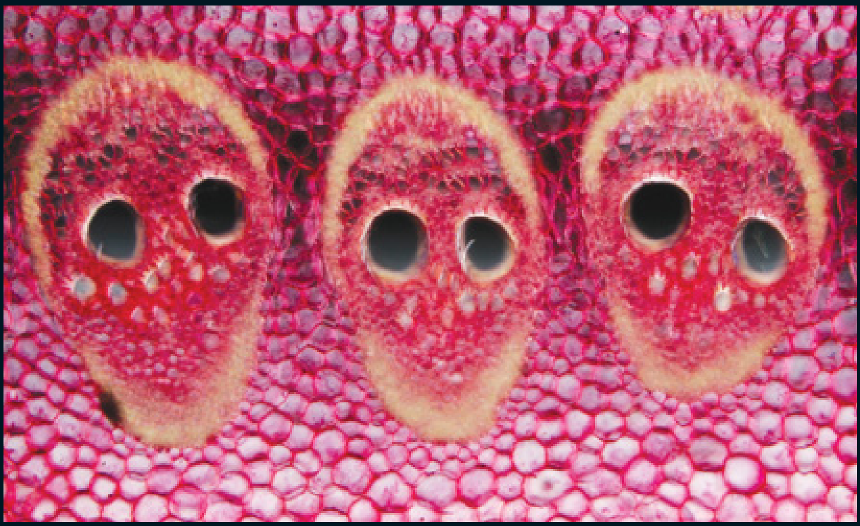


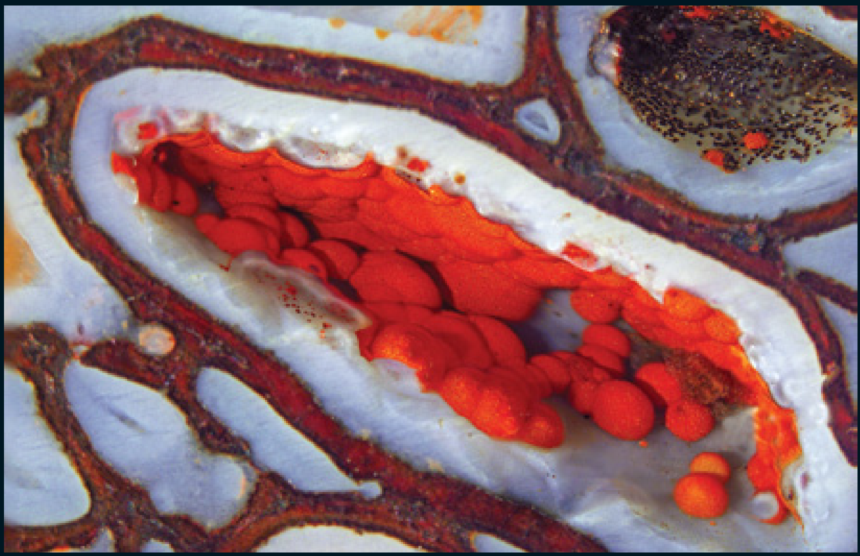
LUNG CELLS

In lieu of harvesting versatile stem cells from human embryos, some researchers revert adult cells to an immature state in which they can become many different kinds of tissue. Human lung cells, each about 130 microns long, are undergoing such a transformation in this image by Ankur Singh of Cornell University. Antibodies hitched to fluorescent proteins make vinculin—a protein that helps cells attach to surfaces—glow green and cause actin fibers, which give a cell its shape, to appear violet. Nuclei are blue.

PALM TREE

Slice up the stem of a *Syagrus comosa* palm, look at it under a microscope, and it just might look back at you. David Maitland of Norfolk, England, photographed this archived cross section, which was probably prepared and dyed red in the early 1900s. The plant's vascular bundles, which carry fluids, sugar and nutrients up and down the trunk, bear an uncanny resemblance to Day of the Dead masks. The "eyeholes" are tubes of xylem that transport water. Each face measures about 620 microns from crown to chin.



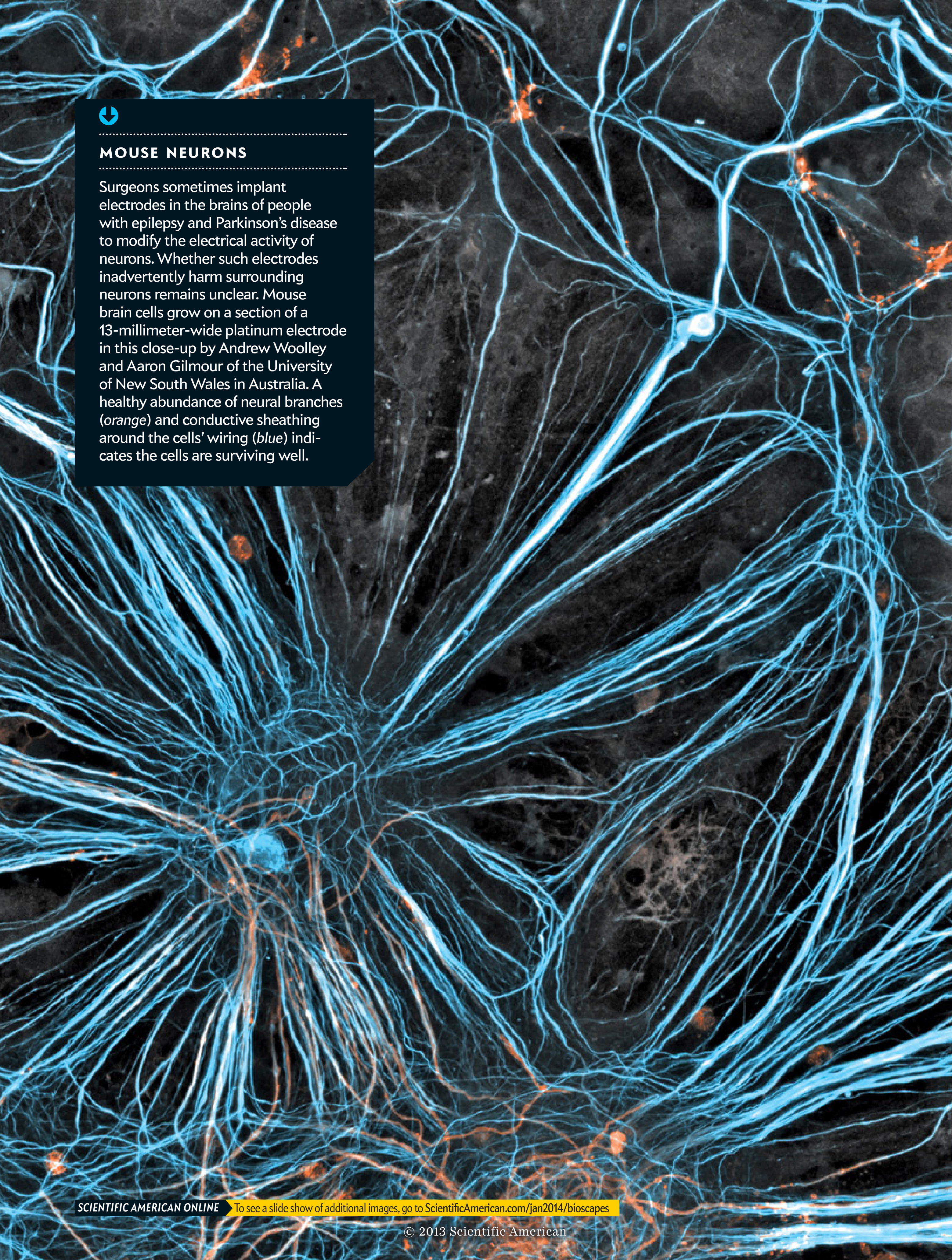


DINOSAUR BONE

Douglas Moore placed a 150-million-year-old slab of dinosaur bone roughly the size of your palm under a stereomicroscope to get a closer look at its once spongy scaffolding (*white*), which is magnified 32 times. The red bubbles he documented in the process may look like blood, but they are in fact iron oxides mixed with a crystalline form of silica known as agate—the same stuff that often makes geodes and petrified wood so colorful. Through a chemical process that has mystified geologists for centuries, silica reacted with bone to "agatize" the entire specimen.

BAT EMBRYO

This black mastiff bat (*Molossus rufus*) embryo, as small as a pencil eraser, was preserved with a mixture of salts and acids in its "peekaboo stage." As the creature matures in the womb, it wraps its rather cumbersome wings across its face, explains developmental biologist Dorit Hockman, currently at the University of Oxford. She took the photograph while investigating how the same set of forelimb bones shared by all vertebrates forms the framework for a flexible and leathery wing as opposed to, say, a mouse's petite paw.



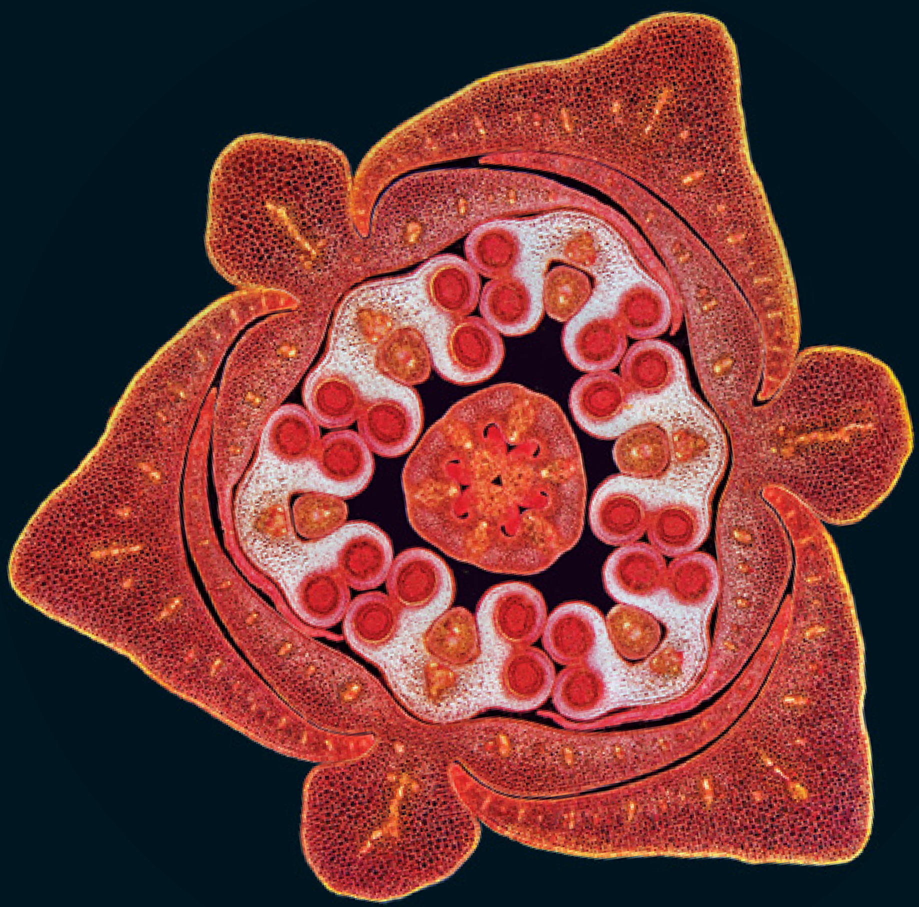
MOUSE NEURONS

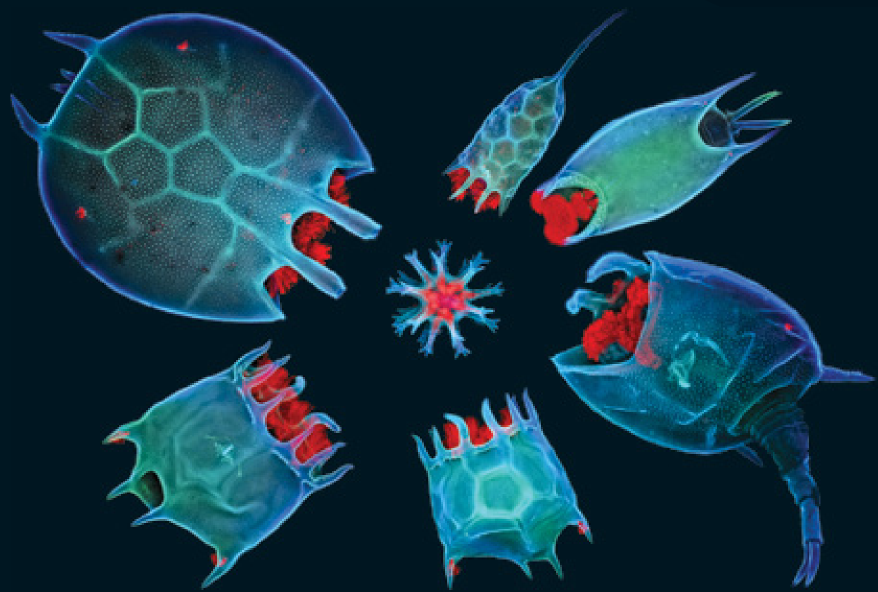
Surgeons sometimes implant electrodes in the brains of people with epilepsy and Parkinson's disease to modify the electrical activity of neurons. Whether such electrodes inadvertently harm surrounding neurons remains unclear. Mouse brain cells grow on a section of a 13-millimeter-wide platinum electrode in this close-up by Andrew Woolley and Aaron Gilmour of the University of New South Wales in Australia. A healthy abundance of neural branches (*orange*) and conductive sheathing around the cells' wiring (*blue*) indicates the cells are surviving well.

SCIENTIFIC AMERICAN ONLINE To see a slide show of additional images, go to ScientificAmerican.com/jan2014/bioscapes

LILY BUD

Spike Walker of Penkridge, England, photographed an old microscope slide containing this cross section of a lily bud, which is as wide as a finger; he thinks the plant was stained with the red dye safranine. Like all flowering plants known as monocotyledons, the lily's parts come in threes. The flower's carpels, which produce seeds, are in the center encircled by pollen-laden anthers, which are in turn surrounded by three petals and three large, protective sepals.





ROTIFERS

Six microscopic swimming animals called rotifers, the largest of which is 205 microns wide (*top left corner*), surround a photosynthetic desmid. Siwanowicz covered the chitin in the critters' armorlike exoskeletons with a fluorescent dye that glows blue under a laser scanning microscope. A red fluorescent dye coats the creatures' cilia—short, hairlike structures that help them eat and swim. When struck by certain wavelengths of light, the desmid's chlorophyll glows red as well.

Ferris Jabr *is an associate editor at* Scientific American.

MORE TO EXPLORE

For more information about the Olympus BioScapes competition, visit www.OlympusBioScapes.com

FROM OUR ARCHIVES

Dazzling Miniatures. Gary Stix; December 2011.
Small Wonders. Kate Wong; January 2013.

QUANTUM PHYSICS

THE ULTIMATE X-RAY MACHINE

What started as a "Star Wars" idea for a 1980s-era antimissile weapon is now a microscope of unprecedented power, able to create exotic forms of matter found nowhere else in the universe

By Nora Berrah and Philip H. Bucksbaum

Photographs by Spencer Lowell

VACUUM CHAMBER (*horizontal structure studded with blue-rimmed ports*) houses specially designed mirrors to focus the world's most powerful x-ray beam to the width of a dust grain.

Nora Berrah, head of the physics department at the University of Connecticut, directs research investigations and construction of advanced instrumentation at the LCLS x-ray laser. Berrah is a specialist in the study of the interaction of photons with atoms, molecules and nanosystems. She is a fellow of the American Physical Society and the recipient of the 2014 Davisson-Germer Prize in Atomic or Surface Physics, one of the field's highest honors.

Philip H. Bucksbaum is Marguerite Blake Wilbur Professor in Natural Science at Stanford University and SLAC, where he directs the PULSE Institute, which is devoted to research using ultrafast lasers and the LCLS. He is a fellow of the American Physical Society and a member of the National Academy of Sciences and of the American Academy of Arts and Sciences.

AN atom, molecule or speck of dust placed at the focus of the world's most powerful x-ray laser doesn't stand a chance. The illuminated matter reaches a temperature in excess of one million kelvins, as hot as the solar corona, in less than a trillionth of a second. Atoms of, for example, neon subjected to such extreme radiation rapidly lose all 10 of their electrons, and once they have lost their protective cloak of electrons, they explode away from neighboring atoms. For physicists, the trail of destruction holds a peculiar fascination.

What makes the process astonishing is that the laser boils away the atoms' electrons from the inside out. The electrons, which surround the nucleus of the atom in onionlike orbital shells, do not all react uniformly to the x-ray beam. The outer shells are nearly transparent to x-rays, so the inner shell takes the brunt of the radiation, much as coffee in a microwave oven is heated long before the cup that holds it. The two electrons in that shell shoot off, leaving empty space in their wake; the atom is hollow. Within a few femtoseconds (quadrillionths of a second), other electrons get sucked in to replace the lost ones, and the cycle of core-hole formation and vacancy filling continues until no electrons are left. This process occurs for molecules as well as solid matter.

The resulting exotic state of matter lasts only a few femtoseconds. In solids, it decays into an ionized state—a plasma—called warm dense matter, which is normally found only in extreme settings such as nuclear fusion reactions and the cores of giant planets. The brief but extreme environment at the focus of an x-ray laser beam has no parallels on Earth.

The x-ray laser itself is as remarkable as the exotic phenomena it reveals. Known as the Linac Coherent Light Source (LCLS) at the SLAC National Accelerator Laboratory, it evokes memories of the 1980s-era "Star Wars" missile-defense system, whose advocates proposed wielding x-ray lasers to shoot down ballistic missiles and satellites, although this real-world x-ray laser owes much more to the great atom smashers developed at about the same time. The device repurposes one of the nation's premier atom smashers, the SLAC linear accelerator, operated by Stanford University for the U.S. Department of Energy. This machine produced many of the discoveries and the Nobel Prizes that kept the U.S. at

IN BRIEF

X-ray lasers have long been a staple of science fiction, but the first one employed for scientific use began operation at Stanford University as a Department of Energy Office of Science facility only four years ago. Known as the Linac Coherent Light Source (LCLS), it is powered by the world's longest linear particle accelerator at the SLAC National Accelerator Laboratory.

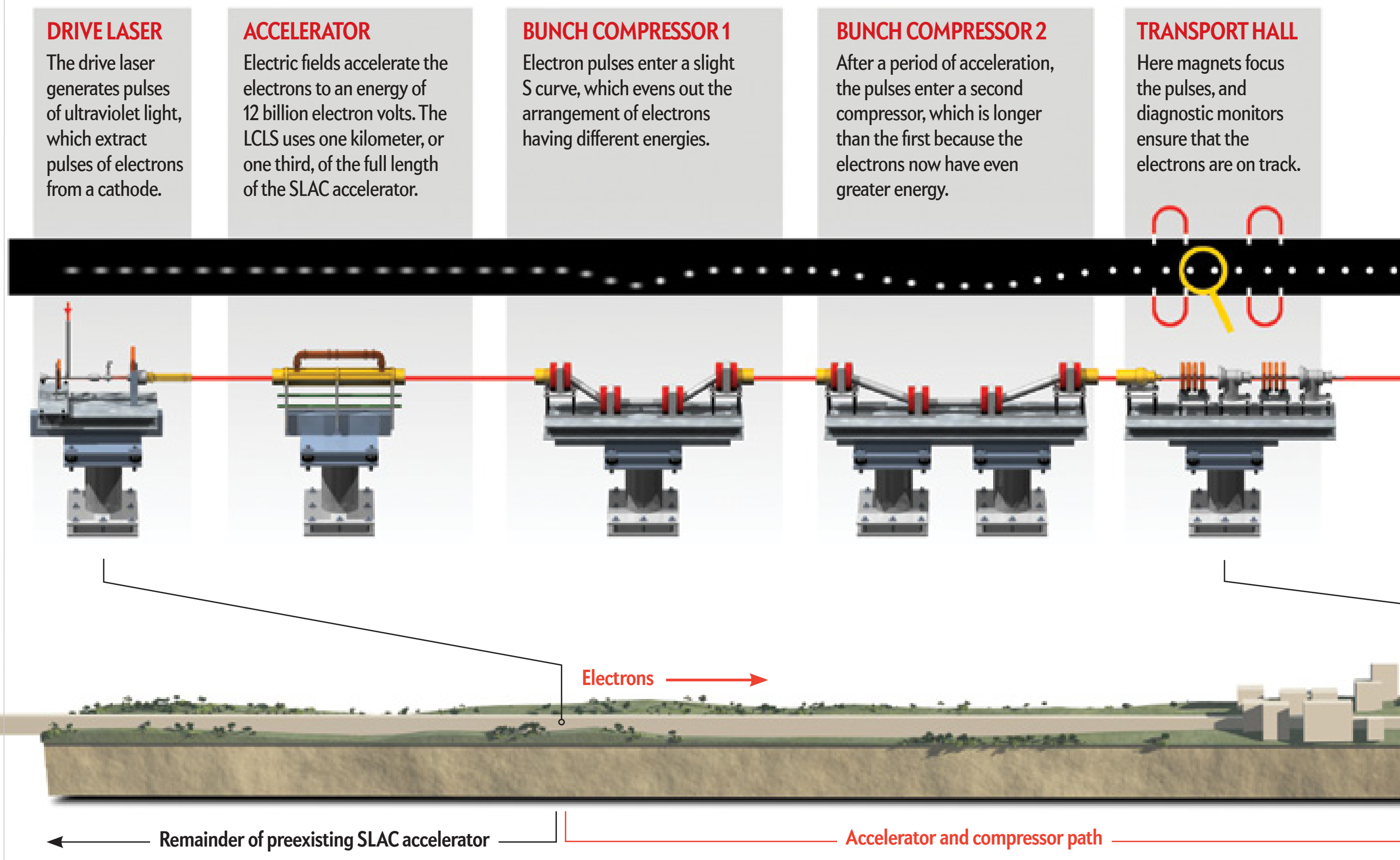
Exotic states of matter that occur nowhere else in the universe have been created by subjecting atoms, molecules and solids to high-intensity x-ray pulses.

Acting as a kind of strobe light, the laser has frozen the motion of atoms, captured high-speed images of proteins and viruses, and recorded physical and chemical transformations that take less than a trillionth of a second.

X-RAY LASER BEAM shoots down a pipe connecting the two experimental halls of the Linac Coherent Light Source.

Anatomy of the X-ray Laser

The LCLS is the closest to a starship laser blaster that earthlings have yet to create. It is powered by a linear particle accelerator, a gigantic version of the electron guns inside old-style TV sets, that fires electrons at near light speed. The heart of the contraption is the undulator, which



the forefront of elementary particle physics for decades. Since its recommissioning as the LCLS x-ray laser in October 2009, it has been to atomic and plasma physics, chemistry, condensed matter physics and biology what the Large Hadron Collider at CERN near Geneva is to elementary particle physics: a way to smash the building blocks of nature with tremendous amounts of energy, creating new forms of matter such as hollow atoms or simply zooming in on the quantum realm like a powerful, high-speed microscope. The LCLS's x-ray pulses can be so short (a few femtoseconds) that they freeze the motion of atoms, allowing physicists to observe chemical reactions in progress. The pulses are also very bright, letting us image proteins and other biological molecules that have been very difficult to study using other x-ray sources.

SHADOWS OF ATOMS

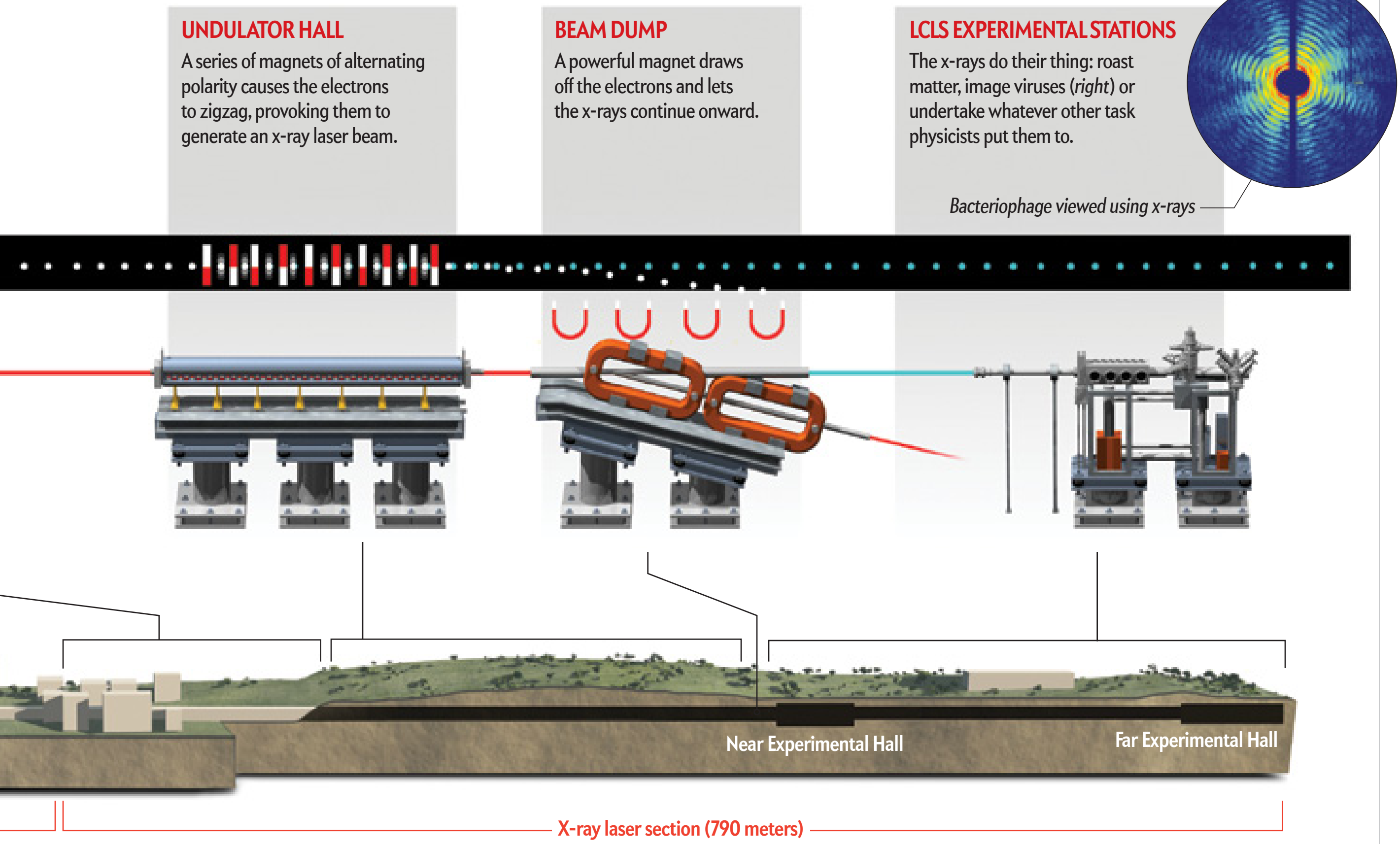
THE X-RAY LASER FUSES two of the main tools used by today's experimental physicists: synchrotron light sources and ultrafast lasers. Synchrotrons are racetrack particle accelerators. Electrons circling through them throw off x-rays, which enter instruments arrayed around the circumference of the machines like pinwheel spokes. One of us (Berrah) has spent a career using synchrotron x-rays to study the deep interior of atoms, molecules and nanosystems. X-ray light is ideal for this purpose. Its wavelengths are atomic-size, so atoms cast a shadow in an x-ray beam. In addition, x-rays can be tuned to pick out specific kinds of atoms—say, only those of iron—and show where they sit in a solid or in a large molecule such as hemoglobin. (Iron is responsible for the red color of our blood.)

What x-rays from synchrotrons cannot do, however, is trace out atomic motion inside a molecule or a solid. All we see is a dim blur; the pulses are not short enough or bright enough. A synchrotron source can image molecules only if they are arrayed in crystals, where local forces hold millions of them in precise ranks like identical soldiers at attention.

Lasers, for their part, are far brighter because they produce coherent light: the electromagnetic field in a laser is not choppy like the surface of a rough sea but smoothly oscillates with controlled regularity. Coherence means that lasers can concentrate enormous energy into a tiny spot and can switch on and off in as little as one femtosecond. One of us (Bucksbaum) uses ultra-

Illustration by Don Foley

causes the electrons to zigzag; whenever electrons change direction, they emit radiation—in this case, x-rays. Because the electrons are moving nearly as fast as the x-rays they produce, the process feeds on itself and produces an unusually pure and intense beam.



STEPHAN KASSEMEYER *Max Planck Institute for Medical Research (bacteriophage)*

fast optical laser pulses as a strobe light to study the motion of atoms and the steps in chemical reactions.

Conventional lasers, however, operate at visible and near-visible wavelengths, more than 1,000 times longer than the wavelength needed to resolve individual atoms. Just as weather radar can see a rainstorm but not resolve the raindrops, conventional lasers can see how collections of atoms are moving but cannot resolve those atoms. To cast a sharp shadow, the wavelength of the light must be at least as small as the object under observation. For that, we need an x-ray laser.

In short, the x-ray laser overcomes the drawbacks that existing tools pose for imaging matter on the tiniest scales. Yet making such a device is no easy task.

DEATH RAYS

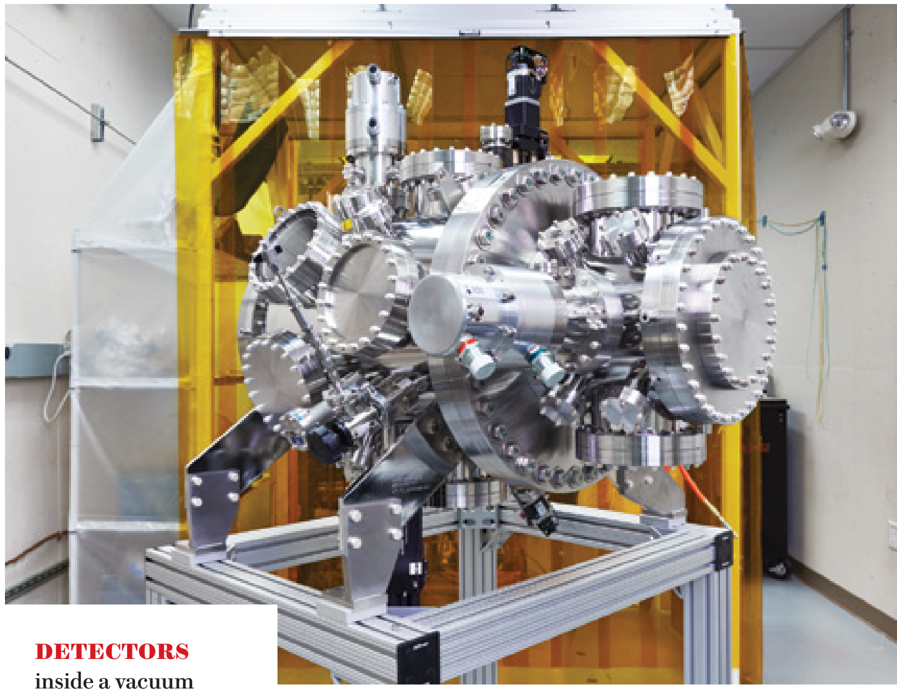
AT ONE TIME, THE IDEA OF BUILDING an x-ray laser seemed outlandish, given that making any laser is challenging. Standard lasers work because atoms are like miniature batteries: they can absorb, store and release small amounts of energy in the form of photons, or particles of light. Typically they release their energy spontaneously, but early in the 20th century Albert Einstein discovered a way to trigger the release, a process known as stimulated emission. If you cause an atom to absorb a certain amount of energy and hit it with a photon having the same amount of energy, the atom can release the originally absorbed energy—producing a clone of the photon. The two photons (the original one and its clone) go forth to trigger the release of energy from a pair of other atoms, and so on, building up a clone army in an exponential chain reaction. Laser beams are the result.

Even when conditions are right, though, atoms do not always clone photons. The probability that a given atom will emit a photon when hit by another is rather small, and the atom has a greater chance of releasing its energy spontaneously before that happens. Conventional lasers overcome this limitation by pumping in energy to prime the atoms and by using mirrors to send the cloned light surging back and forth, picking up new recruits. In a typical helium-neon laser used in supermarket price scanners, a continuous stream of electrons collides with atoms in the gas, and light is recycled 200 times by bouncing back and forth between mirrors.

For an x-ray laser, every step of this process becomes much more difficult. An x-ray photon may contain 1,000 times more energy than an optical photon, so each atom must absorb 1,000 times more energy. The atoms do not hold on to their energy for long. Moreover, x-ray mirrors are hard to come by. Although these impediments are not fundamental, it takes an enormous input of energy to create the lasing conditions.

In fact, the first x-ray laser got its energy from an underground nuclear bomb test. It was built for a secret project, code-named Excalibur, carried out by Lawrence Livermore National Laboratory east of San Francisco. The project is still classified, although quite a bit of information about it has been made public. The device was a component of former president Ronald Reagan's Strategic Defense Initiative, nicknamed "Stars Wars," in the 1980s and was meant to act as a death ray to shoot down missiles and satellites.

During the same decade, Lawrence Livermore also built the first nonnuclear laboratory-scale version of an x-ray laser, with energy supplied by powerful optical lasers that had been designed to test properties of nuclear weapons. These were not practical research instruments, though, and the possibility that x-ray lasers would ever be used routinely for science applications seemed remote.



DETECTORS inside a vacuum chamber can make ultrahigh-resolution images of proteins and cells.

NOT SLAC-ING OFF

THE BREAKTHROUGH that finally enabled investigators to develop x-ray lasers for civilian use came from another Bay Area institution, using a device intended for a different purpose entirely. In the 1960s Stanford built the world's longest electron accelerator, a three-kilometer building that, viewed from space, resembles a needle pointing from the mountains to the heart of the university's campus. The SLAC linac, as the machine is called, accelerates dense bunches of electrons to velocities extremely close to the speed of light (within one centimeter per second). The machine led to three Nobel Prizes for experimental discoveries in particle physics.

It did, however, reach the end of its useful life, and particle physicists now make their discoveries at the Large Hadron Collider. A decade ago Stanford and SLAC's parent agency—the Department of Energy's Office of Science—decided to turn part of the aging machine into an x-ray laser. SLAC outfitted the accelerator with the same device used to produce x-rays at modern synchrotrons: an undulator.

Undulators consist of a series of magnets that generate alternating magnetic fields. Electrons moving through undulators wiggle and emit x-rays. In synchrotrons, which are closed loops, once the electrons leave the undulator, their paths are bent in an arc. That way the particles get out of the way of the x-rays, which are channeled to experimental stations. The electrons keep going around the racetrack, emitting a burst of x-rays each time they pass through the undulator.

The SLAC accelerator, however, is a straight line, and the undulator is unusually long (130 meters). The electrons move along the same path as the photons and at nearly the same speed. The result is a subatomic demolition derby. The electrons cannot get out of the way of the x-ray photons they have emitted, so the photons sideswipe them again and again. In so doing, the photons induce the electrons to emit clone x-ray photons through the process of stimulated emission.

Mirrors are not needed to bounce the light back and forth through the electrons, because they travel together. All it takes to produce the laser is an intense beam of fast electrons and a space big enough to house a long undulator. And SLAC possesses both. If everything is lined up nearly perfectly, voilà, an extraordinarily bright x-ray beam. At the end of the line, the electrons are diverted, and the photons enter the experimental stations. The system is known technically as a free-electron laser.

Though not a gun for "Star Wars," the LCLS is still a formidable device. Its peak focused intensity, 10^{18} watts per square centimeter, is billions of times greater than synchrotron light sources. The laser can cut through steel. Its oscillating electromagnetic field can be 1,000 times stronger than the fields that bind atoms to one another in molecules.

THE HEART OF THE MATTER

THE DEMAND FOR THE LASER is so great that it can accommodate fewer than one in four research proposals to use it. The on-site staff scientists work with large visiting teams of students, postdocs and senior scientists in intense marathons, 12 hours a day for five days. Every microsecond counts.

The research made possible by x-ray lasers is broad. To offer a taste of what is possible, we focus here on two scientific problems that particularly interest us: how matter behaves under extreme conditions and what can be learned from the ultrafast imaging of molecules. These two problems are intimately connected to fundamental processes studied in atomic, molecular and optical physics, our field of expertise.

When the LCLS creates hollow atoms in molecules and solids, it takes advantage of the tendency of electrons from the outer

Staff scientists work with large visiting teams in intense marathons, 12 hours a day for five days. Every microsecond counts.

shells of an atom to fall in to replace those that have been lost from the inner shells. This phenomenon, called Auger relaxation, takes a few femtoseconds. Therefore, if we shine a one-femtosecond x-ray pulse on the system, no outer electrons will have time to drop into the hollow inner-shell spots. Under these conditions, the hollow atoms will be transparent to any additional x-ray photons even if they are extremely intense. We have detected this hollow transparency at the LCLS not only for atoms but also for molecules and larger samples of material.

Theory suggests that inside giant planets such as Jupiter, temperatures reach 20,000 kelvins—four times hotter than the surface of the sun. Hydrogen and helium, the planet's main constituents, presumably take on exotic solid phases with extreme densities and structures. Yet little is known about the specifics. Even the strength of the material, its compression in response to pressure, is not easy to measure and not well understood from basic principles. So far research in this domain has relied heavily on theoretical models. Experiments that can validate the models have been scarce.

Some of the first experiments done at the LCLS attempted to re-create these hostile conditions. The laser's colossal intensity can heat matter with dizzying speed, producing unusual effects. For instance, we observed for the first time how multiple x-rays can gang-tackle molecules made of many atoms to liberate electrons that are strongly bound to atomic nuclei, a process called multiphoton absorption. The high photon density can also strip multiple electrons out of a single atom, molecules or solids, hollowing them out as described earlier, in a process known as sequential absorption. Bright x-rays can, in addition, rapidly break all the bonds in molecules that are expected to reside inside giant planets, including water, methane and ammonia. Measurements of matter in extreme conditions have helped determine the equation of state—the formula that governs the density, temperature and pressure—in cores of giant planets and during meteor impacts.

EXPLODING PROTEINS

THE SECOND LINE OF RESEARCH—exploiting the laser as an x-ray high-speed camera to image molecules and record movies of physical, chemical and biological dynamics—is filling in a serious gap in our knowledge. Researchers know distressingly little about the structure of many biological molecules—in particular, membrane proteins and large macromolecular complexes. The standard technique, crystallography, starts by growing a crystal that is large enough and perfect enough to diffract a beam of synchrotron x-rays. The resulting pattern reveals the structure of the molecule. The drawback is that x-rays readily damage the molecules they are probing. To compensate, researchers must prepare large crystals, yet many molecules of interest, including membrane proteins, are very difficult to crystallize. The synchrotron technique is also slow and thus unable to observe transient phenomena that occur on the femtosecond chemical timescale.

At first glance, the LCLS seems exactly the wrong tool for the job. Because it is billions of times more intense than synchrotron light sources, fragile materials such as proteins or noncrystalline systems cannot survive even one pulse of its x-rays before they explode and turn into a very hot soup of plasma. Ironically, that destructive intensity is just what we need. Because the pulse is so short and bright, it can capture an image faster than the molecule is able to blow up. Consequently, although the laser obliterates the sample, it captures a clear image of the molecule just before its demise.

This concept, called diffraction before destruction, is already beginning to pay off. Scientists have used femtosecond crystallography to record diffraction patterns of nanocrystals, proteins and viruses [*see box on pages 68 and 69*]. Recent work has mapped out the structure of proteins involved in sleeping sickness, a fatal disease caused by protozoan parasites.

Now that the LCLS has pioneered the technology, laboratories in Europe and Asia are also planning or building their own free-electron x-ray lasers. This new generation of machines will be more stable and provide better control of the beam. One particularly important goal is to make the x-ray pulses even shorter. With pulses as short as 0.1 femtosecond (100 attoseconds, or quintillionths of a second), we might begin to observe the motion not just of atoms but also of electrons within atoms and molecules. New devices could even allow us to control this motion. The dream of making movies showing how chemical bonds break and new ones form is within our reach. SA

MORE TO EXPLORE

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HISTORY OF SCIENCE

THE CASE AGAINST COPERNICUS

Copernicus famously said that Earth revolves around the sun. But opposition to this revolutionary idea didn't come just from the religious authorities. Evidence favored a different cosmology

By Dennis Danielson and Christopher M. Graney

IN BRIEF

Copernicus's revolutionary theory that Earth travels around the sun upended more than a millennium's worth of scientific and religious wisdom.

Most scientists refused to accept this theory for many decades—even after Galileo made his epochal observations with his telescope.

Their objections were not only theological. Observational evidence supported a competing cosmology—the "geoheliocentrism" of Tycho Brahe.

Illustrations by Kirk Caldwell

Dennis Danielson is a professor of English at the University of British Columbia who studies the cultural meaning of the Copernican revolution. He was recently a visiting fellow in science history at Ludwig Maximilian University of Munich.

Christopher M. Graney is a professor of physics and astronomy at Jefferson Community and Technical College in Louisville, Ky. He and his wife, Christina, translate 17th-century astronomical texts from Latin.

IN 2011 a team of researchers at CERN near Geneva sent a beam of neutrinos on a 730-kilometer journey to Gran Sasso National Laboratory in L'Aquila, Italy. When the researchers clocked that trip, it appeared as though the neutrinos had somehow surpassed the speed of light in a vacuum. How did the scientific community respond to this surprising result?

Almost everyone, rather than abandoning the well-established teachings of Albert Einstein—who said that nothing travels faster than light—argued that the researchers' measurements had to be wrong (as, indeed, they turned out to be).

Now imagine ourselves four centuries from now, in a future in which Einstein's ideas have been supplanted; scientists have long ago experimentally confirmed that neutrinos really can travel faster than light. How would we then, looking back on physicists today, construe their reluctance to accept the evidence? Would we conclude that 21st-century physicists were just set in their ways? Unreceptive to new ideas? Maybe motivated by nonscientific considerations—a bunch of closed-minded Einsteinians toeing a line dictated by tradition and authority?

We hope today's reluctant scientists would get a fairer shake than that. For their unwillingness to abandon apparently sound conclusions—even if these may eventually be proved wrong—is scientifically reasonable, not merely a sign of stiff-necked prejudice.

Stories such as theirs are not uncommon in the history of science. Astronomers in the 19th century, assuming that the Milky Way galaxy constituted the entire universe, examined the first images of the Andromeda galaxy and justifiably believed that they were looking at a single star surrounded by a nascent solar system—not, as we now know, a distant collection of perhaps a trillion stars. Similarly, Einstein was sure that the universe was static, and so he introduced into his equations a cosmological constant that would keep it that way. Both assumptions were reasonable. Both were wrong. As David Kaiser of the Massachusetts Institute of Technology and Angela N. H. Creager of Princeton University argued in these pages in June 2012, it is possible to be both wrong and very productive. And everything is always clearer in hindsight.

In the case of the speeding neutrinos, of course, we have little hindsight. One famous story whose end we do know, however, is that of Nicolaus Copernicus and his theory of "heliocentrism," the claim that Earth rotates daily and revolves annually around the sun, which we all accept today. The Copernican system was a direct challenge to the long-held belief, codified by second-century astronomer Ptolemy in his book the *Almagest,* that the sun, moon and stars rotate around a fixed Earth at the center of the universe.

Copernicus proposed his revolutionary ideas in 1543 in his book *De Revolutionibus Orbium Coelestium,* which many scientists then read, admired, annotated and used for improving their astronomical predictions. Yet even by 1600, 57 years later, no more than a dozen serious astronomers had given up belief in an unmoving Earth. Most scientists continued to prefer the more commonsense geocentrism we ourselves still appear to endorse when we talk, for example, about the sun rising and setting.

This cosmological logjam is sometimes presented as having been held together by prejudice and broken by Galileo when he assembled a telescope in 1609 and started using it to observe the stars, moon and planets. Neither is true. For a long time after 1609, astronomers still had compelling scientific reasons to doubt Copernicus. Their tale offers a particularly striking illustration of the good reasons that researchers can have for resisting revolutionary ideas—even ones that turn out, in the end, to be spectacularly correct.

BRAHE'S NEW COSMOLOGY

A PARTICULARLY POWERFUL wellspring of doubt came courtesy of Danish astronomer Tycho Brahe, who in 1588 proposed a different kind of geocentric system [*see box at right*]. This new "geoheliocentric" cosmology had two major advantages going for it: it squared with deep intuitions about how the world appeared to behave, and it fit the available data better than Copernicus's system did.

Brahe was a towering figure. He ran a huge research program with a castlelike observatory, a NASA-like budget, and the finest instruments and best assistants money could buy. It was Brahe's data on Mars that Johannes Kepler, an assistant of Brahe's, would eventually use to work out the elliptical nature of planetary motion. Harvard University historian Owen Gingerich often illustrates Brahe's importance with a mid-17th-century compilation by Albert Curtius of all astronomical data gathered since antiquity: the great bulk of *two millennia's worth of data* came from Brahe.

This supremely accomplished astronomer had been impressed by the elegance of the Copernican system. Yet he was bothered by certain aspects of it. One thing that unsettled him was the lack of a physical explanation for what could make Earth move. (Brahe lived more than a century before the invention of Newtonian physics provided just such an explanation.) The size of Earth was known reasonably well, and the weight of a sphere of rock and dirt thousands of kilometers in diameter was clearly huge. What could power such a body around the sun, when it was difficult just to pull a loaded wagon down the street?

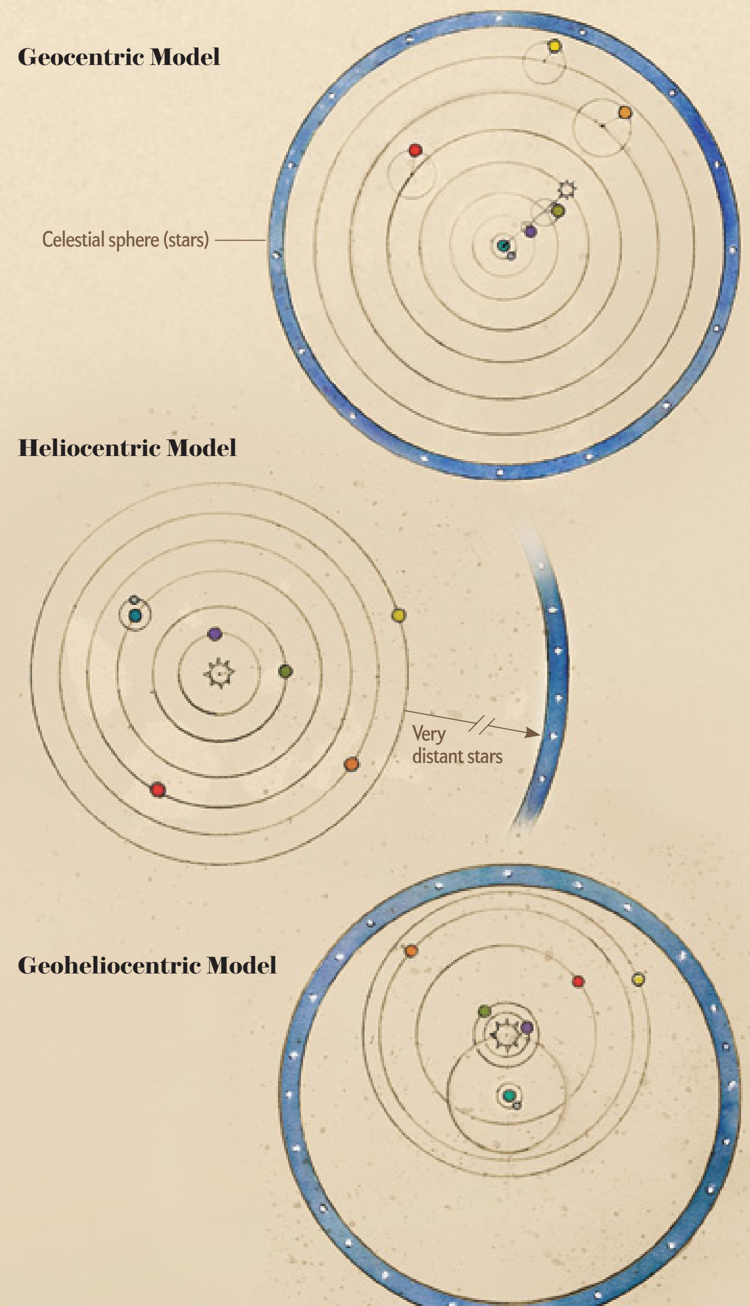
In contrast, the motion of celestial bodies such as stars and planets was easy to explain—astronomers since the time of Aristotle had postulated that celestial bodies were made of a special aethereal substance that was not found on Earth. This substance had a natural tendency toward rapid circular motion, just as a wagon had a natural tendency to come to a halt if not pulled vigorously. Brahe said that the Copernican system "expertly and completely circumvents all that is superfluous or discordant in the system of Ptolemy.... Yet it ascribes to the earth, that hulking, lazy body, unfit for motion, a motion as quick as that of the aethereal torches." In this regard, ancient astronomers had something in common with modern astronomers, who, to explain what they see, postulate that much of the universe is composed of "dark

ANCIENT COSMOLOGIES

The Cosmos Three Ways

Seventeenth-century astronomers had three models for the universe. The geocentric model featured an unmoving Earth circled by the sun, moon, planets and stars. Astronomers accounted for the retrograde motion of the planets with "epicycles," smaller loops added to the main orbits. Nicolaus Copernicus's heliocentric universe appeared simpler, but it presented new conceptual problems—stars had to be unthinkably distant, for example. Tycho Brahe's geoheliocentric model split the difference—the sun, moon and stars orbited Earth, the planets orbited the sun, and the stars came back close.

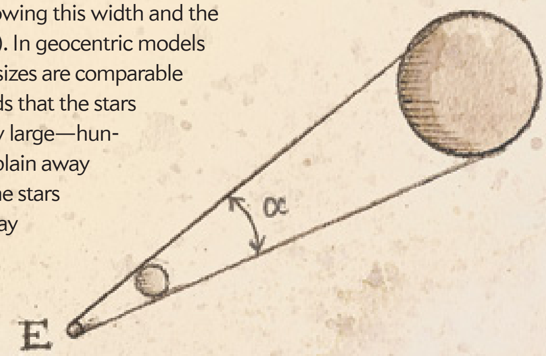
Sun
Earth
Moon
Mercury
Venus
Mars
Jupiter
Saturn

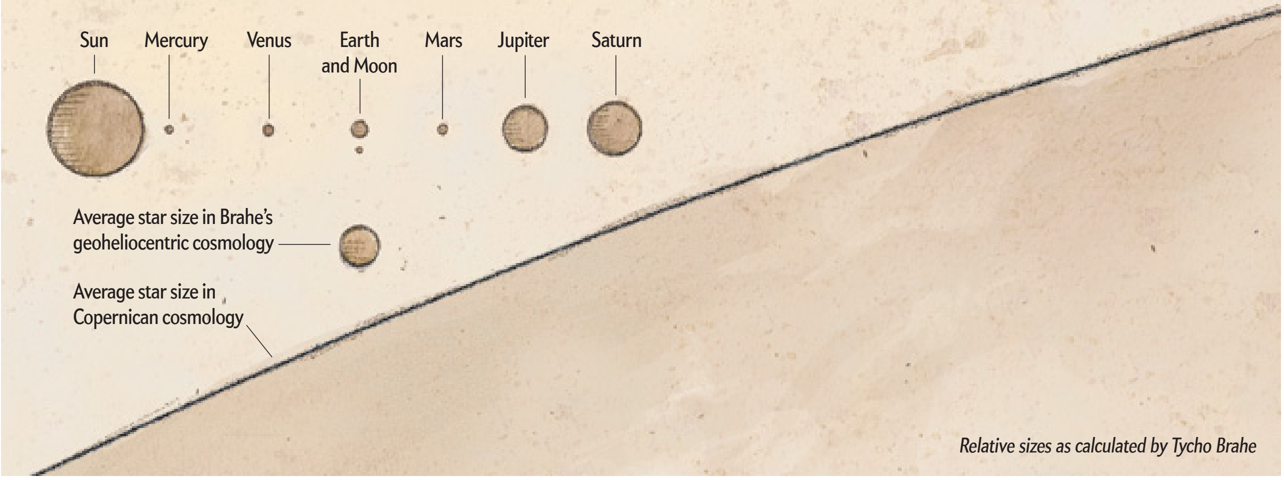


Planets and orbits not to scale

The Problem with Star Sizes

The most devastating argument against the Copernican universe was the star size problem. When we look at a star in the sky, it appears to have a small, fixed width. Knowing this width and the distance to the star, simple geometry reveals how big the star is (*right*). In geocentric models of the universe, the stars lie just beyond the planets, implying that star sizes are comparable to that of the sun (*below*). But Copernicus's heliocentric theory demands that the stars be extremely far away. This in turn implies that they should be absurdly large—hundreds of times bigger than the sun (*bottom*). Copernicans could not explain away the anomalous data without appeals to divine intervention. In reality, the stars are far away, but their apparent width is an illusion, an artifact of the way light behaves as it enters a pupil or telescope—behavior that scientists would not understand for another 200 years.





Relative sizes as calculated by Tycho Brahe

matter" or "dark energy" that is unlike anything we know.

Another thing that bothered Brahe were the stars in the Copernican system. Ptolemy said the sphere of the stars is "immeasurably large" because we can detect no diurnal parallax in them—no noticeable alterations in their positions or appearances caused by the changing angles and distances between an Earth-bound observer and those stars as they pass from the horizon, to overhead, to the horizon. The corollary of this observation is that the diameter of Earth is as nothing compared with stellar distances; Earth is "as a point," Ptolemy wrote.

Copernicus knew, however, that we could not even detect *annual* parallax—changes in the relative positions of stars caused by the movement of Earth in its orbit. If Earth really was revolving around the sun, the absence of annual parallax would imply that the diameter of its orbit (Copernicus called it the *orbis magnus*) was itself as nothing, "as a point," compared with stellar distances. The size of the universe then became a whole new—and almost impossible to believe—kind of "immeasurably large."

Moreover, as Brahe well knew, the Copernican proposal had big implications not only for the size of the universe but also for the size of individual stars. When we look up at the night sky, individual stars appear to have fixed widths, which both Ptolemy and Brahe measured. We now know that the distant stars are effectively point sources of light, and these apparent widths are an artifact of the passage of light waves through a circular aperture such as a telescope or an iris.

Yet at the time, astronomers knew nothing of the wave nature of light. Brahe used simple geometry to calculate that if the stars were to lie at Copernican distances, then they would have to have a width comparable to that of the *orbis magnus*. Even the smallest star would utterly dwarf the sun, just as a grapefruit dwarfs the period at the end of this sentence. That, too, was hugely hard to believe—Brahe said such titanic stars were absurd. As historian Albert Van Helden puts it, Brahe's "logic was impeccable; his measurements above reproach. A Copernican simply had to accept the results of this argument."

Rather than give up their theory in the face of seemingly incontrovertible physical evidence, Copernicans were forced to appeal to divine omnipotence. "These things that vulgar sorts see as absurd at first glance are not easily charged with absurdity, for in fact divine Sapience and Majesty are far greater than they understand," wrote Copernican Christoph Rothmann in a letter to Brahe. "Grant the vastness of the Universe and the sizes of the stars to be as great as you like—these will still bear no proportion to the infinite Creator. It reckons that the greater the king, so much greater and larger the palace befitting his majesty. So how great a palace do you reckon is fitting to GOD?"

Unswayed by arguments such as this, Brahe proposed his own system: the sun,

SCIENTIFIC AMERICAN ONLINE How did epicycles work? Watch a video at ScientificAmerican.com/jan2014/copernicus moon and stars circle an immobile Earth, as in the Ptolemaic system, while the planets circle the sun, as in the Copernican system [*see box on page 75*]. This "Tychonic" system retained the advantages of geocentrism. With it there was no motion of the hulking, lazy Earth to explain. Neither was there any missing annual parallax demanding vastly distant, and giant, stars—the stars in Brahe's system lay just beyond the planets and were quite reasonably sized. Yet so far as the planets were concerned, the Tychonic system and the Copernican system were mathematically identical. Thus, Brahe's system also retained the Copernican mathematical elegance that Brahe thought circumvented all that was superfluous or discordant in Ptolemy's system.

When Galileo began to view the heavens with his telescope, he made a number of findings that directly contradicted Ptolemy's ancient cosmology. He saw that Jupiter had moons, proving that the universe could harbor more than one center of motion. He also observed the phases of Venus, showing that it circled the sun. These findings were not, however, understood as proof that Earth revolves around the sun because they were fully compatible with the Tychonic system.

Rather than give up their theory in the face of seemingly incontrovertible evidence, Copernicans were forced to appeal to divine omnipotence.

THE 200-YEAR ARGUMENT

IN THE MIDDLE OF THE 1600S, well after the deaths of pioneers such as Copernicus, Brahe and Galileo, Italian astronomer Giovanni Battista Riccioli published an encyclopedic assessment of cosmological options that he called (after Ptolemy's great work) the *Almagestum Novum*. Riccioli weighed many arguments for and against the Copernican system, arguments dealing with matters of astronomy, physics and religion. But Riccioli judged that two main arguments tipped the balance decisively against Copernicus. Both were based on scientific objections. Both were rooted in Brahe's ideas. Neither would be answered decisively until some hundreds of years later.

One argument was based on the inability to detect certain effects that Riccioli said a rotating planet *should* produce in projectiles and falling bodies. Brahe had felt that a rotating Earth should deflect a projectile away from a straight path. Yet these deflections would not be observed until the 19th century, when French scientist Gaspard-Gustave de Coriolis worked out a full mathematical description of such effects.

The other argument was the one Brahe had made about star size, which Riccioli updated with telescopic observations. (Brahe had worked without a telescope.) Having designed a repeatable procedure for measuring the diameters of stars, he found that stars looked smaller than Brahe thought. Yet the telescope also increased the sensitivity to annual parallax, which still had not been detected, implying that the stars had to be even farther away than Brahe had assumed. The net effect was that stars still had to be every bit as titanic as Brahe had said.

Riccioli complained about the Copernicans appealing to divine omnipotence to get around this scientific problem. A Jesuit priest, Riccioli could hardly deny the power of God. But still he rejected this approach, saying, "Even if this falsehood cannot be refuted, nevertheless it cannot satisfy the more prudent men."

The acceptance of Copernicanism was thus held back by a lack of hard scientific evidence to confirm its almost incredible claims about cosmic and stellar magnitudes. In 1674 Robert Hooke, curator of experiments for the British Royal Society, admitted, "Whether the Earth move or stand still hath been a problem, that since Copernicus revived it, hath much exercised the wits of our best modern astronomers and philosophers, amongst which notwithstanding there hath not been any one who hath found out a certain manifestation either of the one or the other."

By Hooke's time a growing majority of scientists accepted Copernicanism, although, to a degree, they still did so in the face of scientific difficulties. Nobody convincingly recorded the annual stellar parallax until Friedrich Bessel did it in 1838. Around that same time, George Airy produced the first full theoretical explanation for why stars appear to be wider than they are, and Ferdinand Reich first successfully detected the deflection of falling bodies induced by Earth's rotation. Also, of course, Isaac Newton's physics—which did not work with Brahe's system—had long since provided an explanation of how Brahe's "hulking, lazy" Earth could move.

Back in Galileo's and Riccioli's day, however, those opposed to Copernicanism had some quite respectable, coherent, observationally based science on their side. They were eventually proved wrong, but that did not make them bad scientists. In fact, rigorously disproving the strong arguments of others was and is part of the challenge, as well as part of the fun, of doing science. SA

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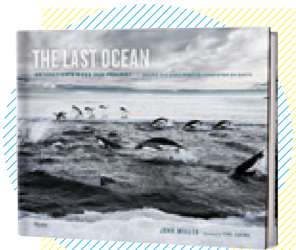


The Last Ocean: Antarctica's Ross Sea Project: Saving the Most Pristine Ecosystem on Earth

by John Weller. Rizzoli, 2013 ($50)

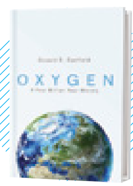
At the edge of Antarctica, shielded by great expanses of thick sea ice, the Ross Sea is one of the coldest, remotest and most inhospitable places on earth. Yet it is also one of the planet's last relatively untouched ecosystems, sheltering large numbers of Adélie and Emperor penguins, Weddell seals, orcas, minke whales and other creatures. All that began to change in 1996, when commercial fishing fleets started harvesting Antarctic toothfish from the frigid, nutrient-rich waters at the bottom of the world. Weller, an accomplished photographer and writer, co-founded the Last Ocean Project in response, an organization devoted to protecting the Ross Sea as a pristine nature reserve. This book documents his research trips to the region in soulful, meditative prose and haunting, otherworldly imagery.

STARFISH (*purple*) cluster together in the frigid waters of the ice-covered Ross Sea.

Romania's Abandoned Children: Deprivation, Brain Development, and the Struggle for Recovery

by Charles A. Nelson, Nathan A. Fox and Charles H. Zeanah. Harvard University Press, 2013 ($29.95)

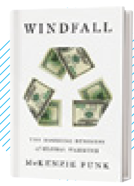
When Nicolae Ceauşescu's Communist regime fell in 1989, it left behind 170,000 orphaned children—remnants of the Romanian leader's aggressive initiative to boost the national birth rate through abortion restrictions and financial incentives. Most of the abandoned children were raised in overcrowded orphanages, receiving only the most rudimentary care. A decade later Nelson, Fox and Zeanah launched the government-backed Bucharest Early Intervention Project to determine just how detrimental institutional life could be for children. Now the researchers are presenting their findings in rigorous and heart-breaking detail. In *Romania's Abandoned Children,* they reveal the best and worst outcomes of childhoods spent in the system, offering vital prescriptions and warnings for all future foster care. —*Rachel Feltman*



Oxygen: A Four Billion Year History

by Donald E. Canfield. Princeton University Press, 2014 ($27.95)

The earth's present atmosphere, made up of 21 percent oxygen, in eons past had very little if any of this life-giving gas, effectively making our planet a hostile, alien world for most of its existence. In *Oxygen,* Canfield, a noted geoscientist, weaves personal anecdotes and cutting-edge research into two epic narratives: how the earth's initially anoxic air transformed over billions of years into the stuff we breathe today and how he and generations of other scientists have laboriously pieced together this atmospheric puzzle. The result of the earth's remarkable oxygenation over geological time is nothing less than our planet's rich biosphere of complex, multicellular life. Through a journey that takes readers from the bottom of the sea to the sunbaked deserts of the Australian outback, from life's first stirrings on the earth to its possible existence on extrasolar planets, Canfield has crafted a challenging, definitive work of scholarship and storytelling that will give readers a newfound appreciation for every breath they take.



Windfall: The Booming Business of Global Warming

by McKenzie Funk. Penguin, 2014 ($27.95)

Can climate change make for good business? Entrepreneurs all over the world are counting on it, claims journalist Funk in his new book *Windfall: The Booming Business of Global Warming*. The effects of a shifting climate, he says, can be divided into melt, drought and deluge (that is, rising sea levels), each of which would mean big paydays for different industries. From companies in Israel using by-products of massive desalination plants to capitalize on ski resorts in need of fake snow, to private firefighters working for California insurance companies, to Dutch architects designing floating cities, Funk's reporting brings him face-to-face with individuals who are investing in planetary crisis. Far from vilifying these opportunists, he attempts to see the warming world through their eyes. —*R.F.*

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Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com). His book *The Believing Brain* is now out in paperback. Follow him on Twitter @michaelshermer

Confessions of a Speciesist

Where do nonhuman mammals fit in our moral hierarchy?

The case for exploiting animals for food, clothing and entertainment often relies on our superior intelligence, language and self-awareness: the rights of the superior being trump those of the inferior. A poignant counterargument is Mark Devries's *Speciesism: The Movie,* which I saw at the premiere in September 2013. The animal advocates who filled the Los Angeles theater cheered wildly for Princeton University ethicist Peter Singer. In the film, Singer and Devries argue that some animals have the mental upper hand over certain humans, such as infants, people in comas, and the severely mentally handicapped. The argument for our moral superiority thus breaks down, Devries told me: "The presumption that nonhuman animals' interests are less important than human interests could be merely a prejudice—similar in kind to prejudices against groups of humans such as racism—termed speciesism."

I guess I am a speciesist. I find few foods more pleasurable than a lean cut of meat. I relish the feel of leather. And I laughed out loud at the joke about the farmer who castrates his horses with two bricks: "Does it hurt?" "Not if you keep your thumbs out of the way." I am also troubled by an analogy made by rights activists that animals are undergoing a "holocaust." Historian Charles Patterson draws the analogy in his 2002 book *Eternal Treblinka,* and Devries makes visual reference to it by comparing the layout of factory-farm buildings with that of prisoner barracks at Auschwitz. The flaw in the analogy is in the motivation of the perpetrators. As someone who has written a book on the Holocaust (*Denying History,* University of California Press, revised edition, 2009), I see a vast moral gulf between farmers and Nazis. Even factory-farm corporate suits motivated by profits are still far down the ladder of evil from Adolf Eichmann and Heinrich Himmler. There are no signs at factory farms reading "*Arbeit Macht Frei.*"

Yet I cannot fully rebuke those who equate factory farms with concentration camps. While working as a graduate student in an experimental psychology animal laboratory in 1978 at California State University, Fullerton, it was my job to dispose of lab rats that had outlived our experiments. I was instructed to euthanize them with chloroform, but I hesitated. I wanted to take them up into the local hills and let them go, figuring that death by predation or starvation was better than gassing. But releasing lab animals was illegal. So I exterminated them … with gas. It was one of the most dreadful things I ever had to do.

Just writing those words saddens me, but nothing like a video clip posted at freefromharm.org. Appropriately described as the "saddest slaughterhouse footage ever," the clip shows a bull waiting in line to die. He hears his mates in front of him being killed, backs up into the rear wall of the metal chute, and turns his head around, seeking an escape. He looks scared. A worker then zaps him with a cattle prod. The bull shuffles forward far enough for the final death wall to come down behind him. His rear legs try one last time to exit the trap and then … Thug! … down he goes in a heap. Dead. Am I projecting human emotions into a head of cattle? Maybe, but as one meat plant worker told an undercover USDA inspector who inquired about the waste stench: "They're scared. They don't want to die."

Mammals are sentient beings that want to live and are afraid to die. Evolution vouchsafed us all with an instinct to survive, reproduce and flourish. Our genealogical connectedness, demonstrated through evolutionary biology, provides a scientific foundation from which to expand the moral sphere to include not just all humans—as rights revolutions of the past two centuries have done—but all nonhuman sentient beings as well. SA

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Illustration by Izhar Cohen

The ongoing search for fundamental farces

Steve Mirsky has been writing the Anti Gravity column since Lee Billings was in the eighth grade. He also hosts the *Scientific American* podcast Science Talk.

Pervspicacity

A new book surveys the wide world of passionate proclivities

When I met with psychologist and author Jesse Bering in October, I asked him when he intended to write a book that I could read on the New York City subway without the cover bringing me unwanted attention. The title of Bering's 2012 book—*Why Is the Penis Shaped Like That?*—was bad enough, even though it offered up fascinating insights into the evolution of anatomy. But that was nothing compared to the pitchforks-and-torches looks from people who spied me perusing his latest work, *Perv: The Sexual Deviant in All of Us.* Bering's response to my entreaty was, "I'm working on it." I'll believe it when I see *it.* [*Editors' note: Scientific American/Farrar, Straus and Giroux publishes Bering's books.*]

In addition to the eye-catching verbiage, the cover of Bering's new book features a picture of a sheep. "That was the publisher's idea," Bering told me. "I went along with it, obviously. I think it's kind of like a Rorschach test in terms of what people see with the sheep on the cover. It's got multiple meanings. I do talk about zoophilia in the book, so it has that much more explicit meaning of bestiality, of course. But also, the lamb represents innocence. A lot of people see that." I confessed that the connection to innocence never occurred to me. "Well, that says a lot about you, actually," he joked. At least, I assume he was joking. I mean, I like a nice wool jacket, but that's as far as it goes.

Bering was kind enough to dedicate *Perv* to me. And to you. And, well, to any reader brave enough to crack the binding. (Still talking about the book here.) The dedication reads, "For you, you pervert, you." That notion would have been even more accurate in 1948, when Alfred Kinsey published *Sexual Behavior in the Human Male*. In *Perv,* Bering notes that Kinsey's research revealed that "75 percent of adult American males were technically 'sex deviants' according to the mental health criteria at the time."

If the vast majority of guys were thus abnormal, what's normal? We all have our little peccadilloes, which may include things that sound like various parts of the word "peccadilloes." "One person's lewd exorbitance," Bering writes, "is another's slow Monday morning." Indeed, the book is tumescent with the expected exorbitances: foot fetishists, amputee adorers, Lycra lovers and S&Mers (who aren't just fans of my initials) will all find themselves dissected (nonnecrophilously) within *Perv*'s pages.

The book's surprises, to my innocent self anyway, come in discussions of people who develop strong attachments to nonliving things. You might think you love your old Dodge Ram (no relation to the sheep on the cover), but what you and your pickup share is a pale imitation of the true, deep and abiding intimacy experienced by objectophiles.

Don't assume that the objectophile's love for that new iPhone 5S feels sadly but necessarily unrequited, either. Bering notes that such people may have a neurological condition called object personification synesthesia, "which causes them to perceive personalities and emotions, including sexual desires, in inanimate objects." Before you borrow that smartphone, you might want to ask where it's been.

Objectophilia extends beyond mere consumer products. Bering tells the story of a Swedish woman who in 1979 married the Berlin Wall. "Today she considers herself a widow," Bering writes. Although I bet she'd admit that trying to have a meaningful conversation with her beloved was like talking to a husband.

Then there's the case of the American woman who goes by the name Erika Eiffel because she (to her satisfaction) consummated a relationship with the towering Paris landmark. It's her second structural situation: she was previously involved with the Golden Gate Bridge. That affair no doubt took a toll. SA

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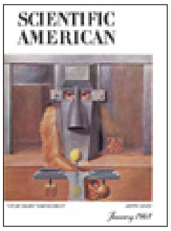
Illustration by Matt Collins

Innovation and discovery as chronicled in *Scientific American*

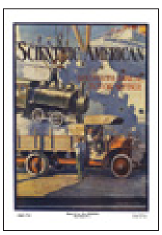


January 1964

Battling Trachoma

"Nearly 500 million people—more than a sixth of the world's population—are infected with the blinding eye disease known since ancient Greek times as trachoma. It is only within the past six years that investigators have positively identified the cause. The agent of the disease is a virus, or near virus, markedly similar to those responsible for psittacosis ('parrot fever') and the venereal disease lymphogranuloma venereum. This knowledge offers the exciting prospect that it may be possible to control the disease by vaccination and thus bring to an end its long career as a major scourge of mankind. In the U.S. the disease has all but disappeared from the 'trachoma belt' that used to extend from West Virginia to Oklahoma."

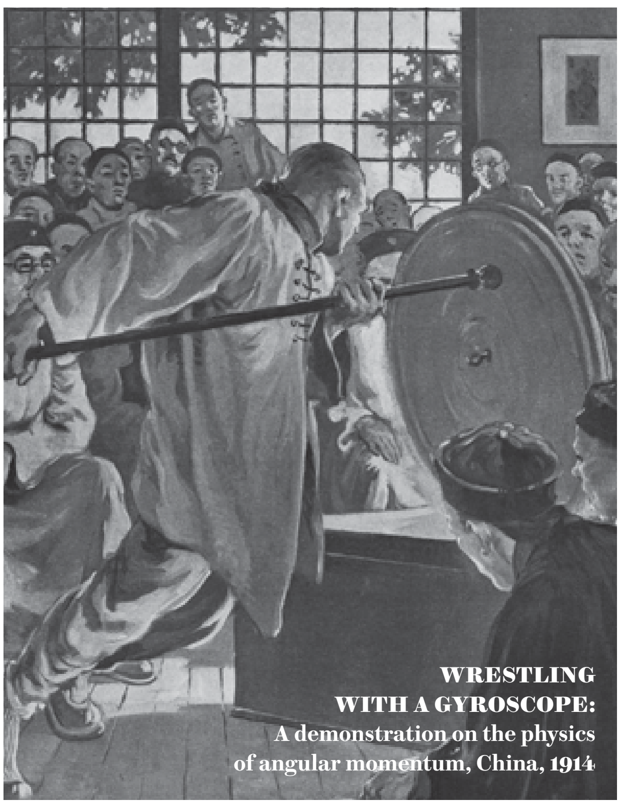
In 1966 the pathogen was identified as an intracellular bacterium.



January 1914

Gyroscope Lecture in China

"The wrestling gyroscope has been one of the very popular features of the Young Men's Christian Association gyroscope lectures in China. It consists of a strong bicycle wheel with the rim loaded with lead pipe. When spun up to high speed and the outer case closed and set upon its edge, it will stand up with a light list to one side, and will precess slowly around on a nearly vertical axis. A member of the audience is invited to use a strong staff padded at one end with a solid rubber ball and make the wheel lie down on its side [*see illustration*]. Unbelievable as it may seem, the strongest man is unable to push it over. This experiment delights the audience. The audience then also readily comprehends how it may be possible for a wheel weighing tons and running thousands of revolutions per minute, to stabilize a monorail car."



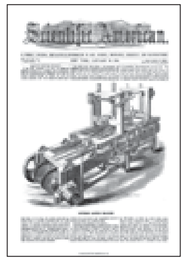
WRESTLING WITH A GYROSCOPE: A demonstration on the physics of angular momentum, China, 1914

SCIENTIFIC AMERICAN, VOL. CX, NO. 4; JANUARY 24, 1914

Wrights' Legal Triumph

"The decision handed down by the Circuit Court of Appeals in the infringement suit brought by the Wright Company settles once and for all, in this country at least, the question: Who invented the flying machine? To be sure, there was never any doubt in the popular mind. The decision of the Circuit Court of Appeals stamps the popular verdict with approval and recognizes Orville and Wilbur Wright as the inventors of the man-carrying, motor-driven aeroplane. The Wright brothers succeeded, not because they built a light motor with their own hands, but because they solved a problem in aero-dynamics which had baffled the best scientific thought of centuries."

For a look at what other civilian aviation pioneers were accomplishing in 1914, see the photograph album at www.ScientificAmerican.com/jan2014/aviation



January 1864

Satirical Rant on Corsets

"Messrs. Editors:—The air we ladies have to breathe up here in Vermont circulates all round the world and is breathed by all the filthy creatures on the face of the earth, by rhinoceroses, cows, elephants, tigers, woodchucks, hens, skunks, minks, grasshoppers, mice, raccoons, and all kinds of bugs, spiders, fleas and lice, lions, tobacco-smokers, catamounts, eagles, crows, rum-drinkers, turkey buzzards, tobacco-chewers, hogs, snakes, toads, lizzards, and millions of other nasty animals, birds, insects and serpents; and we ladies are obliged to breathe it over after them, ough! bah!

"Now we want, and must have, some contrivance that will effectually keep this foul, disgusting stuff out of our lungs. We have tried the three kinds of corsets which you noticed in your paper the last year; but when we do the best with them that we can, about a teacupful of this nasty air will rush into our lungs in spite of these miserable contrivances. If these corsets are worth anything to keep this disgusting air out of a body, and we have not put them on right, please come immediately yourself or send the inventors to show us how. If they are a humbug I hope their inventors will be tarred and feathered and rode on a rail. —Susie Pinkins"

How to Read This Graphic

Each node represents a community of mutually linked Twitter users

Node size corresponds to number of tweets using a specific hashtag (text indicating that a Twitter post pertains to a certain theme or topic)

• 1 tweet ● 61 tweets

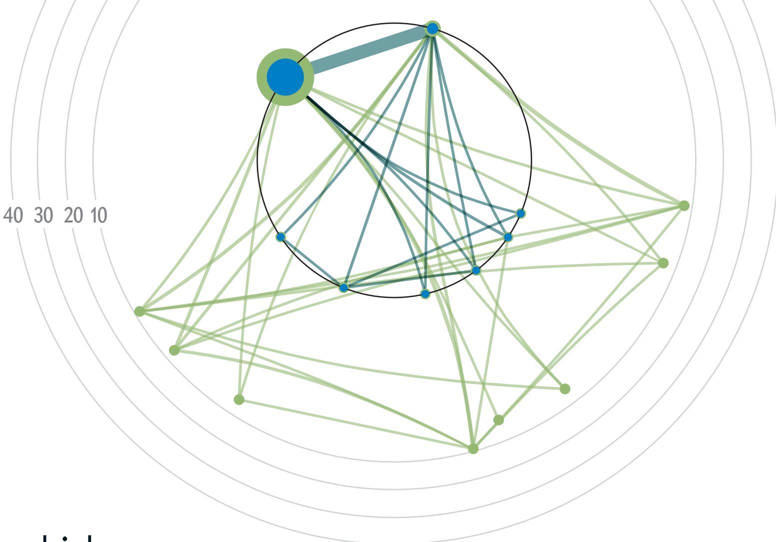
Lines between nodes represent person-to-person links between communities

— Few ▬ Many

Early-stage participants (communities that initiated the first 30 tweets using a hashtag) are in **blue** and are confined to the inner circle, for clarity

Subsequent activity as the meme spreads to new communities is in **green**

Position of a green node on outer rings represents how many links connect the node to other communities



Nonviral Meme (#ProperBand):
Insular start mirrored by insular finish
Of the first 30 tweets (*blue*) using this hashtag, 22 occurred within a single community (*top left node*). Later tweets using the same hashtag (*green*) largely reverberated within that same community, with very few interactions and crossovers among different community nodes. The meme fizzled out after just 65 tweets among the sample of Twitter users studied.

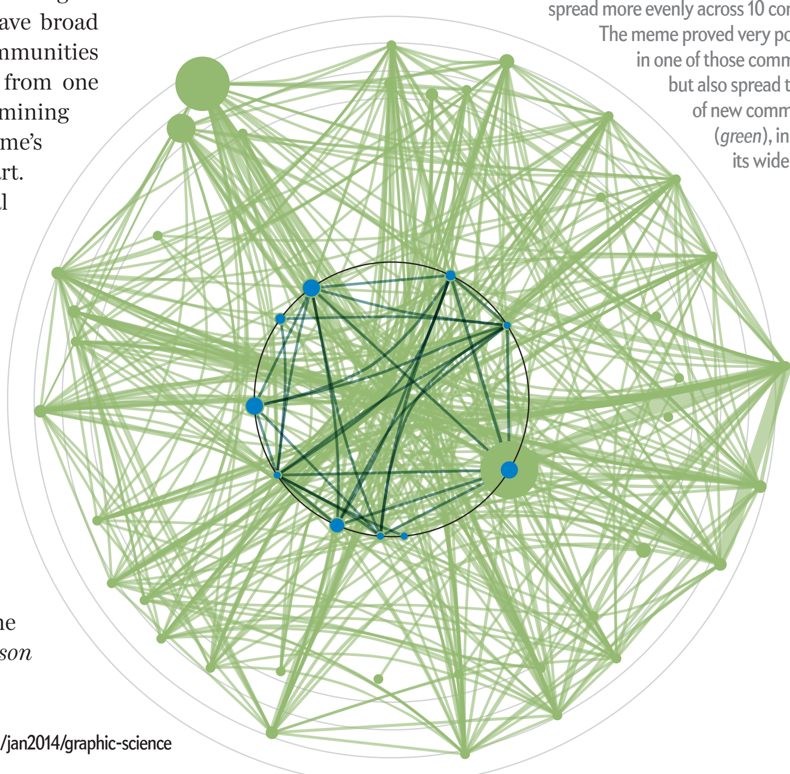
What It Means to Go Viral

Researchers are forecasting which memes will spread far and wide

What makes a meme—an idea, a phrase, an image—go viral? For starters, the meme must have broad appeal, so it can spread not just within communities of like-minded individuals but can leap from one community to the next. Researchers, by mining public Twitter data, have found that a meme's "virality" is often evident from the start. After only a few dozen tweets, a typical viral meme (as defined by tweets using a given hashtag) will already have caught on in numerous communities of Twitter users. In contrast, a meme destined to peter out will resonate in fewer groups.

"We didn't expect to see that the viral memes were going to behave very differently from nonviral memes at their beginnings," says Lilian Weng, a graduate student in informatics at Indiana University Bloomington. Those differences allowed Weng and her colleagues to forecast memes that would go viral with an accuracy of better than 60 percent, the team reported in a 2013 study. —*John Matson*

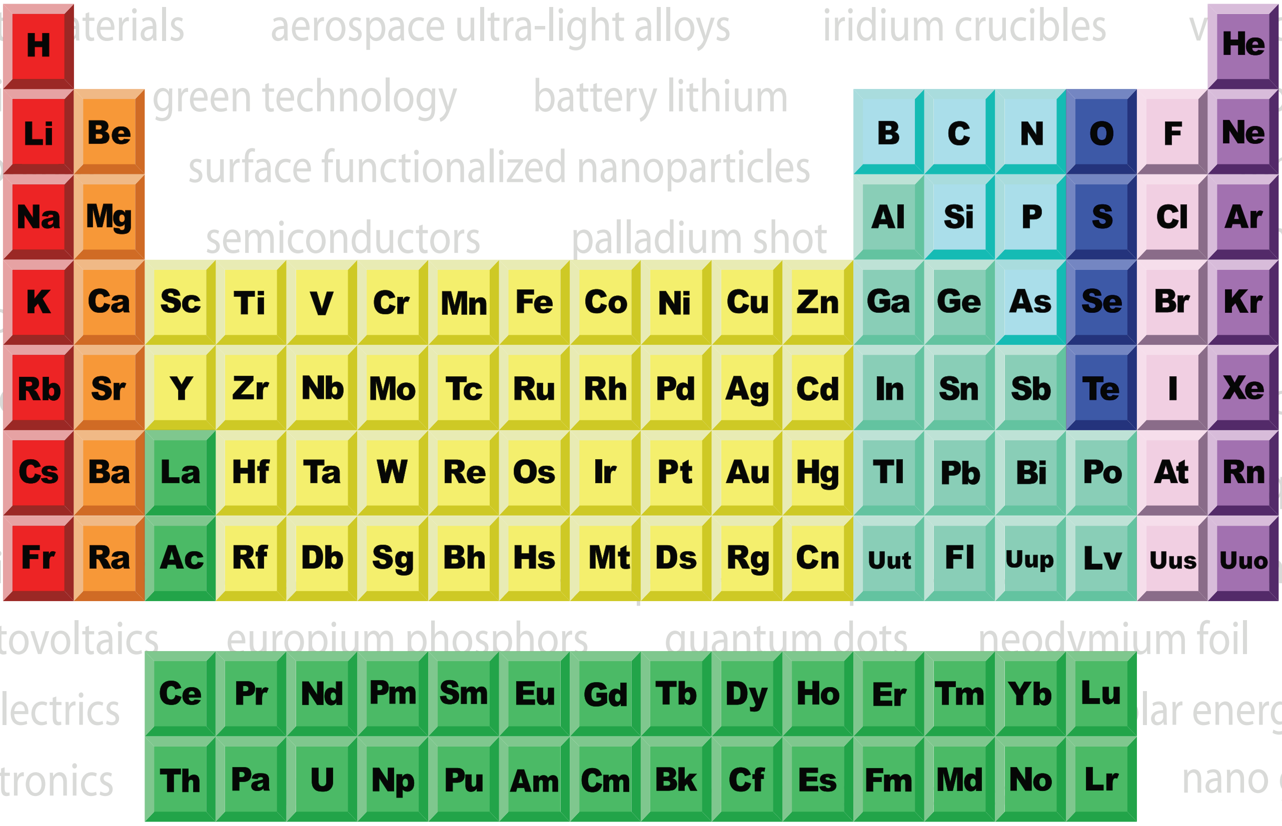
Viral Meme (#ThoughtsDuringSchool):
Early spreading portends broad adoption
The first 30 tweets (*blue*) using this hashtag were spread more evenly across 10 communities. The meme proved very popular in one of those communities but also spread to dozens of new communities (*green*), indicating its wide appeal.



SOURCE: "VIRALITY PREDICTION AND COMMUNITY STRUCTURE IN SOCIAL NETWORKS," BY LILIAN WENG, FILIPPO MENCZER AND YONG-YEOL AHN, IN *SCIENTIFIC REPORTS*, VOL. 3, ARTICLE NO. 2522; AUGUST 28, 2013

SCIENTIFIC AMERICAN ONLINE
See how "Gangnam Style" went viral at ScientificAmerican.com/jan2014/graphic-science

Graphic by Jan Willem Tulp


H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba La Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Ac Rf Db Sg Bh Hs Mt Ds Rg Cn Uut Fl Uup Lv Uus Uuo
Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr