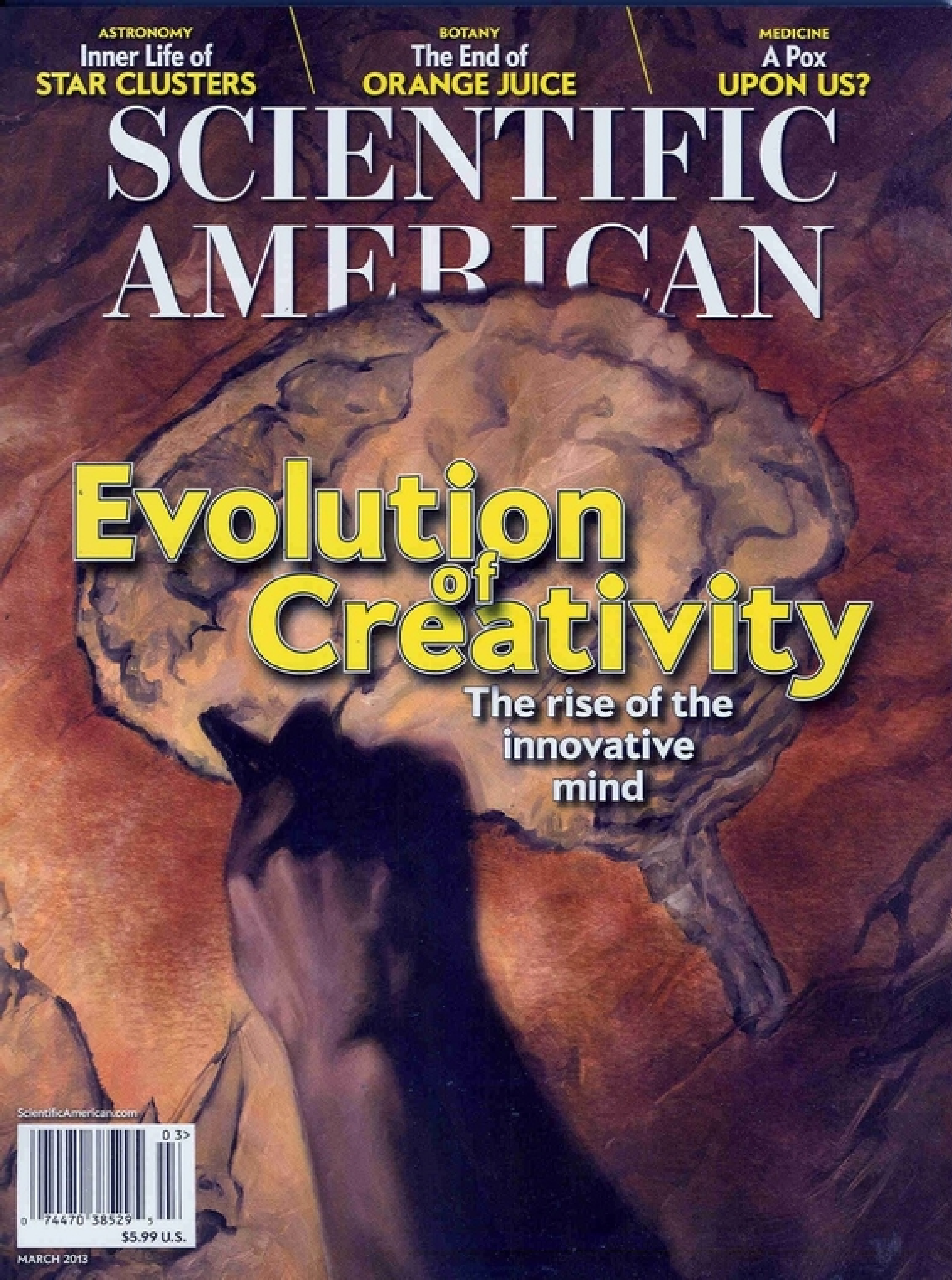
ASTRONOMY
Inner Life of STAR CLUSTERS

BOTANY
The End of ORANGE JUICE

MEDICINE
A Pox UPON US?

SCIENTIFIC AMERICAN



Evolution of Creativity

The rise of the innovative mind

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ON THE COVER

Scientists once thought humanity's knack for innovation exploded some 40,000 years ago, perhaps as a result of a lucky genetic mutation. But recent archaeological discoveries have shown that our ancestors began making sophisticated weapons and art far earlier, suggesting that a complex combination of biological and social factors kindled our powers of creativity. Image by David Palumbo.

SCIENTIFIC AMERICAN

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60

FEATURES

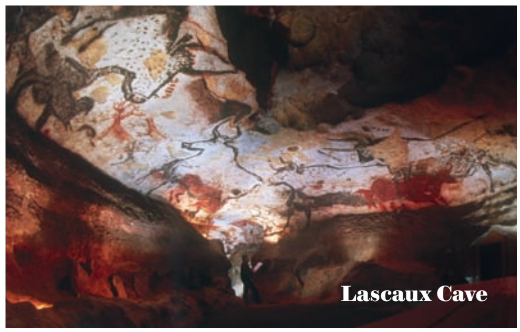
Photograph by Travis Rathbone

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

The Story of Creation

AFTER PASSING THROUGH A DARK SHAFT IN SEPTEMBER 1940, four teenage boys entered an underground chamber filled with wondrous drawings—hundreds of figures of animals, such as horses and deer, and other markings. What must they have thought on first seeing such an array of fantastic imagery from our forbears?

Lascaux Cave, located near Montignac, France, contains more than 2,000 paintings and engravings, which date to some 15,000 or more years ago. The site offers a spectacular example of human creativity, to be sure, but it is far from the first. Still, such a high level of artistry and ingenuity were a long time in coming for our species—as scientists are only now beginning to fully appreciate.



Lascaux Cave

You will learn in our cover story, "The Origins of Creativity," by Heather Pringle, that "although our human lineage emerged in Africa around six million years ago, early family members left behind little visible record of innovation for nearly 3.4 million years"—probably at least partly because tools or any such items were from wood or other plant material. Stone tools eventually materialize in the archaeological record but hardly change in design for more than a million years.

Most researchers have pointed to the Upper Paleolithic, around 40,000 years ago, when *Homo sapiens* started adorning cave walls with images of Ice Age animals and forging inventive beaded designs and other innovations, as when the early spark of creativity finally caught fire—yielding the kind of rapid-fire innovative thought that characterizes our species today. But rather than emerging suddenly, relatively recently in our evolutionary history, our creative powers appear to have developed over hundreds of thousands of years, as various biological and other factors came together. In her article, which begins on page 36, Pringle describes the fascinating detective story behind unraveling these lines of evidence.

It's a good thing we evolved ingenuity because we'll need it to combat some of the pressing challenges that we cover elsewhere in the issue. Consider the unpleasant prospect of "The End of Orange Juice," which senior editor Anna Kuchment describes in her feature, starting on page 52; citrus trees are under a global attack by a bacterial infection. In "New Threat from Poxviruses," beginning on page 66, Sonia Shah writes about the worrisome cousins of smallpox, monkeypox and cowpox. These are certainly serious matters, but our best hope remains with humanity's most innovation-enhancing invention: science. SA

SISSIE BRIMBERG *Getty Images*

Illustration by Nick Higgins

editors@sciam.com

November 2012

ANTISCIENCE ORIGINS

If Shawn Lawrence Otto wants to stop the antiscience movement in the U.S., as he describes in "America's Science Problem," he needs to blame the people who are actually leading the movement. Otto's article makes the ludicrous claim that Democrats ignore science as well as Republicans. Yet while Otto cites numerous examples of Republican legislatures enacting antiscience laws and major Republican leaders pushing policies attacking established scientific facts, he can only counterbalance that with the weak assertion that a few unnamed Democrats fear cell phones and vaccines. (Indeed, the only politician he refers to publically making false statements about the dangers of vaccines is Republican Representative Michele Bachmann of Minnesota.)

Incorrect claims that both parties are antiscience make the problem worse because they make people who want science-based policies feel like they have nowhere to turn. There is no doubt as to which is the only major American party advancing an agenda that rejects science.

Michael Campbell
Eudora, Kan.

> **"Incorrect claims that both parties are antiscience make people feel like they have nowhere to turn."**
> MICHAEL CAMPBELL *EUDORA, KAN.*

Otto's critique of postmodernism as an antiscience philosophy suffers from some of the same ignorance that he attributes to it. It is not a unified ideology that preaches that truth is relative, as he describes, but a descriptive analysis of society since the 1960s (give or take) that can help us understand the antiscience forces Otto fears.

In *The Postmodern Condition: A Report on Knowledge* in 1979, Jean-François Lyotard predicted that as information became more central to the economy, control and manipulation of that information would become more common. He specifically pointed to science as a force to prevent these self-reinforcing feedback loops and the control of information.

James D. Hastings
Berkeley, Calif.

I am appalled by *Scientific American*'s editors' obvious bias toward President Barack Obama in their scoring of his and Governor Mitt Romney's answers to the ScienceDebate.org questions in the "Science in an Election Year" section of the article. On the space question alone, President Obama should have been marked much lower than the score of 3 he was given, considering that his stated goals for NASA are contradicted by his slashing of funding for the program. When I went to the Web page of the candidates' full responses. Governor Romney gave much more of an answer than President Obama.

Joshua McDonald
via e-mail

ADDING PREONS

"The Inner Life of Quarks," by Don Lincoln, describes possible building blocks of quarks and leptons called preons. Lincoln summarizes Haim Harari and Michael A. Shupe's prescription for composing known particles from preons in the box "A Particle Cookbook," which gives the preon content for a positron as three preons of a certain type (+ + +), for an electron as three of its antimatter companions (- - -) and for a photon as one of each (+ -).

There is a well-known, experimentally verified and reversible reaction in which an electron-positron pair annihilates into two photons. Yet according to the box, in terms of preons, this would mean there would be an extra photon. What gives?

Bill Karsh
via e-mail

LINCOLN REPLIES: On the face of it, the preon count doesn't seem to balance. Matter and antimatter preons, however, can annihilate each other. Thus, one of the + preons annihilates along with one of the - preons and returns to the vacuum. This leaves the correct number of preons to make the two observed photons.

QUANTUM DILEMMA

In "A New Enlightenment," George Musser interprets research on the subject of quantum mechanics and the Prisoner's Dilemma scenario (in which two caught thieves will go to jail if both snitch or will go free if both stay mum, but if only one snitches, she will receive a reward, and the other will receive a maximum sentence). Musser indicates that quantum methods may help solve the dilemma if the prisoners can take particles entangled with each other into the interrogation.

Actually the jailer would have to cooperate by performing an entangled measurement. Further, I think the empirical behavior of players in the dilemma can be understood without invoking the metaphor of quantum superposition but by using a concept that cognitive scientist Douglas Hofstadter has called "superrationality"—that is, based on players thinking, "My opponent is like me, so he will do what I do."

Howard Barnum
commenting at
www.ScientificAmerican.com

MUSSER REPLIES: Jailers in the real world are unlikely to let prisoners use entangled particles anytime soon. The question is how to model an expanded notion of rationality mathematically; it is one thing to suppose that human beings do behave rationally in some sense, quite another to capture this notion with precision. That is where quantum superposition might help. It provides a useful set of *mathematical tools without having to assume that our thought processes literally are quantum.*

RIGOROUS REPLICATION?

Michael Shermer's notion that the *Dateline NBC* program he worked on, as described in "Shock and Awe" [Skeptic], replicated Stanley Milgram's famous shock experiment (in which an authority figure instructs a subject to take action that the latter believes is harming a second subject) is flawed. The point of the original experiment was testing whether people would follow authority, and scientists doing a scientific experiment were used as that authority.

Shermer's *Dateline* "replication" told the subjects that the purpose was a reality TV show! "Trusting authority" does not mean "trusting anybody who tries to make me do something."

Alice Savage
via e-mail

SHERMER REPLIES: Savage makes an excellent point, but this would apply to Milgram's original studies as well because they were inspired by the obedience to authority the psychologist thought was on display in the Holocaust. At no stage of the extermination of Jews and others did the Nazi perpetrators think they were being instructed by scientific authorities conducting research in the name of science for the betterment of humanity. Their motives were entirely different from those of the subjects in Milgram's lab or in our TV studio.

The most such social psychological research can hope for is an approximation of conditions that an institutional research board will approve of, and neither this experiment, nor Philip Zimbardo's famous Stanford Prison Experiment, will likely ever be approved for replication again. So we have to come at these social problems from different angles and interpret our provisional results cautiously and extrapolate them judiciously.

CLARIFICATION

"What Is It?" by Ann Chin [Advances], asserted that "about 97 percent of Greenland's ice sheet melted" last summer. It should have stated that 97 percent of the surface of the ice sheet melted.

LETTERS TO THE EDITOR

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Letters may be edited for length and clarity. We regret that we cannot answer each one. Post a comment on any article at ScientificAmerican.com/mar2013

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Ready. Aim. Investigate

Like it or not, guns are here to stay. To keep ourselves safer, we must study how they are used to kill

Like the firearms industry today, the automobile industry at midcentury was central to American culture and identity. Cars were big and beautiful, throbbing with power. Yet with that power came danger. By the 1960s motor vehicle accidents killed more than 50,000 people a year. The common wisdom, promulgated by carmakers since the 1920s, held that traffic fatalities were exclusively the fault of individual drivers (or, to put it another way: cars don't kill people; drivers kill people). This assertion, of course, was false, but at the time we had no way of knowing for certain, because we lacked data on the proximate causes of accident deaths.

We now find ourselves in a similar state of ignorance regarding gun fatalities. What factors shape the risk that a gun will be used for violence? What technologies (such as trigger locks) and policies (such as waiting periods) work best to reduce injuries and deaths? What is the relation—if any—between violent entertainment and actual violence? Guns, unlike cars, of course, are meant to kill, but why do they kill so many?

In the wake of the massacre at Sandy Hook Elementary School in Newtown, Conn., the nation is engaged in a fierce debate over how to reduce firearms deaths without infringing on the rights of citizens to bear arms. A critical first step is to conduct thorough and vigorous research on how to make gun ownership safer.

In autos, the blinders began to come off in the mid-1950s, when physicians suggested that vehicle design was as much to blame for high fatality rates as bad drivers. Through evidence-based work, they found that deaths could be lowered with simple safety devices such as seat belts. The National Traffic and Motor Vehicle Safety Act of 1966 mandated many of these improvements. It also set into motion a decades-long federal effort to better understand highway safety. As a result of those studies—and policies based on their findings—the death rate per mile traveled has fallen 80 percent since 1966. If present trends hold, in two years car crashes will no longer constitute the number-one cause of violent death in the U.S. That dubious honor will go to gunshot wounds.

Unfortunately, the National Rifle Association of America (NRA) has been scandalously successful in suppressing public safety research into guns. The problems began when investigators funded by the U.S. Centers for Disease Control and Prevention found that having a gun in the home tripled the chance that a family member would get shot. Outraged that reality was not falling into line with presuppositions, then representative Jay Dickey of Arkansas added language to federal law in 1996 that barred the CDC from conducting research that might be used "to advocate or promote gun control." This deliberately vague wording, coupled with a campaign of harassment of researchers, effectively halted federally funded gun safety research.

In January, President Barack Obama instructed the CDC to resume studying the causes and prevention of gun violence. He also asked for $10 million to support gun safety research at the CDC—a request that Congress must pass. But these measures are not enough. If history is any guide, the NRA will attempt to impede these new investigations. Doctors, scientists and ordinary citizens will have to keep up the pressure to protect research (and researchers) from political meddling.

The NRA has cynically framed the debate as a choice between banning all guns and doing nothing. It is a false choice. Congressman Dickey, for one, has recanted; he has publicly stated that firearms research is the best way to reduce the violence. We didn't have to ban automobiles to cut roadway fatalities, and we don't have to ban all guns to reduce gun-related deaths. All we need is a willingness to examine the causes of violence with dispassion—and the stomach to go where the data lead. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/mar2013

Illustration by Michael Glenwood

Dennis M. Bartels is executive director of the Exploratorium in San Francisco.

What Is Your Question?

Critical thinking is a teachable skill best taught outside the K–12 classroom

A democracy relies on an electorate of critical thinkers. Yet formal education, which is driven by test taking, is increasingly failing to require students to ask the kind of questions that lead to informed decisions.

More than a decade ago cognitive scientists John D. Bransford and Daniel L. Schwartz, both then at Vanderbilt University, found that what distinguished young adults from children was not the ability to retain facts or apply prior knowledge to a new situation but a quality they called "preparation for future learning." The researchers asked fifth graders and college students to create a recovery plan to protect bald eagles from extinction. Shockingly, the two groups came up with plans of similar quality (although the college students had better spelling skills). From the standpoint of a traditional educator, this outcome indicated that schooling had failed to help students think about ecosystems and extinction, major scientific ideas.

The researchers decided to delve deeper, however. They asked both groups to generate questions about important issues needed to create recovery plans. On this task, they found large differences. College students focused on critical issues of interdependence between eagles and their habitats ("What type of ecosystem supports eagles?" and "What different kinds of specialists are needed for different recovery areas?"). Fifth graders tended to focus on features of individual eagles ("How big are they?" and "What do they eat?"). The college students had cultivated the ability to ask questions, the cornerstone of critical thinking. They had learned how to learn.

Museums and other institutions of informal learning may be better suited to teach this skill than elementary and secondary schools. At the Exploratorium in San Francisco, we recently studied how learning to ask good questions can affect the quality of people's scientific inquiry. We found that when we taught participants to ask "What if?" and "How can?" questions that nobody present would know the answer to and that would spark exploration, they engaged in better inquiry at the next exhibit—asking more questions, performing more experiments and making better interpretations of their results. Specifically, their questions became more comprehensive at the new exhibit. Rather than merely asking about something they wanted to try ("What happens when you block out a magnet?"), they tended to include both cause and effect in their question ("What if we pull this one magnet out and see if the other ones move by the same amount?"). Asking juicy questions appears to be a transferable skill for deepening collaborative inquiry into the science content found in exhibits.

This type of learning is not confined to museums or institutional settings. One of the best examples is *The Daily Show with Jon Stewart,* in which the eponymous host expertly shreds political, commercial and scientific-sounding claims in the press by using numbers, logic and old video. The Maker Faire, which conducts techie do-it-yourself projects, has reintroduced the idea that our learning is richer for our mistakes: D.I.Y. experimentalists get stuck, reframe the question and figure things out.

Informal learning environments tolerate failure better than schools. Perhaps many teachers have too little time to allow students to form and pursue their own questions and too much ground to cover in the curriculum and for standardized tests. But people must acquire this skill somewhere. Our society depends on them being able to make critical decisions, about their own medical treatment, say, or what we must do about global energy needs and demands. For that, we have a robust informal learning system that eschews grades, takes all comers, and is available even on holidays and weekends. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/mar2013

Illustration by Ellen Weinstein

MICROBIOLOGY

Up with Microbes

Cloud-borne bacteria may affect human health and the environment

Louis Pasteur opened a glass flask on Montanvert Glacier in the French Alps in 1860 and collected some air. A few days later the bottom of that flask was teeming with goo—proof to Pasteur and his colleagues that there was something in the air, something invisible but quite real. Today we understand what that invisible stuff is—microbes aloft in our atmosphere—but despite the more than 150 years that have passed since Pasteur's experiment, scientists are just beginning to understand how microorganisms in the air affect life on earth.

Recently scientists captured more than 2,100 species of microbes traversing the Pacific Ocean from Asia to North America on huge plumes of air in the upper troposphere—up to 12 miles above the surface of the earth. A good fraction of them were bacteria, which can mean trouble for human health. In Africa, in a region known as the meningitis belt, dust storms carry the bacterium *Neisseria meningitidis* (*pictured above*), which infects around 200,000 people there annually. Yet for most people in most places, the microbes in the air are totally harmless, says David Smith, a microbiologist at the NASA Kennedy Space Center and lead author on the work that found the 2,100 traveling microbes. "You don't need to be worried," says Smith, whose findings were published online last December in the journal *Applied and Environmental Microbiology*. "This has been happening naturally, always."

Beyond health, microbes in the atmosphere might also be important for climate. "We're interested in whether they can contribute appreciably to the concentrations of cloud nuclei," says Susannah Burrows, an atmospheric scientist at Pacific Northwest National Laboratory in Richland, Wash. Bacteria can clump together, forming the seed around which clouds form and thus providing a key component of our atmosphere, she notes.

Other researchers wonder exactly how microbes behave while aloft and if they can reproduce as they travel. "We have several indications that microbes in the air are alive and active" and not just hitching a ride, says Paraskevi Polymenakou, an atmospheric microbiologist at the Hellenic Center for Marine Research in Greece.

For Dale Griffin, a microbiologist at the U.S. Geological Survey, the questions push beyond the atmosphere. "No matter how high we look, we seem to be able to find life," he says. Smith wonders not just how high that life goes but how it survives at such heights. "As a student in biology, I felt like everything had already been investigated," he says. "The atmosphere allows the opportunity to characterize a place where nobody has looked for life." —*Rose Eveleth*

DENNIS KUNKEL MICROSCOPY, INC. *Corbis*

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ENVIRONMENT

A Drying Rain Forest

The Peruvian Amazon struggles to adapt to a warmer, drier future

The western Amazon is under siege from a combination of a warming climate and human population growth that it has never faced before. Just in the past few years that region has been hit by two "once-in-a-century droughts"—one in 2005 and another in 2010. These dry spells may become more frequent as temperatures in the tropical North Atlantic Ocean rise and as humans continue to burn thousands of square kilometers of forest for farming.

Less forest means less precipitation. "About 50 percent of the rain that falls in the Amazon is generated by the forest itself, through transpiration and evaporation," says Gregory Asner, a tropical ecologist at the Carnegie Institution for Science at Stanford University, who presented his preliminary findings on the drought damage in Peru's Ucayali region at last December's American Geophysical Union meeting in San Francisco. "Deforestation exacerbates the drought problem because it removes that internal engine." Clearing fields and pastures also leaves more exposed forest edges, drying out the interior and making it more likely to burn if an agricultural fire escapes.

Faced with warmer, drier conditions, species can acclimate, adapt—or go extinct. A floral species can expand its range into a cooler region, but only as fast as seed dispersal allows, says Kenneth Feeley, a biologist at Florida International University, who studies trees on the eastern slope of the Peruvian Andes. He was surprised to see range changes there in just a few years. "Species are moving upslope about three vertical meters a year—that's really fast," he notes, adding that it may not be fast enough. "Based on the climate change already happening, they need to move nine or 10 vertical meters a year." In the lowlands, deforestation reduces the areas to which species can move, and pastures and roads create barriers to dispersal. Peru has some large protected areas, but scientists do not know if they are big enough—or in the right places—to allow species to migrate in a rapidly changing climate.

To help answer that question, Asner flies a plane equipped with a laser-imaging system and spectrometer that can identify chemical fingerprints of species with 80 percent accuracy—enough to create a diversity map of canopy species in the western Amazon, from Colombia to Bolivia, that will give scientists a baseline against which to compare future changes. He foresees "major shifts in the basic configuration of the Amazon" within his lifetime. "I'm 44," he says. "If I am lucky enough to live to be 80, I will see all of it."

—Barbara Fraser

GREGORY G. DIMIJIAN *Photo Researchers, Inc.*

COMMENT AT ScientificAmerican.com/mar2013

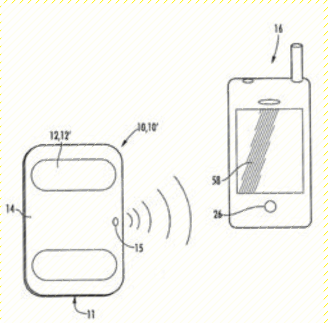
PATENT WATCH

Wireless, ultrasonic personal health monitoring system: Instantaneous and personal health information at your fingertips—that is the oft-imagined innovation that could change medicine. Physician-inventor David Albert, chief medical officer of AliveCor, headquartered in San Francisco, first envisioned a portable, easy way to measure personal heart health when Palm Pilots debuted in the late 1990s. Smartphone processors, however, were not powerful enough until the latest generation of devices such as the Droid and the iPhone.

After several clinical trials, the U.S. Food and Drug Administration approved Patent no. 8,301,232 for use last November. The patent describes an electrocardiogram (ECG) device that snaps in place around a smartphone, currently the iPhone 4 or 4S, like a protective cover. The case is embedded with sensors and electronics that measure the electrical activity of the heart. Users can record their heart rate by placing their fingers on the sensors. An ultrasonic signal relays data from the monitor to the smartphone and the AliveECG app. A distant physician can examine the pattern over a secure wireless connection. The readout is not as complete as a typical 12-lead ECG, but the smartphone version provides an accurate proxy in tests.

"The ECG is a valuable and extremely well understood way of assessing the heart and allowing us to diagnose problems," Albert says. "We wanted to put that power into the pocket of any physician, nurse, EMT—and ultimately give power to the patient as well."

The display still requires a trained eye to decipher, but the company is rolling out improvements. For example, one pending patent details a software enhancement that automatically detects atrial fibrillation—a common arrhythmia responsible for one third of all strokes. *—Marissa Fessenden*



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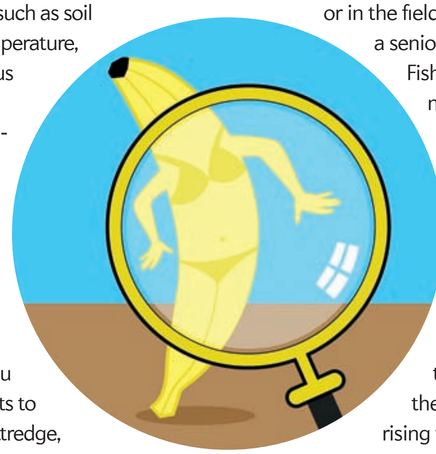
NUTRITION

From A to Zinc

A mobile scanner may tell shoppers which piece of fruit has the most vitamins

Are organic foods more nutritious than conventionally raised ones? Stanford University scientists cast doubt on that concept last year in a widely publicized report. But the gritty little secret is that whether your apples and spinach are organic or not, nutrient levels can vary dramatically depending on growing conditions, such as soil type and quality, temperature, and days of sun versus rain. As a consumer, you have no independent way of verifying that you have chosen a superior batch. But what if you had a handheld scanner that would allow you to check nutrient density? "You could compare carrots to carrots," says Dan Kittredge, executive director of the Bionutrient Food Association, which is raising the funds to research such a device. "If this batch is a dud, pass. If the next one is good, that's where you spend your money."



The basic technology has existed for decades. Near-infrared (NIR) spectroscopy—the modality that Kittredge is currently focusing on—has found applications in pharmaceutical manufacturing, medicine, agriculture and astronomy. NIR works on the principle that different molecules vibrate in slightly different ways. When infrared light is transmitted through or reflected from a given sample, certain wavelengths are absorbed more than others by the vibrating chemical bonds. By measuring the fraction of near-infrared light absorbed at each wavelength, scientists can obtain a distinct fingerprint that is characteristic of the sample. The results are precise—and fast. "Gas chromatography can easily take half a day," says Magdi Mossoba, a research chemist at the FDA's Center for Food Safety and Applied Nutrition. "NIR can give results in seconds."

Until recently, NIR and related forms of vibrational spectroscopy were confined to the laboratory, where they required large benchtop instruments that only skilled scientists could operate. Now, with miniaturization, they are being packaged in simple handheld devices that "a worker without a Ph.D. in chemistry can use in a warehouse or in the field," says Maggie Pax, a senior director at Thermo Fisher Scientific, a leading manufacturer of these tools. Pharmaceutical companies are using them to determine whether batches of raw ingredients are correctly labeled. More than a dozen countries have purchased them to help combat the rising tide of counterfeit drugs. And farmers use them to measure protein levels in grain, which helps to determine its market value.

Still, NIR has one major limitation as far as a supermarket scanner is concerned, which is that it cannot give readings for compounds at a concentration of less than 0.1 percent. The average vegetable is 92 percent water. After that come macronutrients such as carbohydrates and protein (in large enough quantities to be read by NIR), followed by micronutrients, including vitamins, minerals and antioxidants (most of which are too low to detect). The entire concept would be dead if not for one key observation. "Plants develop certain types of compounds in a predictable order and in specific ratios to various minerals, proteins and lipids," Kittredge says. The task he is undertaking now with the Linus Pauling Institute at Oregon State University is to run thousands of assays on key foods to establish the algorithms needed to develop a workable scanner. "This will happen," he asserts. "What we don't know is whether it will take three years or 30."

—*Anne Underwood*

Illustrations by Thomas Fuchs

HEALTH

No Harm Done?

A majority of teens see marijuana as risk-free

Although teen smoking rates are at a record low, more of them are smoking pot and fewer than ever believe it is bad for them. Data released last December as part of the National Institute on Drug Abuse's Monitoring the Future project show that only 44.1 percent of 12th graders believe regular marijuana use is harmful, the lowest level since 1973. That may explain why more than one third of high school seniors tried pot in 2012, and one in 15 smoked it daily.

The growing acceptance of medical marijuana may be behind teens' changing attitudes. Since 1996, 18 states, plus the District of Columbia, have made it legal for adults to obtain pot with a doctor's prescription. And last November, Colorado and Washington became the first states to legalize marijuana for anyone older than 21 years. "This shift in perceived risk may very well have resulted from the widespread endorsement of medical marijuana use," says Lloyd Johnston of the University of Michigan, who led the Monitoring the Future project.

But pot poses a higher risk for teens than for adults. In August investigators at Duke University and other institutions published the results of a 25-year study suggesting that heavy use among adolescents can do permanent cognitive damage. Subjects who were diagnosed with marijuana dependence as teens and adults suffered IQ declines of up to eight points between the ages of 13 and 38, even after the researchers controlled for other drug dependence, schizophrenia and education. (Abstainers' IQs rose slightly.) Moreover, the IQs of teen users did not recover even if they quit in adulthood.

How much marijuana is too much? "It's hard to find out," says lead study author and Duke clinical psychologist Madeline Meier. There is no accurate way to measure consumption because marijuana joints are rarely identical and potency varies. What is clear is that adolescent brains are particularly vulnerable to marijuana's effects, so teens would be smart to abstain—and may stay smarter for it, too.

—*Melinda Wenner Moyer*

BRENT LEWIN *Getty Images*

MARINE BIOLOGY

Beyond the Ocean's Surface

A robotic sub sets a distance record while recording a trove of data

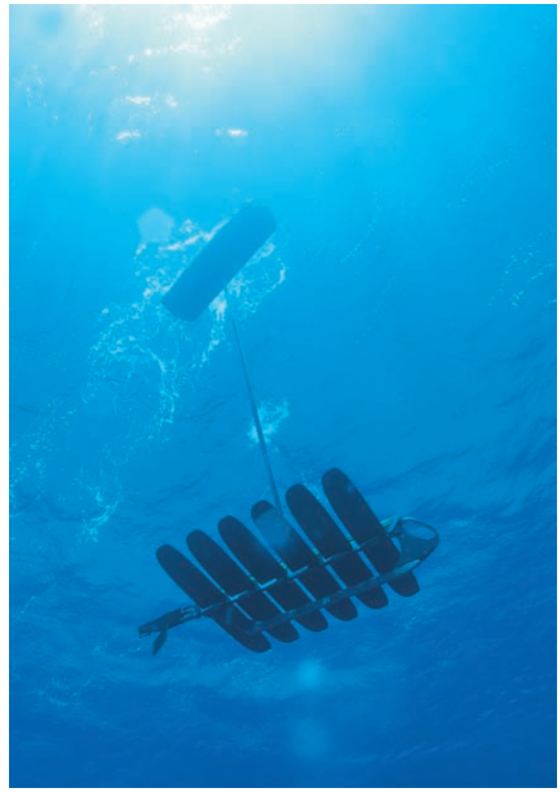
Several scientists are poring over data recorded by a robotic submarine that set a distance record for autonomous vehicles when it crossed the Pacific Ocean late last year. The surfboard-size, wave-powered Papa Mau traveled 16,668 kilometers from San Francisco to Australia's Hervey Bay, tracking information about ocean currents, wind speed and organisms critical to ocean life.

The submersible had been at sea for more than a year, one of a fleet of four robotic vehicles called Wave Gliders launched by Sunnyvale, Calif.–based Liquid Robotics. The company's CEO, Bill Vass, says his submarines provide more precise data than satellites, which are used to track wind speeds, wave heights and algal blooms. Satellites "make their best guess" from 400 kilometers up, Vass says, and can track only conditions near the water's surface, but the gliders "feel the full breadth of the current." This ability could make them better at determining current speed and direction, which have major effects on the shipping industry, oil and gas operations, and global weather.

Oscar Schofield, a Rutgers University professor of bio-optical oceanography, agrees that satellites are limited, but "they are the only way to provide a global view of the ocean, albeit weighted to the surface." The question is how to fill in the subsurface, three-dimensional structure. Scott Glenn, a Rutgers professor who specializes in physical oceanography, says combining data from satellites and gliders might provide a fuller picture. Satellites create maps of instants in time, whereas surface wave gliders and underwater profiling gliders provide vertical profiles of the water and can be redirected to areas of greatest interest, Glenn says.

Liquid Robotics has chosen five scientists to study the data from the Papa Mau and its other gliders. Researchers at the University of California, Merced, the University of California, Santa Cruz, the Scripps Institution of Oceanography, the University of Texas at Austin and Boston-based software firm Wise Eddy will use the information to analyze the ocean's health and respiration, its biomass and other information critical to marine life.

—Karen A. Frenkel



Wave Glider off the coast of Hawaii

CLIP FILES

Medical Advice before Taking a Spaceflight

The following is excerpted from a feature that appeared last December in the medical journal BMJ:

As access to space travel for personal or employment reasons increases, clinicians may be faced with new medical challenges and questions in their daily practice. For example: How long after a hip replacement can my patient safely embark on a ballistic two-hour flight to Australia? Can my patient with stable angina and a pacemaker for complete heart block participate in a suborbital Virgin Galactic flight? What is the maximum allowable time that my patient with osteoporosis can spend on a planned vacation at a space hotel? Of course, all physicians will not be expected to be experts in space medicine, just as they are currently not experts in the physiology of airplane flight, but they will have to understand how it affects their patients.

Medical Conditions Associated with Spaceflight and Potential Countermeasures

Motion sickness:
Antinauseant

Conjunctival irritation (foreign body in the eye):
Removal of foreign body

Radiation exposure:
Keep as low as reasonably achievable

Hypothetical Spaceflight Considerations for Common Medical Entities

Gastrointestinal reflux:
May become exacerbated because of lack of gravity

Psychiatric problems:
May become exacerbated (or possibly improve)

WEATHER

Before the Deluge

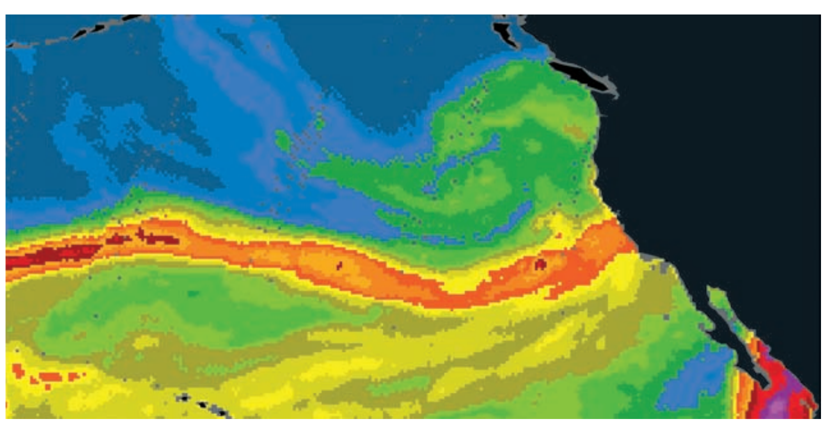
New observatories may help predict flooding from Pacific storms

An atmospheric river—a long, narrow conveyor belt of rainstorms—flows about 1.5 kilometers above the ocean surface and can extend thousands of kilometers toward land from out at sea, carrying as much water as 15 Mississippi Rivers. It strikes a coast as a series of storms that move from west to east with prevailing winds and arrive for days or weeks on end. Meteorologists have had some difficulty predicting the amounts and types of precipitation from these systems and, therefore, possible flooding.

A weather sensor network for California, to be completed in 2014, should allow forecasters to predict upcoming storms and floods with much greater precision. Satellite radars can track airborne water vapor well over the ocean but not so well over land. They also do not give a good assessment of winds within the corridor of water vapor, which affects how quickly the rain moves inland. Furthermore, the amount of flooding is strongly influenced by how wet or dry a region's soil is before and during the storms, which can only be accurately measured by sensors embedded in the ground. Knowing how much of the precipitation will fall as rain or snow is also important because rain causes more immediate flooding, whereas snow may cause delayed flooding.

The new warning system will provide all that information and more. The system's centerpiece will be four unique "atmospheric river observatories," located about 400 kilometers from one another. The units, each about the size of a dump truck, look upward and show precise wind speed and direction at several altitudes, the elevation at which precipitation is rain or snow, and the total amount of water vapor above the site. They also indicate standard weather data such as temperature, humidity and atmospheric pressure. Snow radars and soil-moisture sensors are now being deployed at multiple sites across California, reported Michael Dettinger, a research hydrologist at the Scripps Institution of Oceanography, who spoke at the annual American Geophysical Union conference in San Francisco last December.

When the system is complete, the data it generates will be available to the public online, in real time. The system could provide a model for better prediction around the world. Atmospheric rivers can strike the western coasts of most continents and landmasses; in mid-November 2012 a series of atmospheric-river storms caused the heaviest flooding in western England and Wales since the 1960s. *—Mark Fischetti*



Satellite image of an atmospheric river (*orange*) hitting California

COURTESY OF NOAA/ESRL/PSD

COMMENT AT ScientificAmerican.com/mar2013

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.

The New Age of Medical Monitoring

Mobile phones and tiny sensors are making it easier to quickly flag health trends

At any moment, someone in the U.S. most likely is having an asthma attack. The breath-robbing disease afflicts around 25 million Americans, and every year about half of them lose control of their asthma. They may rush to the emergency room or reach for a rescue inhaler, a source of quick-acting drugs that can relax constricted airways in minutes. Predicting who is at risk of such crises is difficult, however, because the relevant statistics that would identify trends come from the patients' own recollections days or weeks after the emergency.

In several U.S. cities, a new technology may change that. In Louisville, Ky., in parts of California and in Washington State, asthma patients are using rescue inhalers topped with a small sensor that wirelessly broadcasts when, where and how often the device is used. The data pass through a secure server to patients' mobile phones and a physician's Web dashboard, providing an instant record of how well a patient is doing and archiving the information for future reference.

The device and data-monitoring system—which are collectively called Asthmapolis and which were approved by the U.S. Food and Drug Administration last July—constitute just one example of an emerging strategy in a movement so new that no one has yet coined a catchy name for it. That movement holds great promise because it combines traditional medical record keeping and public health surveillance with data mining and mobile phone technologies. Together these tools produce deep, up-to-date reports that can benefit patients and medical researchers, as well as public health and environmental authorities, all at the same time.

"If you think about the driving forces that are going to shape health care for the next 20 to 30 years, three things stand out: major aging in the population, massive growth of chronic disease, not enough caregivers," says Steven DeMello, director of health care at the Center for Information Technology Research in the Interest of Society at the University of California, Berkeley. DeMello says that mobile diagnosis and surveillance could help blunt the impact of changing demographic trends by recognizing health crises early, by providing connections for remote care and by giving patients enough information to gain control of their disorder.

FIRST BREATH

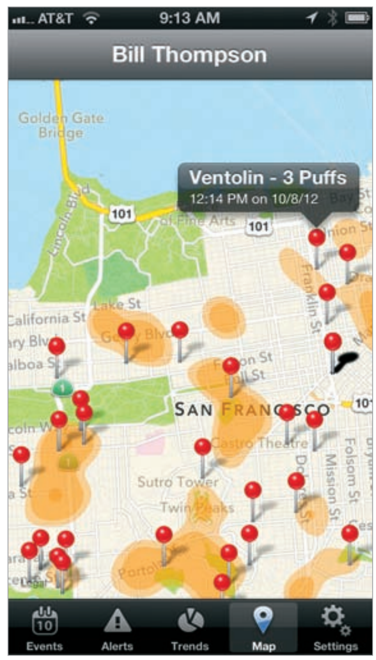
ASTHMAPOLIS emerged from co-founder David Van Sickle's frustration with government asthma data, a feeling that burgeoned after he received his Ph.D. and while he was serving as a disease detective in the National Asthma Control Program at the Centers for Disease Control and Prevention. "Despite all that we know about asthma and how to treat it, the majority of individual patients actually have uncontrolled disease," he says. "Their physicians can't course-correct, because patients don't report how poorly they're doing, and so they end up at higher risk of ER visits, hospitalizations, missed days of school and work—and that's all below public health's radar."

Van Sickle realized that patients were already carrying around devices that could objectively report their status: rescue inhalers. Most asthma patients take slow-acting drugs daily to keep their condition in check; repeated use of an inhaler signals a developing emergency. Beginning in 2006, Van Sickle and several partners created a wireless sensor that is now being tested in various settings. In Louisville, for example, researchers are using the device to identify local environmental triggers of asthma; in Sacramento, the focus is on proper follow-up care.

The Louisville project's sponsor is the municipal government. Ted Smith, its director of innovation, says Louisville hopes to deploy at least 500 sensors to construct a yearlong portrait of the impact of the disease on the population and the role that the city's

Illustration by Mark Allen Miller

notably poor air quality plays in making it worse. The Sacramento project is based inside Woodland Healthcare and Mercy Medical Group, two subsidiaries of the health care system Dignity Health. The goal is to test whether patients' health is improved by real-time feedback of their symptoms to their physicians. Michael Patmas, Woodland's chief medical officer, says the project may benefit other patients as well. First, many local asthma patients are farmworkers whose dusty outdoor work provokes their attacks; better management of their health might keep them out of the ER and thus reduce overcrowding. Plus, comparing the aggregated data from the patients' sensors with local weather reports could allow the hospital to alert all patients to possible risks through, for example, short text messages (SMS). "If it's dry, and it's hot, and the wind is blowing in a certain direction, we can send an SMS warning: 'Bad weather conditions today,' " Patmas says.



DATA MINE: The red pins in this Asthmapolis screenshot show where a patient used his rescue inhaler. Orange areas indicate where others needed to use theirs.

TRACKING TRENDS

TECHNOLOGIES such as Asthmapolis represent the confluence of two trends that are themselves new: the remote monitoring of patients and the collection of surveillance data from untraditional sources.

Remote monitoring tracks patients with chronic conditions, such as congestive heart failure, that might flare up into emergencies. Patients keep devices in their homes or on their person that wirelessly or electronically alert health care workers to worrying changes. The Veterans Health Administration (VHA) has been experimenting with remote monitoring for over a decade. The linked devices range from glucose meters for diabetics to bathroom scales because weight changes can indicate worsening congestive heart failure. Trials outside the VHA have included electrocardiographs hooked up to a home phone line to check for early signs of heart failure; daily medication dispensers that wirelessly communicate whether they have been opened; smartphone apps through which diabetics can report what they have eaten and how much insulin they have self-administered; and Bluetooth-enabled peak-flow meters, which asthma patients can use to detect whether their airways are becoming constricted.

Because most of these technologies are new, only a few comprehensive studies have been done. So far they report big increases in patients' sense of control over their illness and overall satisfaction with their care. The technology may not prove its full worth for improving health care until sensors are used by larger groups of patients.

Most of the data gathered during remote monitoring travels from one patient to that person's doctor or team, thus targeting that single person's care. In the other trend that has helped birth Asthmapolis and similar projects, the information flow is from the many to the many—that is, extracted from multiple sources of data to benefit multiple users, who can range from public health authorities to members of the general public.

Traditionally, disease-surveillance data arise from, and stay within, medicine and public health: they originate from physicians, flow through health departments and are published by government agencies. The earliest iteration of this new, crowdsourced style of surveillance was probably ProMED-mail (*Pro*gram for *M*onitoring *E*merging *D*iseases), an electronic mailing list run by academic volunteers that began in 1994 and now reaches about 60,000 subscribers. ProMED-mail takes contributions from a wide array of correspondents and accepts data from official sources such as governments and from unofficial ones such as news reports. A second generation of the same concept is HealthMap, founded in 2006 by a team at Boston Children's Hospital. It combines the active contributions of readers—ProMED-mail's bread and butter—with passive, automatic-intelligence processing of government data, news reports and social-media chatter in order to produce real-time maps of disease outbreaks around the world.

Both projects have demonstrated that they can identify important developments more quickly than traditional surveillance. In February 2003 ProMED-mail relayed a query that broke through the wall of silence that the People's Republic of China had constructed around the burgeoning SARS epidemic. And in April 2009 HealthMap's Web-scraping tools spotted respiratory illness reports in Mexican newspapers a couple of weeks before the CDC announced the first cases in the H1N1 flu pandemic.

Meanwhile others are working on a generation of portable devices that gather health data. Fitbit in San Francisco, for example, makes a family of wearable sensors that communicate information about sleep and exercise to a mobile app and Web dashboard. The Scout, announced in late 2012 by Scanadu in Moffett Field, Calif., has been likened to the "medical tricorder" from *Star Trek* because the handheld device simultaneously measures pulse, temperature and blood oxygen.

The challenge for these new devices, as with the earliest remote monitors and e-mail lists, will be persuading people to use them. There, DeMello says, the latest toys have an edge. "The idea is, you have a core monitoring technology, wrapped in a product—preferably a lovely little piece of design—wrapped in a service," he says. "You need all of those to be successful."

But lovely design comes at a cost. Fitbit's least expensive device, the Zip, is $59.95, and Scanadu says consumers will pay "less than $150" for Scout. If only a small slice of the population can afford the devices in the first place, then their larger promise—providing deep data on the health of large groups—may go unrealized. SA

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COURTESY OF ASTHMAPOLIS

David Pogue is the personal-technology columnist for the *New York Times* and an Emmy Award–winning correspondent for *CBS News.*

Term of Confusion

Online privacy and service agreements should sound like what they mean

Instagram, the phone app that lets you take pictures, apply artsy filters and then share them, is huge. So huge that in 2012 Facebook bought it for $1 billion.

Then, late last year, Instagram did something massively stupid: it changed its terms of use, the document of rules for using the service. The new terms included this gem: "You agree that a business or other entity may pay us to display your username, likeness, photos . . . without any compensation to you."

The backlash was swift and vicious. Bloggers heaped disdain. People quit Instagram en masse. Lawyers filed a class-action suit.

The CEO of Instagram sheepishly apologized, reinstated the older agreement and explained: "Instagram has no intention of selling your photos, and we never did." He had also remarked that "legal documents are easy to misinterpret."

Yes, apparently they are. Instagram was hardly the first Web company to publish appallingly rapacious, tone-deaf terms of service, trigger a public revolt, and then backpedal and apologize.

In 2009 Facebook's new agreement stated that users gave the company *perpetual* license "to use, copy, publish . . . modify, edit, frame, translate, excerpt, adapt, create derivative works and distribute . . . any User Content you Post."

After a ferocious public backlash, the company reverted back to its older terms (although it has again offered new ones). "It was never our intention to confuse people," a spokesperson said. "Facebook does not, nor have we ever, claimed ownership over people's content." Wait, what?

Google has lived through this cycle, too. When it introduced its online Google Drive storage, the terms-of-use document said (and Google's general policy still says) that if you put files onto the Google Drive, you give Google "a worldwide license to use, host, store, reproduce, modify . . . and distribute such content."

After ire from users, Google pointed to other language in its service agreement that says, "What belongs to you stays yours."

What's going on here? Who owns your material?

"That sort of language is typical in any site with user-generated content," says Los Angeles–based intellectual-property attorney Alan Friel, who writes these agreements all day long.

This "license to use, modify, distribute" talk is called facilitative rights. You're giving the company permission to process and display your stuff on their site. "Modify" means, say, "reformat for Facebook's template"; "perform" means "permitting playback of music or video you've posted"; "distribute" means "copying to multiple Facebook servers"; and so on.

What about the "derivative works" language? That's to protect media companies from lawsuits. "They're concerned that if they let users start posting stuff or submitting ideas, then they'll get sued when they create a TV show that may be similar," Friel says.

In each terms-of-service drama, the public seems to think that the Web company is claiming *ownership* of content. Instead these agreements give the company a nonexclusive *license* to use your stuff, usually in innocent, or at least understandable, ways. But could a company take those rights literally? Could it "modify" your post beyond recognition? Could it license your Instagram photograph for use in an ad for something like the NRA?

Technically, yes. Yet it's unlikely. Consumers would revolt—and flee the service in droves. And by distributing a user's content to outside parties, a company such as Facebook or Instagram would cease to be protected legally if the content, say, was already copyrighted.

In the meantime, it's perfectly possible to write less inflammatory agreements. Compare Google's language with the terms for Microsoft, which offers a very similar SkyDrive service: "Your content remains your content, and you are responsible for it. We do not control, verify, pay for, or endorse the content that you and others make available on the services." Boom. Done.

Surely these companies realize that normal people aren't lawyers. Why can't they say what they mean? Then again, we should be careful what we wish for. If these companies *really* said what they meant, they'd say, "We're here to exploit your creativity. If you don't like it, leave." SA

SCIENTIFIC AMERICAN ONLINE
Why your stuff on Facebook stays yours: ScientificAmerican.com/mar2013/pogue

Illustration by Ben Wiseman

Human Evolution

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The Origins of Creativity

Heather Pringle

New evidence of ancient ingenuity forces scientists to reconsider when our ancestors started thinking outside the box

CREDIT: *David Palumbo*

In Brief

- Scientists long thought that early humans were stuck in a creative rut until some 40,000 years ago, when their powers of innovation seemed to explode.
- But archaeological discoveries made in recent years have shown that our ancestors had flashes of brilliance far earlier than that.
- These findings indicate that the human capacity for innovation emerged over hundreds of thousands of years, driven by both biological and social factors.

Unsigned and undated, inventory number 779 hangs behind thick glass in the Louvre's brilliantly lit Salle des États. A few minutes after the stroke of nine each morning, except for Tuesdays when the museum remains closed, Parisians and tourists, art lovers and curiosity seekers begin flooding into the room. As their hushed voices blend into a steady hivelike hum, some crane for the best view; others stretch their arms urgently upward, clicking cell-phone cameras. Most, however, tilt forward, a look of rapt wonder on their faces, as they study one of humanity's most celebrated creations: the *Mona Lisa*, by Leonardo da Vinci.

several years he applied translucent glazes in delicate films—some no more than the thickness of a red blood cell—to the painting, most likely with the sensitive tip of his finger. Gradually stacking as many as 30 of these films one on top of another, Leonardo subtly softened lines and color gradations until it seemed as if the entire composition lay behind a veil of smoke.

The *Mona Lisa* is clearly a work of inventive genius, a masterpiece that stands alongside the music of Mozart, the jewels of Fabergé, the choreography of Martha Graham, and other such classics. But these renowned works are only the grandest manifestations of a trait that has long seemed part of our human hardwiring: the ability to create something new and desirable, the knack of continually improving designs and technologies—from the latest zero-emissions cars made in Japan to the sleekly engineered spacecraft on nasa's launchpads. Modern humans, says Christopher Henshilwood, an archaeologist at the University of the Witwatersrand, Johannesburg, “are inventors of note. We advance and experiment with technology constantly.”

Just how we came by this seemingly infinite capacity to create is the subject of intense scientific study: we were not always such whirlwinds of invention. Although our human lineage emerged in Africa around six million years ago, early family members left behind little visible record of innovation for nearly 3.4 million years, suggesting that they obtained plant and animal foods by hand, with tools such as digging or jabbing sticks that did not preserve. Then, at some point, wandering hominins started flaking water-worn cobblestones with hammerstones to produce cutting tools. That was an act of astonishing ingenuity, to be sure, but a long plateau followed—during which very little seems to have happened on the creativity front. Our early ancestors apparently knapped the same style of handheld, multipurpose hand ax for 1.6 million years, with only minor tweaks to the template. “Those tools are really kind of stereotypical,” says Sally McBrearty, an archaeologist at the University of Connecticut.

So when did the human mind begin churning with new ideas for technology and art? Until recently, most researchers pointed to the start of the Upper Paleolithic period 40,000 years ago, when *Homo sapiens* embarked on what seemed a sudden, wondrous invention spree in Europe: fashioning shell-bead necklaces, adorning cave walls with elegant paintings of aurochs and other Ice Age animals, and knapping a wide variety of new stone and bone tools. The finds prompted a popular theory proposing that a random genetic mutation at around that time had spurred a sudden leap in human cognition, igniting a creative “big bang.”

New evidence, however, has cast grave doubt on the mutation theory. Over the past decade archaeologists have uncovered far older evidence of art and advanced technology, suggesting that the human capacity to cook up new ideas evolved much earlier than previously thought—even before the emergence of *H. sapiens* 200,000 years ago. Yet although our capacity for creativity sparked early on, it then smoldered for millennia before finally catching fire in our species in Africa and Europe. The evidence seems to indicate that our power of innovation did not burst into existence fully formed late in our evolutionary history but rather gained steam over hundreds of thousands of years, fueled by a complex mix of biological and social factors.

Exactly when did humankind begin thinking outside the box, and what factors converged to ultimately fan our brilliant creative fire? Understanding this scenario requires following a detective story composed of several strands of evidence, starting with the one showing that the biological roots of our creativity date back much further than scientists once thought.

Mother of Invention

spectacular cave art of the Upper Paleolithic clearly signals the presence of people who thought as we do. But more recently, experts have begun searching for hints of other kinds of modern behavior and its antecedents in the archaeological record—and coming up with fascinating clues.

Archaeologist Lyn Wadley of the University of the Witwatersrand has spent much of her career studying ancient cognition, research that led her in the 1990s to open excavations at Sibudu Cave, some 40 kilometers north of Durban, South Africa. Two years ago she and her team discovered a layer of strange, white, fibrous plant material there. To Wadley, the pale, brittle mash looked like ancient bedding—rushes and other plants that later people often scattered on the ground for sitting and sleeping on. But the layer could also have formed from wind-borne leaf litter. The only way to tell one from the other was to encase the entire layer in a protective plaster jacket and take it back to the laboratory. “It took us three weeks to make all that plaster,” Wadley recounts, “and I was really grumpy the whole time. I kept wondering, ‘Am I wasting three weeks in the field?’”

But Wadley's gamble paid off richly. In December 2011 she and her colleagues reported in *Science* that Sibudu's occupants selected leaves from just one of many woody species in the area to make bedding 77,000 years ago—nearly 50,000 years earlier than previously reported examples. What most surprised Wadley, however, was the occupants' sophisticated knowledge of the local vegetation. Analysis showed that the chosen leaves came from *Cryptocarya woodii*, a tree containing traces of natural insecticides and larvicides effective against the mosquitoes that carry deadly disease today. “And that's very handy to have in your bedding, particularly if you live near a river,” Wadley observes.

The creative minds at Sibudu did not stop there, however. They most likely devised snares to capture small antelopes, whose remains litter the site, and crafted bows and arrows to bring down more dangerous prey, judging from the sizes, shapes and wear patterns of several stone points from the cave. Moreover, Sibudu's hunters concocted various valuable new chemical compounds. By shooting a high-energy beam of charged particles at dark residues on stone points from the cave, Wadley's team detected multi-ingredient glues that once fastened the points to wood hafts. She and her colleagues then set about experimentally replicating these adhesives, mixing ocher particles of different sizes with plant gums and heating the mixtures over wood fires. Publishing the results in *Science*, the team concluded that Sibudu's occupants were very likely “competent chemists, alchemists and pyrotechnologists” by 70,000 years ago.

Elsewhere in southern Africa, researchers have recently turned up traces of many other early inventions. The hunter-gatherers who inhabited Blombos Cave between 100,000 and 72,000 years ago, for example, engraved patterns on chunks of ocher; fashioned bone awls, perhaps for tailoring hide clothing; adorned themselves with strands of shimmering shell beads; and created an artists' studio where they ground red ocher and stored it in the earliest known containers, made from abalone shells. Farther west, at the site of Pinnacle Point, people engineered the stone they worked with 164,000 years ago, heating a low-grade, local rock known as silcrete over a controlled fire to transform it into a lustrous, easily knappable material. “We are seeing behaviors that we didn't even dream about 10 years ago,” Henshilwood remarks.

Moreover, technological ingenuity was not the sole preserve of modern humans: other hominins possessed a creative streak, too. In northern Italy a research team headed by University of Florence archaeologist Paul Peter Anthony Mazza discovered that our near kin, the Neandertals, who first emerged in Europe some 300,000 years ago, concocted a birch bark–tar glue to fasten stone flakes to wood handles, fabricating hafted tools some 200,000 years ago. Likewise, a study published in *Science* last November concluded that stone that an even earlier hominin, *Homo erectus*, learned to kindle fires for warmth and protection from predators as early as one million years ago.

Even our very distant ancestors were capable on occasion of coining new ideas. At two sites near the Kada Gona River in Ethiopia, a team led by paleoanthropologist Sileshi Semaw of Indiana University Bloomington found the oldest known stone tools—2.6-million-year-old choppers knapped by *Australopithecus garhi* or one of its contemporaries, likely for stripping meat from animal carcasses. Such tools look crude to us, a far cry from the smartphones, laptops and tablets that roll off assembly lines today. “But when the world consisted solely of naturally formed objects, the capacity to imagine something and turn it into a reality may well have seemed almost magical,” write cognitive scientist Liane Gabora of the University of British Columbia and psychologist Scott Barry Kaufman, now at New York University, in a chapter appearing in *The Cambridge Handbook of Creativity* (Cambridge University Press, 2010).

Cognition and Creation

Yet impressive as these early flashes of creativity are, the great disparity in the depth and breadth of innovation between modern humans and our distant forbears demands an explanation. What changes in the brain set our kind apart from our predecessors? By poring over three-dimensional scans of ancient hominin braincases and by examining the brains of our nearest living evolutionary kin—chimpanzees and bonobos, whose ancestors branched off from our lineage some six million years ago—researchers are beginning to unlock this puzzle. Their data show just how extensively human gray matter evolved over time.

Generally speaking, natural selection favored large brains in humans. Whereas our australopithecine kin possessed an estimated mean cranial capacity of 450 cubic centimeters, roughly that of some chimpanzees, *H. erectus* more than doubled that capacity by 1.6 million years ago, with a mean of 930 cubic centimeters. And by 100,000 years ago *H. sapiens* had a mean capacity of 1,330 cubic centimeters. Inside this spacious braincase, an estimated 100 billion neurons processed information and transmitted it along nearly 165,000 kilometers of myelinated nerve fibers and across some 0.15 quadrillion synapses. “And if you look at what this correlates with in the archaeological record,” says Dean Falk, a paleoneurologist at Florida State University, “there does seem to be an association between brain size and technology or intellectual productivity.

But size was not the only major change over time. At the University of California, San Diego, physical anthropologist Katerina Semendeferi has been studying a part of the brain known as the prefrontal cortex, which appears to orchestrate thought and action to accomplish goals. Examining this region in modern humans and in both chimpanzees and bonobos, Semendeferi and her colleagues discovered that several key subareas underwent a major reorganization during hominin evolution. Brodmann area 10, for example—which is implicated in bringing plans to fruition and organizing sensory input—nearly doubled in volume after chimpanzees and bonobos branched off from our human lineage. Moreover, the horizontal spaces between neurons in this subarea widened by nearly 50 percent, creating more room for axons and dendrites. “This means that you can have more complicated connections and ones that go farther away, so you can get more complex and more synthetic communication between neurons,” Falk comments.

Pinpointing just how a bigger, reorganized brain spurred creativity is a tricky business. But Gabora thinks that psychological studies of creative people today supply a key clue. Such individuals are excellent woolgatherers, she explains. When tackling a problem, they first let their minds wander, allowing one memory or thought to analytic mode of thought. “They zero in on only the most relevant properties,” Gabora says, and they start refining an idea to make it workable.

In all likelihood, Gabora notes, a bigger brain led to a greater ability to free-associate. More stimuli could be encoded in a brain made up of many billions of neurons. In addition, more neurons could participate in the encoding of a particular episode, leading to a finer-grained memory and more potential routes for associating one stimulus with another. Imagine, Gabora says, that a hominin brushes against a spiny shrub and sharp thorns tear its flesh. An australopithecine might encode this episode very simply—as a minor pain and as an identifiable feature of the shrub. But *H. erectus*, with its larger assembly of neurons, could conceivably encode many aspects of the episode, including the sharp points of the thorns and its own raked flesh. Then, when this hominin begins hunting, its need to kill prey might activate all memory locations encoding torn flesh, bringing to mind the encounter with the sharp pointed thorns. That memory, in turn, could inspire a fresh idea for a weapon: a spear with a sharp pointed tip.

But large-brained hominins could not afford to linger too long in an associative state in which one thing immediately reminded them of a flood of other things, both important and inconsequential. Their survival depended mostly on analytic thought—the default mode. So our ancestors had to develop a way of switching smoothly from one mode to another by subtly altering concentrations of dopamine and other neurotransmitters. Gabora now hypothesizes that *H. sapiens* needed tens of thousands of years to fine-tune this mechanism before they could reap the full creative benefit of their large brains, and she and her students are now testing these ideas on an artificial neural network. Through a computer model, they simulate the brain's ability to switch between the analytic and associative mode to see how it could help someone break out of a cognitive rut and see things in a new way. “Just having more neurons isn't enough,” Gabora asserts. “You have to be able to make use of all that extra gray matter.” Once that final piece of the biological puzzle fell into place—perhaps a little more than 100,000 years ago—the ancestral mind was a virtual tinder box, awaiting the right social circumstances to burst into flame.

Building on Brilliance

In the autumn of 1987 two researchers from the University of Zurich—Christophe and Hedwig Boesche—observed a behavior they had never seen before in a group of chimpanzees foraging for food in Tai National Park in Ivory Coast. Near a ground nest belonging to a species of driver ants, a female stopped and picked up a twig. She dipped one end into the loose soil covering the nest's entrance and waited for the colony's soldier ants to attack. When the dark swarm had advanced nearly 10 centimeters up the twig, the female chimpanzee plucked it from the nest and deftly rolled it toward her mouth, snacking on the ants. She then repeated the process until she had eaten her fill.

Chimpanzees are highly adept at using a wide range of tools—cracking open nuts with stones, sponging up water from tree hollows with leaves and unearthing nutritious plant roots with digging sticks. But they seem unable to build on this knowledge or to craft ever more advanced technology. “Chimps can show other chimps how to hunt termites,” Henshilwood says, “but they don't improve on it, they don't say, ‘Let's do it with a different kind of probe’—they just do the same thing over and over.” Modern humans, in contrast, suffer from no such limitations. Indeed, we daily take the ideas of others and put our own twist on them, adding one modification after another, until we end up with something new and very complex. No one individual, for

Anthropologists call this knack of ours cultural ratcheting. It requires, first and foremost, the ability to pass on knowledge from one individual to another, or from one generation to the next, until someone comes along with an idea for an improvement. Last March a study published in *Science* by Lewis Dean, a behavioral primatologist now at the Physiological Society in London, and four colleagues, revealed why human beings can do this and chimpanzees and capuchin monkeys cannot. Dean and his team designed an experimental puzzle box, with three sequential and incrementally difficult levels: then they presented it to groups of chimpanzees in Texas, capuchin monkeys in France and nursery schoolchildren in England. Only one of the 55 nonhuman primates—a chimpanzee—reached the highest level after more than 30 hours of trying. The children, however, fared far better. Unlike the groups of monkeys, the children worked collaboratively—talking among themselves, offering encouragement and showing one another the right way to do things. After two and a half hours, 15 of the 35 children had reached level three.

Equipped with these social skills and cognitive abilities, our ancestors could readily transmit knowledge to others—a key prerequisite for cultural ratcheting. Yet something else was needed to propel the ratcheting process and push *H. sapiens* to new creative heights in Africa some 90,000 to 60,000 years ago and in Europe 40,000 years ago. Mark Thomas, an evolutionary geneticist at University College London, thinks this push came from demography. His premise is simple. The larger a hunter-gatherer group is, the greater the chances are that one member will dream up an idea that could advance a technology. Moreover, individuals in a large group who frequently rubbed shoulders with neighbors had a better chance of learning a new innovation than those in small, isolated groups. “It's not how smart you are,” Thomas says. “It's how well connected you are.”

> It's not how smart you are. It's how well connected you are.
>
> Mark Thomas
> *University College London*

To test these ideas, Thomas and two colleagues developed a computer model to simulate the effects of demography on the ratcheting process. With genetic data from modern Europeans, the team estimated the size of modern human populations in Europe at the beginning of the Upper Paleolithic, when evidence of human creativity started to spike, and calculated the population density. Then the researchers examined African populations over time, simulating their growth and patterns of migratory activity. Their model showed that African populations reached the same density as the early Upper Paleolithic Europeans around 101,000 years ago, just before innovation began to take off in sub-Saharan regions, according to the archaeological record. It also showed that large social networks actively spur human creativity.

New archaeological evidence published in *Nature* in November 2012 sheds light on the tech renaissance that followed the rise of population density in southern Africa. Some 71,000 years ago at Pinnacle Point, *H. sapiens* devised and passed down to others a complex technological recipe to make lightweight stone blades for projectile weapons—cooking silcrete to a specific temperature to improve its flaking qualities, knapping the finished material into blades little more than a couple of centimeters long, and mounting them on wood or bone shafts with homemade glue. “Like viruses,” note archaeologists Fiona Coward of Royal Holloway, University of London, and Matt Grove of the University of Liverpool in England in a paper published in *PaleoAnthropology* in 2011, “cultural innovations need very particular social conditions to spread—most notably ... large connected populations who can ‘infect’ one another.”

Which brings us to the jostling, teeming, intimately linked world we live in today. Never before have humans crowded together in such massive cities, accessing vast realms of knowledge with a click of the keyboard and fashions, new electronics, new cars, new music, new architecture.

Half a millennium after Leonardo da Vinci conceived of his most celebrated work, we marvel at his inventive genius—a genius built on the countless ideas and inventions of a lineage of artists stretching back into the Paleolithic past. And even now a new crop of artists gaze at the *Mona Lisa* with an eye to turning it into something fresh and dazzlingly creative. The human chain of invention remains unbroken, and in our superbly connected world, our singular talent to create races on ahead of us.

THE AUTHOR

Heather Pringle is a Canadian science writer and a contributing editor to *Archaeology* magazine.

CREDIT: Nick Higgins

Heather Pringle

MORE TO EXPLORE

Middle Stone Age Bedding Construction and Settlement Patterns at Sibudu, South Africa. Lyn Wadley et al. in *Science*, Vol. 334, pages 1388–1391; December 9, 2011.

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ASTROPHYSICS

THE INNER LIFE OF STAR CLUSTERS

All stars are born in groups but then slowly disperse into space. A new theory seeks to explain how these groups form and fall apart or, in rare cases, persist for hundreds of millions of years

By Steven W. Stahler

STAR STUCK: The Pleiades, known as an "open" cluster, is one of the most stable stellar groups in the Milky Way.

Steven W. Stahler is a theoretical astrophysicist at the University of California, Berkeley, and co-author, with Francesco Palla, of *The Formation of Stars,* the first comprehensive textbook on star creation (Wiley-VCH, 2004).

THE NIGHT SKY IS A FIELD OF STARS.

In every direction, stars bright and dim fill the horizon to brimming. Some seem to form distinct patterns, which we recognize as constellations. Yet as beguiling as those patterns may be, most of them are no more than projections of the human mind. The vast majority of stars, in our own galaxy and in others, have no true physical connection to one another.

At least, not anymore. Every star actually begins its life in a group, surrounded by siblings of nearly the same age that only later drift apart. Astronomers know this because some of these stellar nurseries, called star clusters, still exist. The Orion nebula cluster is perhaps the most famous one: in images from the Hubble Space Telescope, its stars wink from within churning clouds of dust and gas. You can see the Pleiades cluster from your backyard: it is the fuzzy patch in the constellation Taurus.

Star clusters vary enormously, ranging from fragile associations with just a few dozen members to dense aggregates of up to a million stars. Some groups are very young—only a few million years old—and others date from the dawn of the universe. Within them, we find stars in every stage of the stellar life cycle. Indeed, observations of star clusters provided the main evidence for today's accepted theory of how individual stars evolve over time. The theory of stellar evolution is one of the triumphs of 20th-century astrophysics.

Yet relatively little is known about the inner workings and evolution of the clusters themselves. What accounts for the variety of forms that astronomers observe? We understand far more about individual stars than we do about the cradles of their formation!

The irony of this situation first struck me 20 years ago, when I began writing a graduate textbook on star formation with Francesco Palla of Arcetri Astrophysical Observatory in Florence, Italy. At the time, the two of us were regularly trading visits between Berkeley, Calif., and Florence. As we followed the many strands of research in this rich field, the unanswered questions about star clusters always lurked in the back of our minds.

One afternoon, as we took a break at Caffe Strada (located in Berkeley, naturally), the germ of an answer came to me. Perhaps the same physical forces had shaped all clusters, regardless of their present ages and sizes. And perhaps one simple variable could account for the way those forces act on an individual cluster: the mass of the parent cloud from which each cluster is born. It would take me the better part of the ensuing decades to gather evidence for this hunch.

CLOUDY WITH A CHANCE OF STARLIGHT

WHEN I BEGAN this work, astronomers knew a lot about how stars form and a good bit about the kinds of clusters they form in. Stars do not materialize from empty space; rather they coalesce within vast clouds composed chiefly of hydrogen molecules, along with other elements and a small admixture of dust. These so-called molecular clouds are distributed throughout all galaxies, and each exerts a gravitational pull—not only on stars and other objects outside the cloud but also on regions in the cloud itself. Because of the cloud's own gravity, regions where gas and dust are especially dense collapse into protostars. In this way, clusters of anywhere from a few dozen to thousands of stars can arise from a single molecular cloud.

Clusters generally occur in five types, distinguished in part by their age and in part by the number and density of the stars they contain. The very youngest stellar groups, called embedded clusters, lie in clouds so thick that light in the visible wavelengths radiating from their member stars is completely obscured.

IN BRIEF

Stars form in clusters, within clouds composed of gas mixed with dust.

Three types of clusters can be seen in the Milky Way, with differing structures and evolutionary histories.

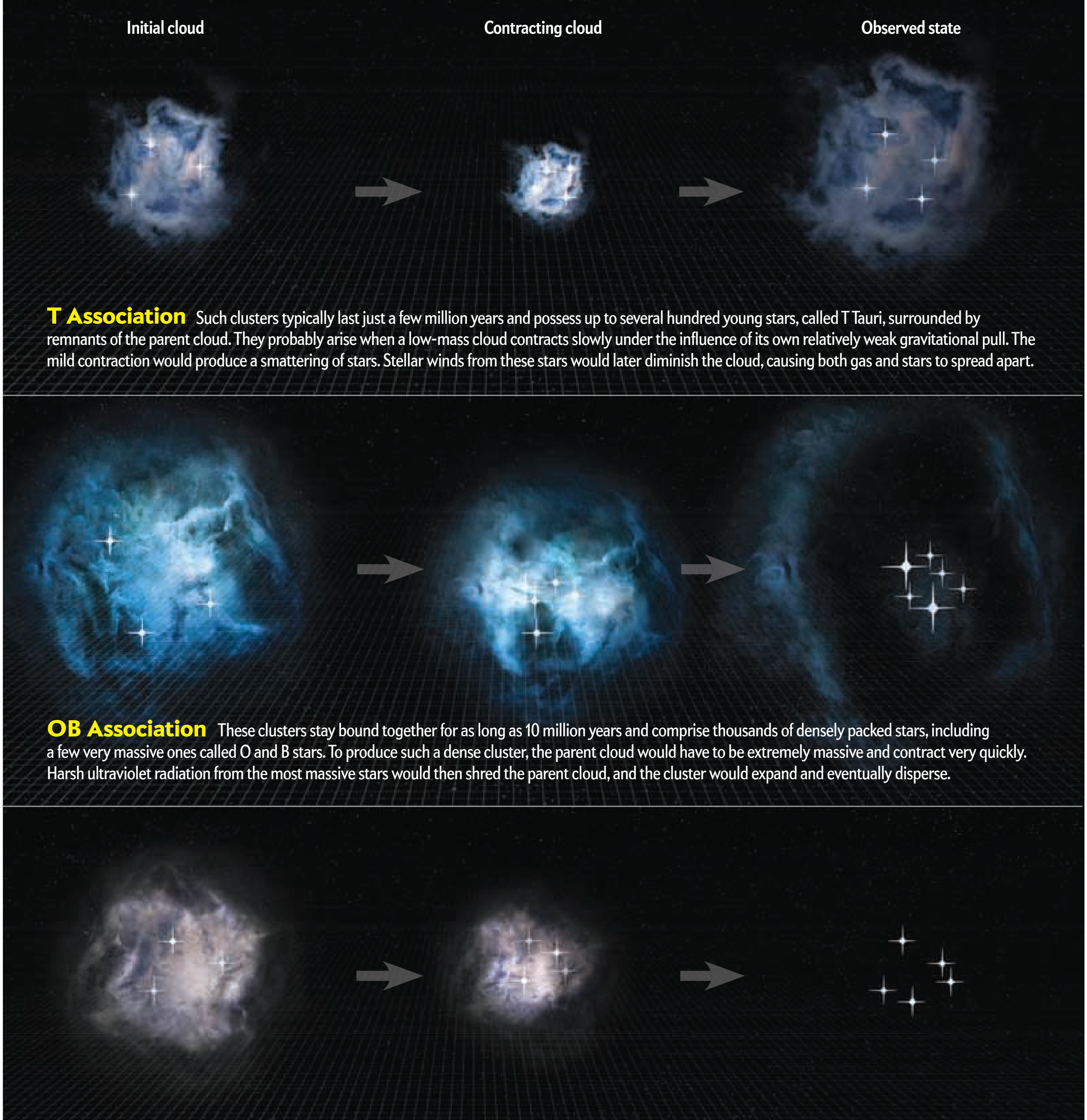
The mass of the cloud that spawns a stellar group may account for these differences, by affecting the balance of contraction and expansion in the cluster.

Only open clusters remain intact after the parent cloud has dispersed.

PRECEDING PAGES: COURTESY OF NASA, ESA, AURA AND CALTECH

One Driver, Three Outcomes

The three most readily observed star clusters in our Milky Way Galaxy all began as a diffuse cloud of dust and gas, within which small regions condensed to form stars. The author proposes that a single factor—the mass of the parent cloud—accounts for the differences in the clusters' subsequent evolution and structure (*below*). First, the clouds contracted, accelerating star production at rates determined by the starting mass; higher-mass clouds contracted most and generated stars most quickly. Later, the clusters expanded, and the clouds dispersed partly or fully, depending on the number and kinds of stars present.



T Association Such clusters typically last just a few million years and possess up to several hundred young stars, called T Tauri, surrounded by remnants of the parent cloud. They probably arise when a low-mass cloud contracts slowly under the influence of its own relatively weak gravitational pull. The mild contraction would produce a smattering of stars. Stellar winds from these stars would later diminish the cloud, causing both gas and stars to spread apart.

OB Association These clusters stay bound together for as long as 10 million years and comprise thousands of densely packed stars, including a few very massive ones called O and B stars. To produce such a dense cluster, the parent cloud would have to be extremely massive and contract very quickly. Harsh ultraviolet radiation from the most massive stars would then shred the parent cloud, and the cluster would expand and eventually disperse.

Open Cluster The longest lasting of the three, open clusters can persist for hundreds of millions of years, but they have far fewer stars than OB associations do. These groups probably arise when a cloud of intermediate mass contracts. Although stellar winds drive the cloud away, the cluster does not disperse for a very long time.

Illustrations by Malcolm Godwin

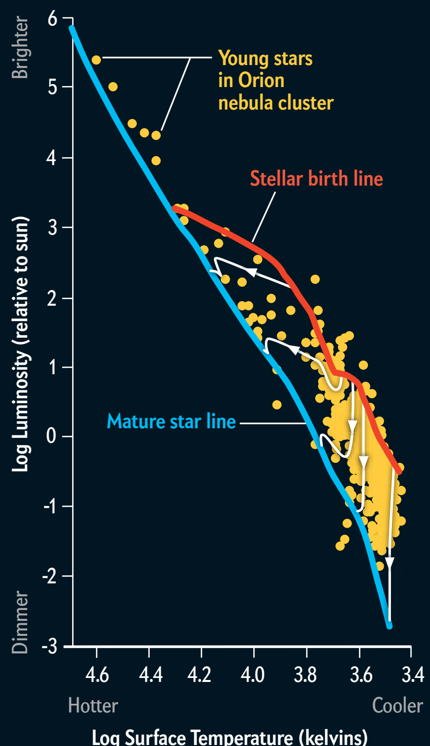
Cluster's History Supports Theory

Data from the Orion nebula cluster, an OB association in the Orion nebula (*photograph*), support the author's theory that cloud contraction occurs early in cluster evolution, causing star formation to accelerate as the density of the parent cloud rises. Star formation in the cluster stopped about 100,000 years ago, but until then the parent cloud probably contracted for millions of years. To show that contraction happened, the author first determined the ages of the cluster's young stars (*yellow dots in left graph*), which can be gleaned from their temperature and brightness.

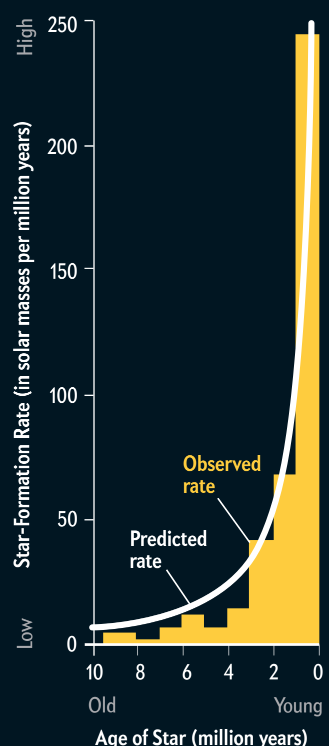
In general, the red line represents very young stars that are newly visible in optical wavelengths; these stars get hotter and dimmer in predictable ways as they age (*white arrows in left graph*), until ultimately they are plotted on the blue line. Thus, a star's position between the red and blue lines indicates its age.

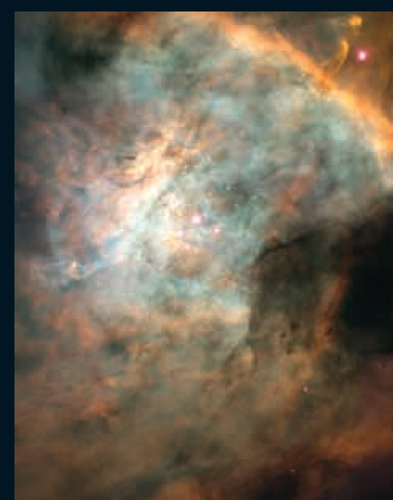
The author then calculated the collective mass of the stars (relative to the mass of the sun) in each million-year age group, revealing the star-formation rate in the cluster during that period (*right graph*). The results indicate that star production increased dramatically over time, just as theoretical modeling (*white line*) predicted.

Young Stars Show Their Age



Star Formation Has Accelerated





Instead we see only the infrared glow of dust heated by the embedded stars and cannot discern the detailed structure of these primitive clusters. They remain an abiding mystery.

Globular clusters, in contrast, are the oldest and most populous stellar group. They date to the dawn of the universe and can contain as many as one million stars packed very closely together. The parent clouds of these mature clusters have disappeared, and the stars within are entirely visible. Yet the closest globular clusters lie at some remove from the disk of the Milky Way galaxy, and so they, too, are difficult for astronomers to study in detail.

For practical reasons, then, I have restricted my theorizing to the three types of clusters that occur in the plane of our galaxy and thus can be seen best of all. The sparsest of these is called a T association because it consists largely of the most common kind of young star, called a T Tauri. (Our sun was a T Tauri star in its youth.) Each T association contains up to several hundred of these stars surrounded, but not totally obscured, by the parent cloud. T associations do not stay together for long: the most aged ones observed are some five million years old—the blink of an eye from a cosmic perspective.

Scientists have known for some time that the mass of the parent cloud in a T association is far greater than that of its collective stellar progeny. I believe this feature accounts for the short life span of these clusters. Mass determines the strength of gravitational force: the greater the mass is, the stronger the gravitational pull is. So if the mass of the parent cloud in a T association is much greater than that of its member stars, the gravity of the cloud—not the gravity exerted by the stars on one another—must be what holds the cluster together. And if the cloud disperses, the stars will drift apart. Astronomers think that stellar winds—jets of gas propelled forcefully outward from the stars—eventually strip away the parent cloud of a T association, freeing the previously bound stars to head into space.

SOURCES: "STAR FORMATION IN THE ORION NEBULA CLUSTER," BY FRANCESCO PALLA AND STEVEN W. STAHLER, IN *ASTROPHYSICAL JOURNAL*, VOL. 525; 1999 (*left*); COURTESY OF NASA, HST, C. R. O'DELL AND S. K. WONG (*right*)

The second type of stellar group readily observed in the Milky Way is named after two extraordinary kinds of stars, designated O and B, that are the most luminous and the most massive stars in the universe. These clusters, called OB associations, typically have about 10 times more stars than T associations do, including a few O and B types. The Orion nebula cluster is a familiar example; located some 1,500 light-years away, it comprises four truly massive stars and about 2,000 lesser ones, including many T Tauri stars. It has the highest stellar density of any region in our part of the galaxy.

All young OB associations have similarly high densities and arise from especially massive parent clouds. Yet despite the tremendous gravity within these systems, the stars in older OB associations are not just gradually dispersing but are actively flinging themselves out into space. Astronomers know this because images of mature OB associations taken just a few decades apart show that the member stars have moved farther away from one another.

One reason for this rapid dispersal is that the stars are moving very quickly to begin with. The terrific gravity of the parent cloud in an OB association spurs its stellar members to orbit at high velocities. Young OB associations are chock-full of these speeding stars, poised to escape the cluster should the parent cloud diminish. And in OB associations, the parent cloud is under siege from the harsh ultraviolet radiation that O and B stars emit during their brief lifetimes. These stars are powered by nuclear fusion, as our sun is, but they burn far more fiercely. A typical O star has 30 times the mass of the sun, for example, yet it exhausts its fuel in just a few million years.

In the course of this self-immolation, ultraviolet radiation streams from the star and ionizes surrounding gas—in effect, burning up the parent cloud. The dust and gas in the Orion nebula cluster are glowing from this ionization. As the parent cloud burns away, its gravity dwindles. When the massive stars have finally expired and the parent cloud is gone, the gravity of the system can no longer contain those smaller, speeding stars, and they are flung far afield.

Thus, both T and OB associations undo themselves, whether through gentle attrition or violent agitation. The third, much less common, kind of stellar group in the Milky Way is remarkably stable, however. Called open clusters, these groups have up to 1,000 ordinary stars and persist for hundreds of millions, and even billions, of years. Yet their molecular clouds and any attendant gravity have long since vanished.

The Pleiades is one such cluster. It is 125 million years old, and its parent cloud has probably been gone for 120 million years or more. The equally famous Hyades cluster, not far from the Pleiades in the sky, is 630 million years old. In the outskirts of our galaxy dwell dozens of open clusters that are even older. The cluster M67, a system of 1,000 stars, arose four billion years ago.

Even open clusters are not immortal; very few are older than M67. Astronomers believe that, eventually, the gravity of molecular clouds passing close by begins to shred and disperse these systems. Yet they still pose a vexing problem. Over the past few decades researchers have arrived at satisfying explanations for how the dispersal of parent clouds causes T and OB associations to fall apart. But they still have no answer for why the stars in open clusters survive cloud dispersal to remain bound together for many millions of years.

PUSH AND PULL

As I wrote my book on star formation, I had ample cause to wonder about the diversity of cluster forms. I saw the mystery of open clusters as part of a larger class of questions: Why does our galaxy host only a limited variety of star clusters? How does a molecular cloud "decide" what kind of cluster it is going to produce?

I considered the forces at work in star clusters. Taken together, the life stages of the three types I chose to study point to two countervailing processes: contraction, caused by the gravity of the parent cloud, and expansion, promoted by stellar winds and ionizing radiation. Each star-producing cloud is subject to these two opposing influences to varying degrees. In the case of T and OB associations, expansion eventually wins. In the case of open clusters, expansion and contraction seem to stay in balance, at least during the critical epoch during which member stars are forming.

The balance of forces in a cloud, I reasoned, thus determines its fate as well as the destiny of the stellar cluster it produces. And I suspected that the key to this balance might be the original mass of the parent cloud. As I have explained, the mass of a cloud certainly determines its gravity; the cloud's gravity, in turn, governs the rate at which it contracts. Cloud mass also determines the number of stars the cloud produces. A low-mass cloud, for example, would contract slowly, causing a gradual increase in its density that would produce a smattering of ordinary stars. Later, winds from those stars would gradually strip away the cloud, reversing the contraction and releasing member stars into space. That scenario fits what we observe in T associations today.

At the opposite extreme, a cloud with an order of magnitude more mass would undergo a rapid contraction, forming many new stars in close proximity. Eventually this cloud's core would reach a density so great that a few massive stars would be born. Then, as we see in OB associations, harsh radiation from the massive stars would quickly disperse the cloud, and the speeding stars within would move outward.

Finally, it seems probable that an intermediate range of cloud masses exists for which the two effects are comparable. These clouds would contract at about the same rate at which they lose mass. The result is a molecular cloud containing an ever increasing fraction of young, tightly knit stars but no truly massive ones. Even when stellar winds drive away the cloud, the gravitational attraction among these closely packed stars themselves would be enough to keep them bound for a very long time in a configuration not unlike the one astronomers call an open cluster.

CLOUD CONTRACTION

My force-balance theory described how the starting mass of a parent cloud could determine the interplay of contraction and expansion in, and thus the evolution of, the resulting cluster. Yet although astronomers can observe expansion and dispersal directly in OB associations, no one had found evidence that molecular clouds ever contract at all, let alone in the ways my theory suggested. Such contraction would surely occur in the very first stages of cluster formation, but the youngest stellar groups—the embedded clusters—resisted direct examination. I would have to figure out a way to demonstrate that more mature clusters had undergone contraction long ago.

I gained a clue from work done in the late 1950s by astronomer Maarten Schmidt of the California Institute of Technology. Schmidt observed that the birth rate of new stars depends on the density of the surrounding gas. So, I reasoned, if a parent cloud had in fact contracted in the past, its density would have increased, and the rate of star formation would have accelerated, too. My theory therefore posited an acceleration of star formation in the early life of every stellar group.

To test that prediction, I needed to figure out how to measure historical star-formation rates in clusters. Fortunately, the theory of stellar evolution provides a way to do just that. Among many other things, the theory describes how young stars that are not yet burning nuclear fuel—such as T Tauri types—behave over time. T Tauri stars are about as massive as our sun, and they are just as luminous. But instead of shining because of nuclear fusion, they radiate the heat generated by compression as their own gravity causes them to contract. With time, the rate of their compression slows, while their surface temperature climbs. The stars thus get both dimmer and hotter in a predictable pattern as they age.

If you know the surface temperature and luminosity of a T Tauri star as well as its distance from Earth, you can tell how long it has been contracting—in effect, you can tell how old it is. I realized that the collective set of ages of all these stars in a cluster would reveal the star-formation history of the group—when and at what rate the member stars formed over time.

It was not difficult to apply this method to nearby stellar groups, for which the required data are most readily available. Palla and I found that, for all groups that still possess copious cloud gas, the total star-formation rate has been increasing with time. In 2000, for example, we published data showing that the rate of star formation in the Orion nebula cluster accelerated for millions of years before its parent cloud dispersed. This finding encouraged me to believe that my assumption was correct: early in their history, all cluster-forming clouds probably *do* contract.

In 2007 then graduate student Eric Huff, now at Ohio State University, and I constructed a theoretical model of the parent cloud of the Orion nebula cluster. Our model included the forces of contraction and expansion postulated by my theory. In computer simulations based on the model, the simulated cloud contracted, just as we predicted it would. We then applied an empirical prescription known as the Schmidt-Kennicutt law, derived from Schmidt's observations and many subsequent ones, to show how the increase in density in a parcel of the cloud over time would affect the local star-formation rate.

Our modeling yielded an accelerating rate of star formation that matched the acceleration Palla and I had derived from ages of stars in the Orion nebula cluster. This additional finding further corroborated the force-balance theory's assumption that parent clouds contract in the early stages of cluster evolution.

CLUSTER EXPANSION

UNFORTUNATELY, the methods I used to measure and model early star-formation rates in clusters such as the Orion nebula group cannot be applied to open clusters, those strangely persistent groups that lack any trace of a parent cloud yet remain bound by gravity. Most open clusters are just too old; their epoch of contraction and star formation—which lasted for just a few million years—amounts to a tiny fraction of these clusters' total lifetimes. The tools for discerning stellar ages do not have nearly the resolution needed. And we cannot yet simulate the parent clouds of open clusters, either; the clouds dispersed so long ago that we cannot even guess at their masses or behavior. So far the early stages of open-cluster evolution remain inaccessible even to indirect observation.

It is possible, however, to model the evolution of an open cluster whose parent cloud has already vanished using so-called N-body simulations. In such simulations, the computer solves the complex, interlocking equations that describe the motion of multiple objects under the influence of their mutual gravitational attraction. This approach has elucidated what happens in open clusters *after* the initial star-forming contraction proposed by my theory and has provided some unexpected insights into the forces that shape cluster expansion.

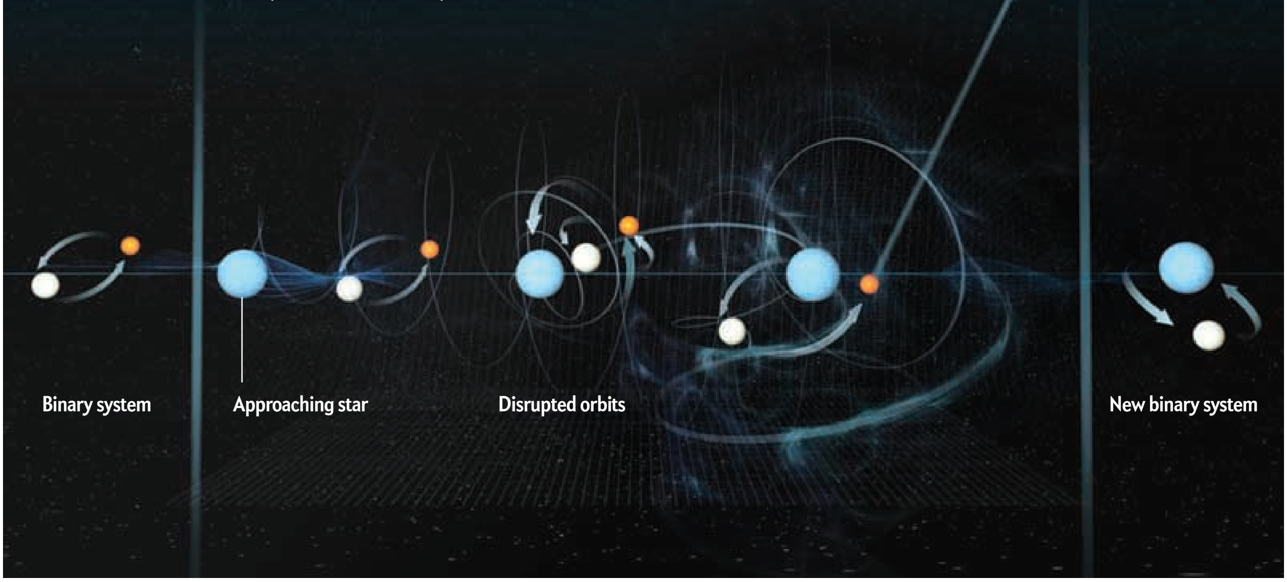
Although open clusters are remarkably stable, they are not static. The mutual gravity among member stars creates a constant, slow churning, as the orbiting stars weave in and out of one another like bees swarming in a hive. N-body codes describe this gravity-induced dance, and they are so efficient that they can simulate the evolution of a 1,200-member group such as the Pleiades on a standard desktop computer. Several years ago my graduate student Joseph M. Converse, now at the University of Toledo, and I took this numerical path to elucidate the history of the Pleiades. Our strategy was to guess an arbitrary initial configuration for the cluster and then to let it evolve for 125 million years. We compared the resulting simulated cluster with its actual counterpart and changed the initial conditions until the N-body simulation produced a group that resembled the real thing.

What we saw surprised us. It seems that while remaining gravitationally bound, the Pleiades cluster has expanded, more or less uniformly, since its cloud dispersed. The stars in their busy orbits move away from one another at a stately, steady pace. This result conflicts with prior analyses, which had predicted that the stars in open clusters would slowly segregate into an inner clump of heavier ones and an outer envelope of relatively light ones. This pattern of segregation is called dynamical relaxation, and it is the standard description of how gravitationally bound clusters evolve over time. Globular clusters, for example, are known to behave this way. Yet even when we let our N-body simulation run for 900 million years into the future, expansion continued uniformly, showing what an inflated but still intact Pleiades will look like at the age of a billion years.

This finding suggests that the classical analysis overlooked some critical factor in the balance of forces shaping cluster evolution. What drives the uniform expansion of open clusters? Converse and I demonstrated that the key is binary stars: pairs of close, orbiting companions that are quite common in stellar groups. Simulations performed by Douglas Heggie, now at the University of Edinburgh in Scotland, showed in the mid-1970s that when a third star approaches such a pair, the three engage in a complicated dance, after which the lightest of the three is usually ejected at high speed. The ejected star soon encounters other members and shares its energy with them, increasing those stars' orbital velocities and effectively "heating up" the cluster. In our N-body simulations, it was the energy from these binary encounters that caused the open cluster to expand—albeit so slowly that the expansion could easily go unnoticed by astronomers.

A Binary Pas de Trois

In computer simulations, open clusters continue to expand slowly for hundreds of millions of years. The author proposes that this expansion is fueled by binary systems, pairs of orbiting stars that are quite common in star clusters (*below*). First, a passing star enters and disrupts a binary's orbit. After a complicated gravitational dance, the lightest of the three stars gets ejected at great speed. The ejected star goes on to encounter other stars in the cluster, transferring its momentum as it passes by. This energetic exchange speeds up the other stars, enlarging their orbits and pushing the boundaries of the group farther out into space.



ENDURING MYSTERIES

MY INVESTIGATION of star clusters offers some evidence for my proposal that the original mass of a molecular cloud determines both the structure of a cluster and its evolution. The work also offers promising directions for future research. For example, astronomers should look for ways to observe the uniform expansion of open clusters predicted by my studies.

But my findings also serve to highlight the many things we still do not know about star clusters in general. Despite the advances in computer simulations, we do not yet have the tools to model how certain regions of parent clouds become dense enough to form stars. And several decades of radio and infrared observations have failed to reveal the patterns of internal motion in these clouds. The birth phase of stellar groups—a phase that takes place within the thick dust of embedded clusters—remains shrouded in mystery.

Yet the force-balance model my colleagues and I developed can help us figure out more details about this phase and other aspects of cluster evolution. We want to verify, through a combination of analytic studies and N-body simulations, that a cloud losing mass at the same rate as it contracts will indeed produce a gravitationally bound system resembling an open cluster. We also want to use modeling to explore how nascent T associations might reverse the cloud contraction and then disperse into space. Do stellar winds really play the pivotal role astronomers have assumed, for instance?

The impact of this research will extend far beyond the clusters themselves. Although the study of stellar groups in the Milky Way was long a backwater of astronomy, it is fast becoming central to other research. Some astronomers believe, for example, that the sun formed in a crowded OB association and that the close presence of neighboring stars perturbed the surrounding disk of gas and dust in ways that shaped our solar system. The molecular clouds that spawn clusters are also important players in the evolution of the interstellar medium and of galaxies as a whole. Star clusters may thus hold the key to a better understanding of the entire universe: from the birth of our solar system to the past and future of all that exists beyond it. SA

MORE TO EXPLORE

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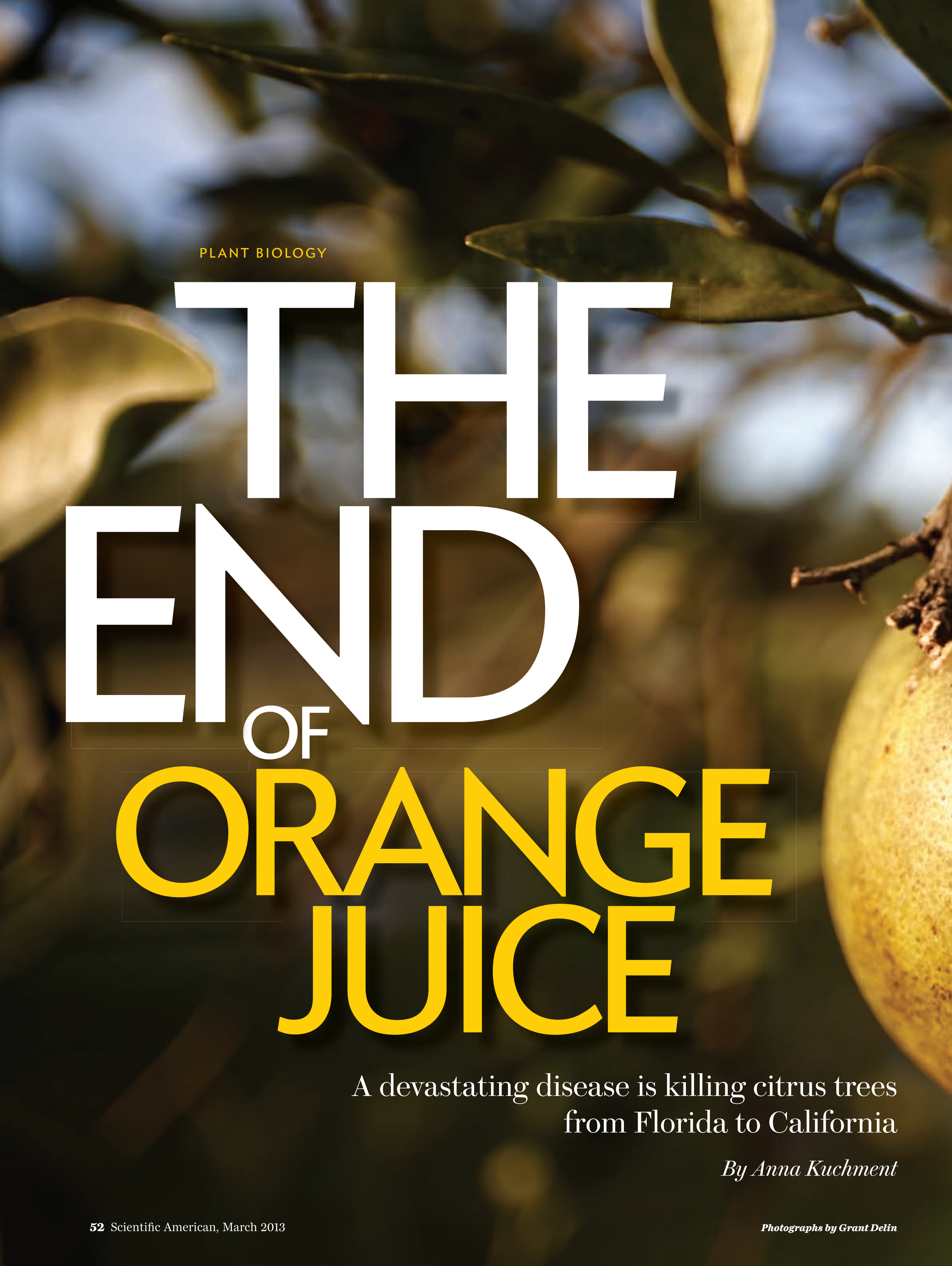
Take a virtual flight through the Orion nebula cluster, complete with gas clouds, stars and very young planets at ScientificAmerican.com/mar2013/orion



PLANT BIOLOGY

THE END OF ORANGE JUICE

A devastating disease is killing citrus trees from Florida to California

By Anna Kuchment

Photographs by Grant Delin

GROWING SCOURGE: An invasive insect known as the Asian citrus psyllid is spreading deadly bacteria through the world's citrus groves, leaving fruit misshapen and unripe.

One day

in 2005, just before Hurricane Katrina blew through Florida and devastated New Orleans, Susan Halbert stood before a pomelo tree on a farm outside Miami. Something about this tree did not look right. It seemed undernourished: its leaves were sparse, and its melon-size citrus fruit was lopsided. Yet all the other plants in the garden were thriving, and the woman who took care of them had carefully tended the pomelo with a fresh layer of fertilizer. "She clearly knew how to grow plants," says Halbert, an entomologist for the Florida Department of Agriculture and Consumer Services (FDACS).

Halbert scrutinized the tree like a detective at a crime scene, mentally ticking off every condition she could think of. She ruled out root rot, which is caused by a fungus, because the tree showed none of the characteristic signs of decay. Next, she considered a viral disease known as citrus tristeza—Spanish and Portuguese for "sadness"—which affects trees that have been grafted. (Citrus growers often raise trees not from seeds but by inserting a branch from one tree into the bark of another.) The pomelo, however, had not been grafted. Eventually Halbert got to the bottom of her list to the most devastating disease of citrus plants in the world—huanglongbing, Chinese for "yellow dragon disease."

Huanglongbing, which is also called HLB or citrus greening, had been spreading slowly through India, China, Indonesia and South Africa. Just the year before, it had turned up in Brazil. It kills trees by gumming up their circulatory systems and leaving deformed, bitter fruit. It is the work of bacteria that hide in the salivary glands of a tiny winged insect called the Asian citrus psyllid, which injects the germ into plants as it sips sap from their leaves. There is no known cure—no pesticide that kills psyllids in large enough numbers, no effective treatment for the disease.

Apprehensively, Halbert snipped off a few tree branches and took them back to her laboratory for testing. Within a few days her suspicion was confirmed. Citrus greening had made landfall at the heart of America's orange juice industry.

Halbert sounded the alarm. Scientists and growers responded by throwing every resource into containing the disease. They uprooted infected plants, sprayed copious amounts of pesticides, encased entire nurseries in protective screens and imported wasps from Asia to prey on the psyllids. Researchers began injecting antibiotics into tree trunks and looking for resistant genes to splice into orange trees. But huanglongbing continues to spread. In the past eight years it has infected more than half of Florida's citrus trees and, between 2006 and 2011, cost the state $4.54 billion and more than 8,200 jobs. "Five years from now, there may be no more Florida orange juice," says J. Glenn Morris, director of the Emerging Pathogens Institute at the University of Florida.

Since Halbert's discovery, the disease has traversed Georgia, South Carolina, Louisiana and Texas. Last spring it was found in Los Angeles. In November inspectors found the first psyllids—which can herald the arrival of the disease—in California's commercial orange groves. The disease could cripple the U.S. citrus industry unless scientists find a way to stop it.

MEET THE PSYLLID

TO REACH HALBERT'S OFFICE in Gainesville, Fla., visitors pass a reception area with glass cases of yellow jacket colonies and live tarantulas. Just across the hall is the Florida State Collection of Arthropods: some nine million insects, each dried and mounted inside slim wood drawers that fill several rooms of tall metal cabinets. As an entomologist in the FDACS Division of Plant Industry, Halbert uses the collection to help identify the dozens of insects that state inspectors pick off produce and potted plants, drop into glass vials of alcohol, and mail to her in small, yellow business envelopes, which pile up in a tray on her desk.

Halbert, who is in her 60s and wears her hair in a low, braided bun, could pass for a kindly librarian. She is militant, however, when it comes to battling bugs that threaten Florida's multibillion-dollar produce industry. Halbert is one of eight entomologists for the state and one of two of its experts on Hemiptera—

IN BRIEF

A gnat-sized insect known as the Asian citrus psyllid has been spreading a deadly plant disease through America's citrus groves. Early attempts to contain the disease, known as huanglongbing, have failed, and it has become a major threat to the U.S. citrus industry.

Huanglongbing is caused by bacteria in the genus *Candidatus Liberibacter,* which Asian citrus psyllids carry in their salivary glands. The bacteria infiltrate plants' circulatory systems, which results in blockages that disrupt the flow of nutrients from leaves to roots.

To slow huanglongbing, scientists have imported wasps from Asia to prey on the psyllids, among many other approaches. The best long-term solution may be genetic modification, which faces a long and costly road to regulatory approval and public acceptance.

ON THE LOOKOUT: **Asian citrus psyllids sit at a 45-degree angle (*1*). Psyllid nymphs excrete honeydew (*2*). A salivary toxin that even healthy psyllids emit can deform leaves (*3*). Trees at a field-test site grow inside protective psyllid-proof screens (*4*).**

insects such as aphids, leafhoppers and psyllids that suck juice from plants. Her main responsibility is alerting growers and regulatory agencies to the arrival of any new pests. "It's my job to keep things on my radar, to know what the bad actors are out there," Halbert says.

Greening has been on Halbert's radar since the mid-1990s, when she first heard about the disease's devastation from some colleagues in South Africa. In June 1998 she was inspecting citrus trees in Palm Beach County, when she became the first person to spot a psyllid in the U.S. She recognized it by its characteristic stance: it sticks its behind up in the air at a 45-degree angle.

In retrospect, Halbert should have felt more alarmed by this discovery, she says. Yet Brazil had lived with psyllids since the 1940s and by 1998 had not had a single case of greening. So Halbert and her colleagues decided to watch and wait. They returned to Palm Beach with a team of inspectors and fanned out by car in all directions to see how far the pests had spread. Armed with plastic sticks and white plastic trays, Halbert and her colleagues literally beat the bushes in search of psyllids: they hunted for shrubs and trees in the citrus family, whacked them with their batons and counted how many psyllids fell onto their trays. Psyllid numbers, they found, grew sparser as they headed away from Palm Beach County and soon petered out. The infestation seemed to be limited to a 60-mile stretch of coastline, and none of the bugs they examined tested positive for huanglongbing.

That was a good sign. Yet Halbert and her co-workers stayed alert for symptoms of greening, regularly testing psyllids and trees. In 2005 she decided to undertake more wide-ranging surveys, branching out to ethnic neighborhoods whose populations hailed from greening-infested regions. And that is how she found the diseased pomelo tree in Miami, which grew in the backyard of a woman from Taiwan. "It was another really bad day," Halbert says.

By the time Halbert confirmed the presence of the disease, it had already spread with devastating speed, in large part because of the psyllid's amazing fecundity. Each female lays up to 800 eggs in her one-month life span, resulting in populations on a single orange tree that can exceed 40,000 bugs. With that many insects hopping and flying around, even pesticides with a kill rate of 99 percent leave plenty of survivors. And it turned out one of the Asian citrus psyllid's favorite plants to feast on was a wildly popular shrub, orange jasmine, that was produced in Miami, sold in nurseries and major discount stores across Florida, and shipped widely, giving the psyllids an easy means of travel.

View to a Kill

Huanglongbing (HLB) is one of the most devastating diseases of citrus plants. Small winged insects, Asian citrus psyllids, transmit the bacteria that cause huanglongbing as they drink sap from the leaves of trees. Inspectors initially found Asian citrus psyllids in the U.S. in 1998 and first detected huanglongbing in 2005. Both were first found in Florida.

The Vector: Asian Citrus Psyllids

Psyllids lay eggs on shoots and leaves as they emerge from buds. Newly hatched, wingless nymphs feed exclusively on this soft growth as they develop into adults. As psyllids of all life stages drink sap from the plant's leaves, they can transmit HLB from their salivary glands. Infected plants can also transmit HLB to psyllids.

The Disease: Huanglongbing

Most scientists believe huanglongbing is caused by three bacteria in the genus *Candidatus Liberibacter,* although researchers have yet to conclusively prove the relation. The three are: *Candidatus Liberibacter asiaticus,* which is the most prevalent and is found in the U.S.; *Candidatus Liberibacter africanus,* found primarily in South Africa; and *Candidatus Liberibacter americanus,* found primarily in Brazil.

The bacteria infect the phloem, the circulatory system that transports sugars from the tree canopy to the roots, resulting in blockages.

The blockages starve the roots, which stop properly absorbing nutrients from the soil to send back up to the tree canopy, a circulatory system known as the xylem.

An Attempt to Fight Back

Because Asian citrus psyllids have no native specialized predators in the U.S., entomologists have brought in tiny parasitic wasps from Asia, *Tamarixia radiata,* to help keep psyllid populations in check. Lab studies suggest that each wasp can kill hundreds of psyllids by drinking their blood and laying eggs on them. The eggs develop into larvae that eventually eat the psyllids from the outside in.

The Result: Dying Plants

HLB can masquerade as a nutrient deficiency. Symptoms include mottled, yellowish leaves and fruit that is lopsided, small, green and bitter and that drops prematurely. The disease weakens plants and makes them more likely to succumb to drought and other stressors.

Illustration by Cherie Sinnen

Florida's deadly hurricane seasons may also have been a factor. Winds from Katrina and other tropical storms may have blown psyllids farther than they could travel on their own. The storms may have also weakened trees and made them more susceptible to infections.

And then there is the fact that as an invasive species, the Asian citrus psyllid has no native, specialized predators in the U.S., allowing them to proliferate quickly. This situation set entomologists in search of an insect that could wreak havoc with psyllids the way psyllids had wreaked havoc with orchards.

SEND IN THE WASPS

ON A HOT DAY LAST SUMMER Mark and Christina Hoddle packed up a rented white Ford sedan and made the one-hour drive from their home in Riverside, Calif., to Los Angeles. A small blue Rubbermaid cooler sat on the backseat. Inside it was an ice pack and half a dozen vials containing wasps feasting on small drops of honey. As Mark drove, Christina flipped through a sheaf of papers with data on the research sites they would visit.

California is the U.S.'s second-largest citrus producer after Florida. While the vast majority of Florida's oranges are squeezed into juice, California provides most of the oranges that Americans eat whole. When the first Asian citrus psyllid was spotted in San Diego County in 2008, the state's priority became keeping the insects away from the commercial groves to the north, in California's Central Valley. Officials began spraying insecticides in San Diego, but soon the psyllids spread to Los Angeles and continued moving up the coast. They needed a new plan.

The Hoddles are entomologists at the University of California, Riverside, and experts on invasive species. Soon after the first Asian citrus psyllid was detected in the state, Mark read a 1927 paper by scientists in Punjab. The authors described the effects of greening in stark terms ("It is not an uncommon sight to see once valuable orchards reduced to unproductive plantations of dried skeletons of trees") and reported on a species of local, parasitic wasp that could kill 95 percent of Asian citrus psyllids. "Could these wasps thrive in California?" Mark wondered.

It made sense that the Asian citrus psyllid's natural enemy would live in South Asia, which is the insect's likely birthplace. When, where and how huanglongbing, psyllids and citrus all met up, however, is still an open question. The genus *Citrus* was long thought to have evolved in China, but recent research by Andrew Beattie of the University of Western Sydney in Australia and his colleagues suggests it first appeared in Australasia some 35 million years ago and spread to Asia. The genus of the bacteria that are thought to cause huanglongbing, *Candidatus Liberibacter* ("*Candidatus*" indicates that scientists do not know for sure because the bacteria have never been cultured), may have evolved in Africa and jumped to citrus trees from a citrus relative only within the past 500 years, judging by the virulence of the disease. (If citrus and huanglongbing had come together earlier, citrus would have either developed resistance by now or died off.)

Beattie suspects this jump took place in Africa, when a citrus psyllid transferred the bacteria to an imported orange or mandarin tree that was then shipped to India as part of the colonial trade. Human cultivation has played a role as well. Psyllids lay their eggs on the tender shoots of budding trees, which are easier for nymphs to feed on. Thanks to irrigation and the use of fertilizer, citrus trees grow and bud rapidly, creating a tempting salad bar for psyllids of all ages.

For the wasps, known as *Tamarixia radiata,* to survive in California's Central Valley, where most of the state's citrus growers are based, the climates of the two regions would have to be similar. Mark entered data into his climate-matching software and discovered that Punjab's and California's citrus regions both had hot, dry summers and cool, foggy winters—an excellent match. He then discovered, seemingly by kismet, that the vice chancellor of the major agricultural university in Punjab was a graduate of U.C. Riverside. "Suddenly, these doors were open that I thought would be incredibly difficult to walk through," says Mark, who is originally from New Zealand. In early 2011 he and Christina headed to Pakistan to learn everything they could about *T. radiata*.

Importing wasps from Pakistan in the post-9/11 era is no simple task. Mark, working with the California Department of Food and Agriculture, secured a permit from the USDA and set up a wasp-rearing operation under quarantine to ensure that the incoming insects were disease-free. He and his postdoctoral student also spent months testing *T. radiata*'s host range—pitting it against native psyllids on their native plants and against beneficial insects that attack noxious weeds—to make sure it would not prey on California's local flora and fauna or disrupt weed biocontrol efforts. Finally, he and Christina set up a complex sequence of cages inside a series of quarantine labs at U.C. Riverside to allow the wasps to multiply on Asian citrus psyllids infesting small citrus plants.

Since December 2011 the Hoddles have released thousands of *T. radiata* wasps at more than 100 sites in Los Angeles, Riverside, Orange County and San Bernardino County. On this summer day they were visiting release sites in Los Angeles to check on the parasites' progress. "This is urban warfare," Mark said from the driver's seat. Despite the heat, he and Christina were dressed in long-sleeved shirts and long pants—the sun-protective clothing they wear in the field.

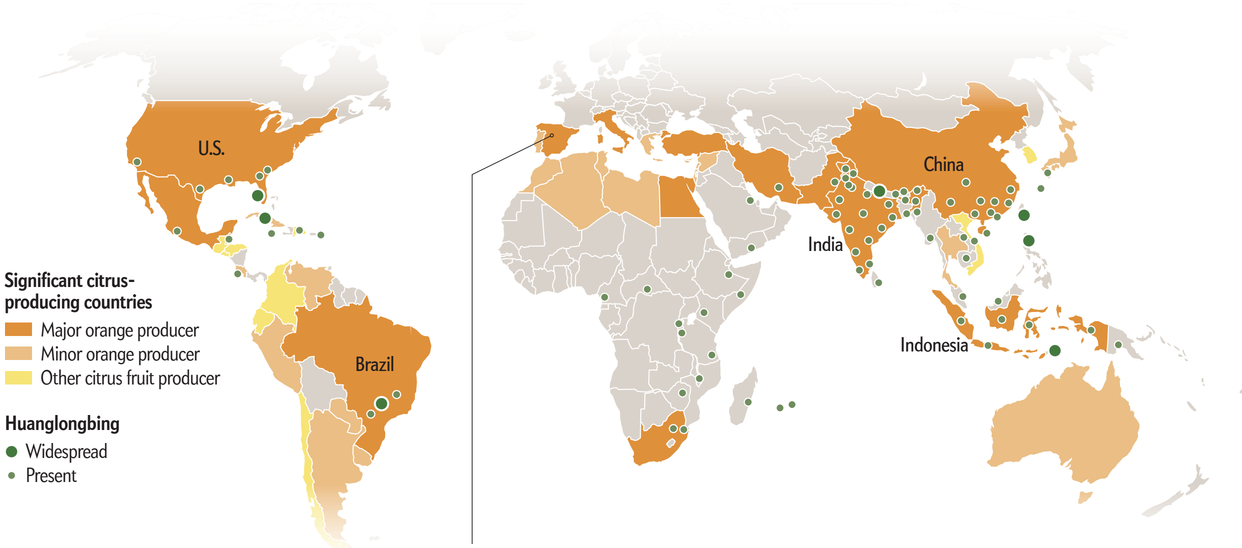
Although the Asian citrus psyllid was first spotted in San Diego, it seems to have moved fastest through Los Angeles. Backyard lemon and lime trees are very popular here, and many people bring them in across the border from Mexico or smuggle cuttings inside their suitcases when flying back from Asia. The branch of an infected lemon tree can easily be grafted onto a lime or pomelo tree, and the plant will produce both varieties of fruit. Once psyllids arrived in Los Angeles, they reproduced feverishly on these backyard trees, just as they did in Florida.

The California Department of Food and Agriculture had started spraying pesticides in Los Angeles to control the psyllids and prevent them from spreading, but the effort rapidly proved futile. One need only glance at census data to see what went wrong. Of the more than three million houses in Los Angeles, about 40 percent had at least one citrus tree in 2010. That means about 1.2 million properties need to be treated. Sprays last only one week to several months and then need to be reapplied. By last October the state had sprayed 46,941 properties, or 4 percent, at a cost of $4.7 million, or $100 per property. "You can see why this quickly became unfeasible," Mark says. Once the state suspended its pesticide campaign in Los Angeles, it was safe for the Hoddles and their wasps to move in.

The Hoddles pulled into a hotel parking lot in Los Angeles's

It Gets Around: How a Deadly Global Traveler Arrived in the U.S.

"From the time citrus was first recognized as an edible fruit with positive nutritional qualities, it has moved with man, and so too have its pests and diseases," wrote Tim R. Gottwald of the USDA in a 2010 review article. That is the story of huanglongbing, also known as citrus greening, which was first recorded in India in the 1700s and now threatens every citrus-producing region of the world.



Wreaking Havoc

Asian citrus psyllids have been present in Brazil, the world's largest orange producer, since the 1940s, but inspectors did not detect HLB there until 2004. Psyllids may have spread to Florida via the Caribbean and to California via Mexico.

Bracing for the Worst

The Mediterranean basin, including major citrus producers Spain, Italy and Turkey, is one of the few regions that remains free of psyllids and of HLB.

Point of Origin?

The bacteria that are thought to cause HLB, from the genus *Candidatus Liberibacter,* may have evolved in Africa but most likely moved into citrus only within the past 500 years, thanks to psyllids and the global trade in oranges and their relatives.

working-class Mexican neighborhood of Azusa and grabbed their cooler. They had found the site by examining state data on the number of psyllids caught in sticky yellow traps set all over Los Angeles. This garden had a particularly high count. Christina headed over to a curry bush (a relative of citrus) at the edge of the parking lot. She examined its shiny green leaves and immediately spotted large clusters of Asian citrus psyllids at every stage of their life cycle. At the tips of the branches, littering the newly sprung buds, were yellowish-orange eggs, whitish wingless nymphs, and brown mottled adults hopping and crawling about. Three weeks earlier the Hoddles had released a few dozen wasps on some lemon trees on the far side of the lot, and they wanted to see if the wasps had made their way to this shrub; if they did, it would show that the wasps were beginning to proliferate on their own.

The news was good: although the wasps, no larger than the size of half a chocolate sprinkle, were hard to spot, they had left death and destruction in their wake. A female wasp kills a psyllid essentially by laying an egg under its belly. Once that egg hatches, the wasp larva—which looks like a pudgy maggot—will start scraping away at the nymph's underbelly, eating its insides over the course of a week until all that is left is a shell. "It's a husk of its former self," Mark says. The wasp larva seals itself inside the shell by spinning silk that attaches the shell firmly to the leaf. It then weaves its cocoon, pops out as an adult and chews a small hole at the top of the psyllid husk to escape. Christina and Mark observed several hollowed-out psyllid husks on the curry plant.

The wasps also destroy psyllids in another way—something Mark calls a "bonus kill." A female wasp stands on the back of a psyllid, stabs it repeatedly with her egg-laying tube and then drinks its blood. "The trauma of being stabbed multiple times and then having your blood drunk is sufficient to kill those Asian citrus psyllid nymphs," he says. Using this powerful combination of killing techniques, a single wasp can kill hundreds of psyllids. Before leaving, the Hoddles hung a few more of their vials on the curry plant and opened the lids to allow the wasps to fly out and begin their hunt.

As of last December, the Hoddles estimate that the wasps they have released have become established at about 40 percent of their release sites in California and are fanning out to new psyllid-infested neighborhoods, sometimes several miles

SOURCES: "CITRUS FRUIT: FRESH AND PROCESSED: ANNUAL STATISTICS 2012," BY U.N. FOOD AND AGRICULTURE ORGANIZATION (*citrus production*); "CITRUS HUANGLONGBING (GREENING) DISEASE," IN *INVASIVE SPECIES COMPENDIUM,* BY CENTER FOR AGRICULTURAL BIOSCIENCE INTERNATIONAL, 2013 *www.cabi.org/isc (HLB disease)*

Map by XNR Productions

away. The wasps will not solve the problem, however. "It's not going to be a silver-bullet solution," Mark says. "I think if we can get a 30 percent kill, that will lower the population pressure in these urban areas and will reduce the rate at which things are spreading out."

THE BEST PATH FORWARD

FLORIDA'S BIOLOGICAL-CONTROL EFFORTS predate California's. The state released its first batch of parasitic wasps in 1999, and starting later this year, it plans to release millions more from Pakistan, Vietnam and China in urban areas where the state has stopped spraying pesticides. (Florida's climate, unlike that of California's Central Valley, is better matched to Vietnam.)

Some of Florida's growers have embarked on another, more controversial approach: helping trees live with the disease. *C. Liberibacter* invades a plant's circulatory system, which then blocks the passage of sugar and other nutrients from its leaves to its roots. "If roots suffer, they're not going to be able to efficiently absorb and move micronutrients and other substances from the soil up into the leaves, so now we have a compounding effect," says Philip Stansly, an entomologist at the University of Florida's Institute of Food and Agricultural Sciences.

The genus *Citrus* was long thought to have evolved in China, but recent research suggests it first appeared in Australasia some 35 million years ago and spread to Asia.

In response, many Florida growers started feeding extra nutrients to the trees through leaf sprays. "I compare it to AIDS," says Tim Willis, a third-generation citrus grower and manager at McKinnon Corporation in Winter Garden, Fla., which operates an orchard. "They keep humans alive now for years with a devastating disease. Why can't we do the same thing to an orange tree?" Even before the arrival of psyllids in Florida, Willis and Maury Boyd, president of McKinnon, had put their trees on what Stansly calls a "Cadillac" nutrition program—they were feeding their plants all the manganese, zinc and boron they could. With the arrival of HLB, plant disease experts advised growers to pull up any tree that was infected. Yet by the time the disease was discovered in Florida, it was so widespread that pulling up infected trees may have run Boyd and Willis out of business. "These trees have taken care of me my whole life," Willis says. "They've put my son through college. You can't just give up."

So McKinnon stepped up its nutrition program and joined with other growers to implement a system of regular, coordinated pesticide sprays. When Boyd and Willis refused to pull up their trees, experts told them their plants would be dead within five years. But seven years later they are still here, and they say their yield is undiminished.

Last November, Willis drove his pickup truck through his groves on a routine survey. The trees were lush and hung with large, ripe yellow Hamlin oranges, an early variety harvested in late fall and early winter. Although nearly 100 percent of his trees had huanglongbing, only a few leaves and trees bore the disease's classic hallmarks: mottled leaves and green, prematurely dropped fruit littering the ground. Still, no one knows how long his good fortune will last. "When we planted a tree, we used to think that tree would be there for generations," Willis says. "A lot of people now think, 'If I get 10, 15 years out of it, it's going to be good.'"

So far published studies have failed to show that nutrition programs like Boyd's can impart any benefit. "You can't fertilize your way out of this," says Tim R. Gottwald, an epidemiologist at the U.S. Department of Agriculture. He and several colleagues have published controlled studies showing that enhanced nutrition programs have no effect on tree health, fruit quality or yield. In fact, Gottwald argues, they can be detrimental because they mask symptoms and turn trees into Typhoid Marys.

Neighboring grower Southern Gardens Citrus, which supplies orange juice to the major brands, took a different path. Rick Kress, president of Southern Gardens, says that the company is replacing more than 650,000 infected trees—one quarter of its stock—with clean nursery trees that have been grown inside psyllid-proof screens. Workers continue to monitor groves for signs of greening, although trees can harbor *C. Liberibacter* for months or years before the bacteria start showing up in lab tests or causing visible symptoms, which makes the disease difficult to eradicate. While Kress has reduced the infection rate of his trees, his costs are up 40 to 50 percent.

Scientists are desperately seeking new approaches. Some studies have shown that feeding penicillin to infected orange trees through their roots and via trunk injections can help them outgrow their symptoms and develop stronger roots. In 2011 Jim Graham of the University of Florida found that the bactericide copper sulfate has a similar effect. Copper sulfate might pass EPA regulations more easily than penicillin because it is not used to treat humans. But plants would need to receive injections for the rest of their lives at a potentially prohibitive cost.

The best long-term prospects may lie with genetic modification. Erik Mirkov, who is a plant pathologist at Texas A&M University, has transferred two genes from spinach into citrus trees, thereby conferring resistance to huanglongbing. Researchers at Cornell University are developing citrus trees that would repel Asian citrus psyllids, and the two technologies may eventually be combined. Both projects are being funded by Southern Gardens, which has spent $6 million on research to stop citrus greening. But genetically modified produce faces a long and expensive path to regulatory approval and public acceptance. Many worry it will not arrive in time to save the industry. Says Halbert, "We need something we haven't thought of before." SA

***Anna Kuchment** is a senior editor at* Scientific American. *She is author of* The Forgotten Cure *(Copernicus Books, 2012).*

MORE TO EXPLORE

Oranges. John McPhee. Farrar, Straus and Giroux, 1967.

Current Epidemiological Understanding of Citrus Huanglongbing. Tim R. Gottwald in *Annual Review of Phytopathology,* Vol. 48, pages 119–139; September 2010.

SCIENTIFIC AMERICAN ONLINE
View a slide show of images and a video of Christina and Mark Hoddle releasing parasitic wasps at **ScientificAmerican.com/mar2013/citrus**

LARGER THAN LIFE: This RoboBee is magnified to show detail; turn the page to view at actual size.

IN BRIEF

RoboBees are flying robots the size of bees. Their size presents a huge assortment of physical and computational challenges. At such small dimensions, off-the-shelf parts such as motors and bearings will prove too inefficient, so the bees must employ specially designed artificial muscles to power and control flight.

In addition, the tiny bees must think on their own, using miniature sensors to process environmental cues and processors to make decisions on what to do next.

Like real bees, RoboBees will work best when employed as swarms of thousands of individuals, coordinating their actions without relying on a single leader. The hive must be resilient enough so that the group can complete its objectives even if many bees fail.


Robert Wood is Charles River Professor of Engineering and Applied Sciences at Harvard University and the Wyss Institute for Biologically Inspired Engineering at Harvard. The National Science Foundation recognized his work with a 2012 Alan T. Waterman Award.


Radhika Nagpal is Fred Kavli Professor of Computer Science at Harvard and the Wyss Institute. Her work on collective behavior spans artificial intelligence, robotics and biology.


Gu-Yeon Wei is Gordon McKay Professor of Electrical Engineering and Computer Science at Harvard. His research interests span a broad range of topics in energy-efficient computing systems.

TECHNOLOGY

flight of the robobees

Thousands of robotic insects will take to the skies in pursuit of a shared goal

By Robert Wood, Radhika Nagpal and Gu-Yeon Wei

NOT TOO LONG AGO A MYSTERIOUS AFFLICTION CALLED colony collapse disorder (CCD) began to wipe out honeybee hives. These bees are responsible for most commercial pollination in the U.S., and their loss provoked fears that agriculture might begin to suffer as well. In 2009 the three of us, along with colleagues at Harvard University and Northeastern University, began to seriously consider what it would take to create a robotic bee colony. We wondered if mechanical bees could replicate not just an individual's behavior but the unique behavior that emerges out of interactions among thousands of bees. We have now created the first RoboBees—flying bee-size robots—and are working on methods to make thousands of them cooperate like a real hive.

Superficially, the task appears nearly impossible. Bees have been sculpted by millions of years of evolution into incredible flying machines. Their tiny bodies can fly for hours, maintain stability during wind gusts, seek out flowers and avoid predators. Try that with a nickel-size robot.

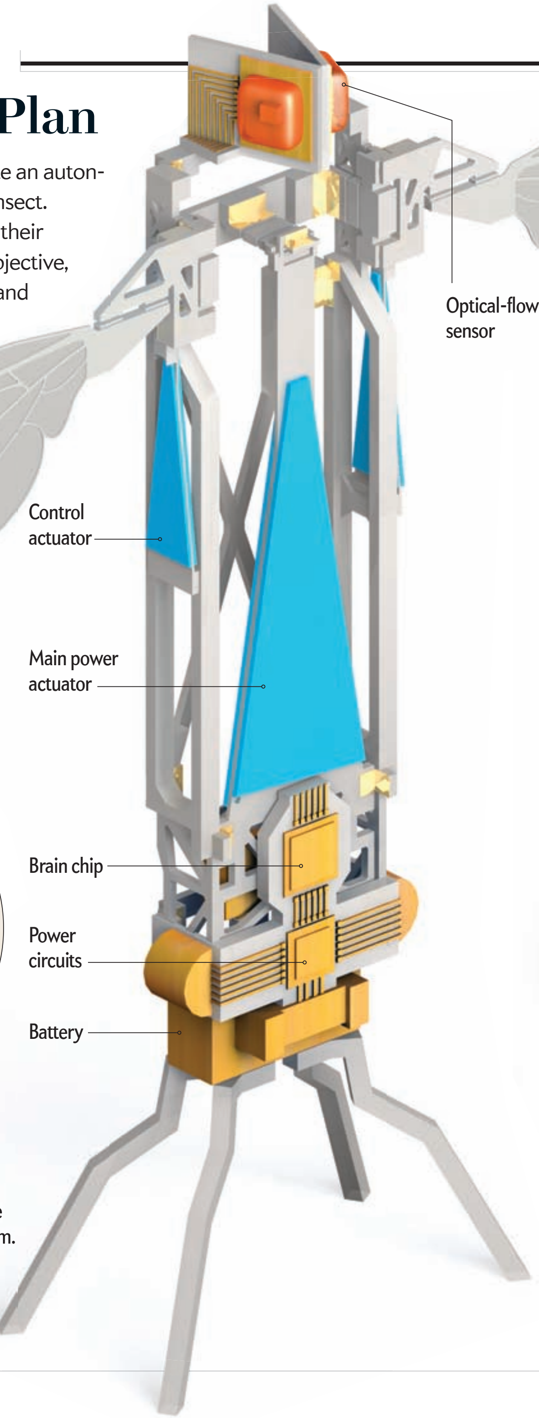
Now consider the hive. A bee colony appears to have no supervisor and no centralized authority. Yet colonies of tens of thousands of honeybees intelligently divide their labor to accomplish tasks critical for the health of the overall hive. When the hive requires more pollen, additional bees forage; when the hive requires tending, the bees stay home. And when something goes wrong—perhaps a queen dies unexpectedly—the bees rapidly adapt to the changing circumstances. How does such a large colony make these complex decisions—without taking forever or caus-

Photograph by Travis Rathbone

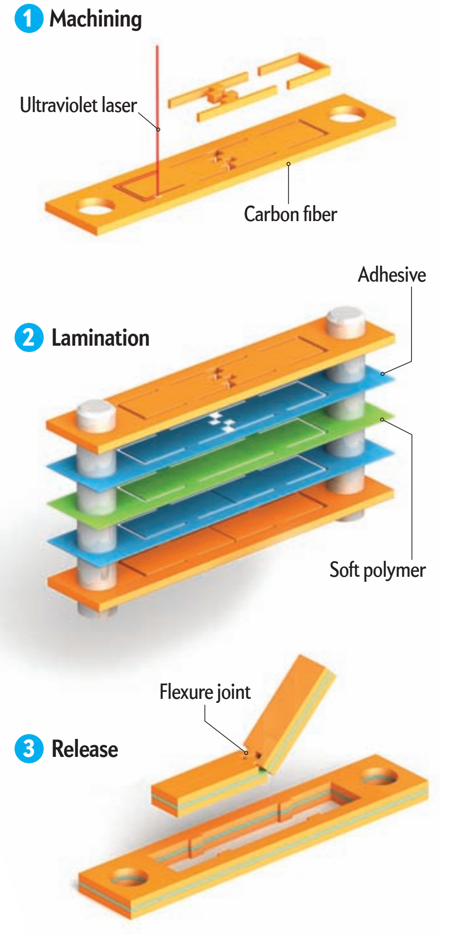
HOW IT WORKS

Micro Flight Plan

The **RoboBee project** aims to create an autonomous flying robot the size of an insect. RoboBees will be able to fly under their own power, navigate toward an objective, adapt to changing circumstances and work together as a group.



RoboBee at Actual Size
On this tiny frame, a RoboBee must carry its artificial muscles, optical-flow sensors, computing processors and a power supply to keep it all running. The total package weighs around half a gram.



ing havoc through miscommunication—if no one is in charge?

A robot hive could do much more than just pollinate flowers (although agriculture is one potential use). Indeed, small, agile, simple, inexpensive robots could perform many tasks more effectively than a few highly capable ones. For example, consider a rescue worker with a box full of 1,000 RoboBees—a package that would weigh less than a kilogram. The RoboBees could be released at the site of a natural disaster to search for the heat, sound or exhaled carbon dioxide signature of survivors. If only three of the robots accomplish their task while the others fail, this is a success for the swarm. The same cannot be said about the current generation of $100,000 rescue robots.

Yet a colony of robotic bees imposes a huge number of technological challenges. These tiny robots would stretch no more than a few centimeters from end to end and weigh around half a gram—about 100th the weight of the world's lightest autonomous flying craft. That minuscule package must hold each bee's flight system, its electronic brain and vision system, and the controls that govern how that bee interacts with other members of its hive. Recent progress in materials science, sensor technology and computing architecture are putting those goals in reach.

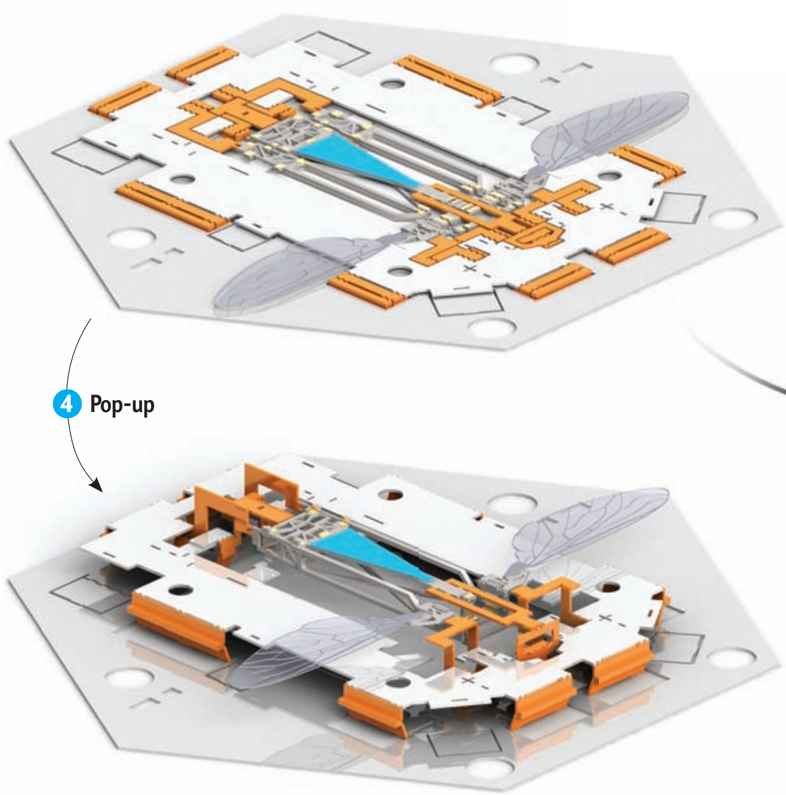
BODY AND FLIGHT

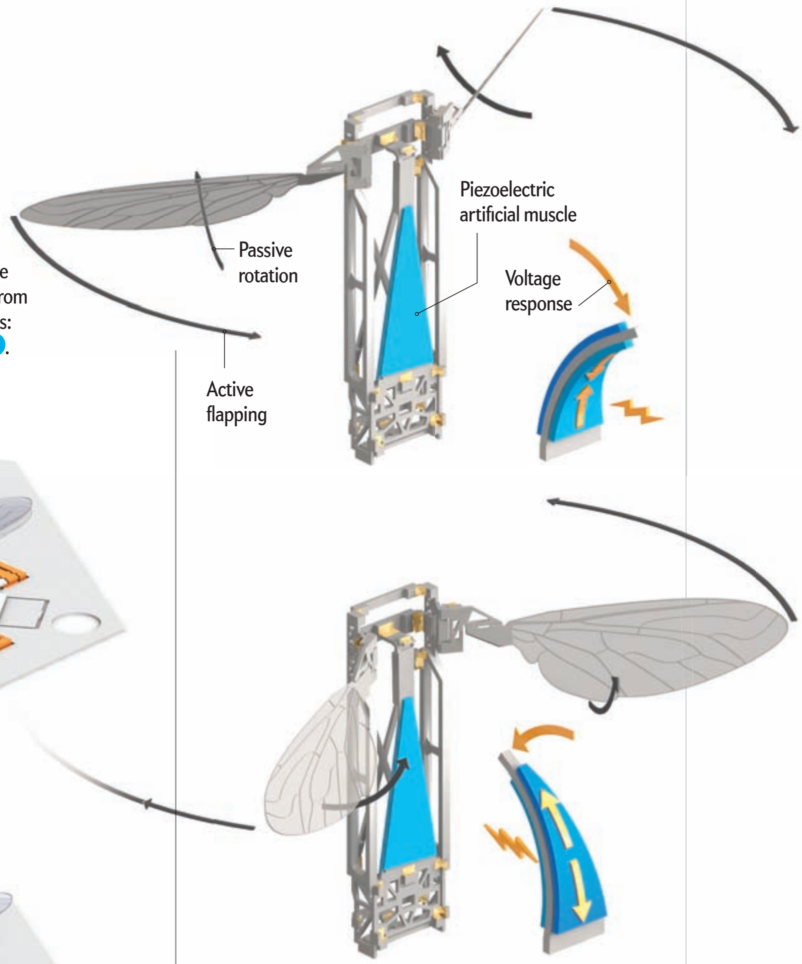
THE MOST OBVIOUS CHALLENGE in creating a small flying robot is figuring out a way to get it to fly. Unfortunately, the steady progress that has been made in miniaturizing robots over the past decade

Illustrations by Bryan Christie; Photograph by Travis Rathbone

Pop-up Assembly Line

Manufacturing such tiny robots carries its own challenges. The team builds each RoboBee from layers of hard material such as carbon fiber, sandwiching softer polymers. Gaps in the carbon fiber allow the polymers to flex, creating a flexure joint. The beauty of this layering method is that it lends itself to an efficient assembly line (*below left*). The researchers first make precise cutouts of the constituent layers using an ultraviolet laser 1. In the second step, they align all the layers of the multilayer sandwich and laminate them together with adhesive 2. They can then release individual components from the substrate 3. Finally, they borrow the final step from children's pop-up books: with one motion, they pop 3-D structures out of the two-dimensional surface 4.





The Big Flap

RoboBee flight relies on so-called artificial muscles—piezoelectric materials that contract when a voltage is applied. The wings can move in two ways—stroking back and forth and rotating their pitch. Instead of the up-and-down motion characteristic of bird flight, think of how you would tread water in a pool with your arms. Muscles control the flapping, but rotation is passive—determined by wing inertia, the interaction of the wing with the air, and the elasticity of the wing hinge.

is of little help to us because the small size of the RoboBee changes the nature of the forces at play. Surface forces such as friction begin to dominate over volume-related forces such as gravity and inertia. This scaling problem rules out most of the mechanical engineer's standard tool kit, including rotary bearings and gears and electromagnetic motors—components ubiquitous in larger robots but too inefficient for a RoboBee.

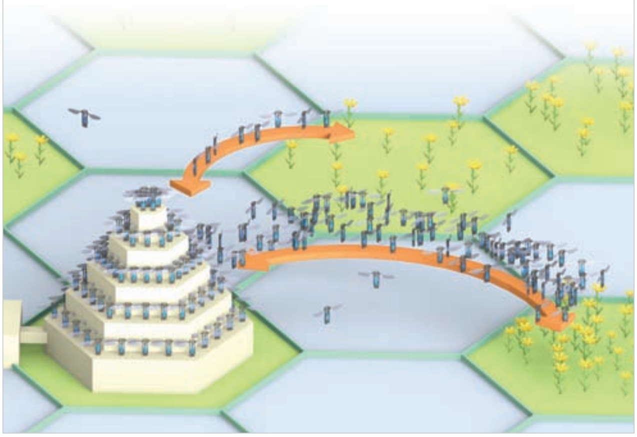
Instead of spinning motors and gears, we designed the RoboBee with an anatomy that closely mirrors an airborne insect—flapping wings powered by (in this case) artificial muscles [*see box above*]. Our muscle system uses separate "muscles" for power and control. Relatively large power actuators oscillate the wing-thorax mechanism to power the wing stroke while smaller control actuators fine-tune wing motions to generate torque for control and maneuvering. Both these actuators work at the joint where the wing meets the body.

The artificial muscle is made of piezoelectric materials that contract when you apply a voltage across their thickness. Such actuators have a few drawbacks—for example, they require high voltage and are brittle—yet this is one case where the physics of scaling is on our side. The smaller these actuators are, the faster they want to move. And because the amount of work delivered per cycle (per unit mass) stays fairly constant, faster flapping leads to more power. In fact, these muscles generate an amount of power comparable to the muscles in insects of similar size.

Over the past few years we have experimented with dozens of

The Colony at Work

A colony of thousands of RoboBees will have to efficiently allocate tasks among individuals even when it lacks a full picture of the environment. In the scenario below, the hive has been assigned to find and pollinate fields of flowers. Individual RoboBees first explore different regions. As they return to the hive with information about where flowers are blooming, the new information affects where future workers will go. More robots will be allocated to areas with more work. The hive-based strategy allows bees to exhibit collective intelligence even if power constraints limit bee-to-bee communication.



different configurations of actuators and joints. One thing we look for in each of these designs is how easy they will be to build. The thousands of bees in a hive will have to be mass-produced.

The best designs we have come up with so far are created from a three-layer sandwich: hard face sheets form the top and bottom layers, and a thin polymer film rests in the middle. We create joints by carving material out of the top and bottom layers, leaving the middle-layer polymer to bend, thereby creating a flexure joint [*see box on preceding page*].

We have made great progress in building a bee-size robot, but we are still trying to figure out the best way to power it. To overcome the demanding energy requirements of flight at small scales, much of the bee's mass must be taken up by the main actuator and power unit (think "battery," although we are also exploring the possibility of using a solid-oxide micro fuel cell). The power question also proves to be something of a catch-22: a large power unit stores more energy but demands a larger propulsion system to handle the increased weight, which in turn requires an even bigger power source.

Although we cannot yet make a RoboBee fly under its own power, we have demonstrated a 100-milligram bee capable of producing enough thrust to take off (we kept it tethered to an external power source). The RoboBee was also able to stabilize itself using a combination of active and passive mechanisms. Given the state of the art in battery energy density and the efficiency of all the body components, our best estimate for flight time remains only a few tens of seconds. To increase flight time, we are working to minimize the mass and maximize the efficiency of each body component.

BRAIN AND NAVIGATION

POWER IS NOT THE ONLY THING keeping our RoboBee tethered. An onboard brain is another unsolved problem. A RoboBee in the wild will have to constantly take stock of its surroundings, decide on the best course of action and control its flight mechanisms. External electronics work as a makeshift solution in the laboratory, but a working RoboBee will require its own brain.

At a high level, the brain constitutes intelligence that is not only responsible for controlling an individual RoboBee but also for managing its interactions with other RoboBees in the colony. We set out to build the brain in layers—sensors to interpret the physical environment, an electronic nervous system that handles basic control functions and a programmable electronic cortex to make high-level decisions. As a first step, we sought to design a brain subsystem that enables autonomous flight. This challenge requires a tight control loop that encompasses sensors, signal processors and the movement of body parts.

To figure out what sensors to use and how to structure the brain circuitry, we once again looked to nature. Flies (and other fauna) use two broad types of sensors to make their way about the world. Proprioceptive sensors give a fly information about its internal states—how fast its wings are flapping, for example, or the charge left in the battery. Exteroceptive sensors provide information about the outside world.

Modern technology offers GPS, accelerometers and multiaxis gyroscopes, but such sensors are typically too heavy or consume too much power (or both) to be useful. Hence, we are investigating an electronic vision system that is similar to what natural bees have—one that analyzes "optical flow," the apparent motion of objects in the visual field of an image sensor. Imagine the view out the passenger window of a car: nearby objects appear to move quickly through your field of view while distant objects move slowly. A visual system that utilizes this information can create a detailed three-dimensional representation of its environment even if it is equipped with only a small, simple image sensor.

Yet the RoboBee brain must be powerful enough to process the stream of data coming out of its image sensors and make appropriate control decisions to drive body actuators. Here again, even advanced off-the-shelf components will not work for us. Consequently, we have been exploring a new class of computer architecture for the RoboBee brain that combines general-purpose computing with specialized circuits called hardware accelerators. Unlike general-purpose processors, the do-anything chips that run ordinary home computers, hardware accelerators are finely tuned circuit blocks that do only one thing but do it well. We would use hardware accelerators to make the fast, real-time computations required by the feedback control loop for stable flight while also staying within strict power budgets.

A major challenge has been to figure out what trade-offs we can get away with. For example, we would like to be able to use a high-resolution camera. High pixel counts, however, require larger image sensors and additional computational power to process the images. Where is the sweet spot?

To help answer these kinds of questions, we have developed a special test chamber. We mount a RoboBee body on a fixed multiaxis force and torque sensor and let it flap its wings in an attempt to fly. On the walls of the test chamber, we project images of the physical environment that the RoboBee would be flying through. In this way, we can explore how our prototype vision system, brain and body work together to navigate through the world.

Flight control is just the beginning, of course. We also have parallel efforts that explore other types of sensors that will let RoboBees accomplish specific tasks—finding a person hidden in earthquake rubble, say.

Unfortunately, one capability that we do not foresee for our current bees is direct bee-to-bee communication—the power costs associated with wireless communications are just too great. Yet that does not mean that the bees will act alone.

COLONY AND COMMUNICATION

AN INDIVIDUAL ROBOBEE will be tiny and limited compared to the world we hope to operate it in, and power and weight budgets severely curtail the types of sensing and communications hardware any individual RoboBee can have. Thus, in addition to our research into the body and brain of a RoboBee, we must also figure out how to build a colony. As with honeybees, a RoboBee in isolation can accomplish little. But a hive? Group behavior will allow RoboBees to explore large areas, make sense of those areas by making many simple observations, efficiently divide labor, and thrive even when individual bees fail. Swarms of small, agile and potentially disposable robots can enable many new applications—pollination, for example, or search and rescue in a disaster scenario—that are not possible with individual robots.

Since the early 1990s computer scientists working in the research area of "swarm intelligence" have elucidated many powerful coordination algorithms inspired by social insects—from coordinated search strategies to smart division of labor. But even with these algorithms in hand, swarms of robots cannot be managed like a single robot.

For one, programming and reasoning at the level of individuals become untenable with thousands of entities. It would be like asking the average software developer to sit down and write out the instructions for each physical bit inside a computer. Instead, just as compilers take the human-readable instructions of a computer program and translate it into the 1's and 0's that control individual transistors inside a microprocessor, we need a higher-level, abstract way of programming the colony as a whole—one that would get translated from global instructions to individual behavioral programs. We need a programming language for colonies.

What is the right language that captures what honeybee colonies do and what we hope to do with RoboBee colonies? There is no simple answer yet, but we have developed two abstract languages to start with. In the Karma language, one can specify a flowchart of tasks that the colony must achieve. The flowchart contains links that represent conditions that trigger new tasks. The Karma system uses information that comes back from individuals to adjust the allocation of resources to tasks in a way that mimics the role of the hive in real honeybee colonies.

A different approach, called OptRAD (*Opt*imizing *R*eaction-*A*dvection-*D*iffusion), treats the colony of aerial robots as a fluid that diffuses through the environment. Any individual RoboBee uses a probabilistic algorithm to determine whether it will execute a task based on the current state of the environment. Treating the system as a fluid allows OptRAD to reason at a high level about the expected outcomes and adjust its behavior to adapt to new circumstances.

We also have a great deal to learn about building and operating a large colony of robots that contains not just tens or hundreds but thousands of autonomous robots that vastly outnumber their human operators. When there are thousands of entities, just operating robots at the level of individuals also becomes untenable. Imagine if every robot had an on/off switch—if it took five seconds to turn each one on, then turning on 1,000 robots would take nearly an hour and a half. Similar constraints apply to everything from cost to maintenance—every robot must be cheap, easy to make and simple to operate at the collective level. Ideally, every operation would be scalable—it would take some fixed amount of time that does not increase with the size of the collective (or at least that increases very slowly).

These challenges have motivated us to create the Kilobot system—a collective of hundreds of robots, each about the width of a quarter, that move by vibrating and that communicate with other nearby Kilobots. We can use this collective to test the efficacy of our programming languages and our mathematical models of emergent behavior. After all, without playing with real hardware, we are unlikely to understand the emergent behavior of physical systems.

The collective can be used to test many group behaviors that we would eventually want the RoboBee colony to achieve. For example, we can ask the group to search for targets in an environment, then, once an individual Kilobot finds a target, report the location back to the group. We have also made the Kilobot design open source for groups wanting to make their own. Or one can purchase premade Kilobots from K-Team, an educational robotics company. We hope such a standardized robotics kit will help generate new ideas and spur collective advances in science that individual groups cannot do—after all, we, too, rely on collective power to become more than the sum of our parts.

THE FUTURE

ALTHOUGH WE HAVE MADE a lot of progress, much work remains. We anticipate that within a few years we will have RoboBees flying under tightly controlled lab conditions. Within five to 10 years beyond that, you may see them in widespread use.

In 1989 renowned roboticist Rodney Brooks wrote a paper on the benefits of small robots for space exploration entitled "Fast, Cheap, and Out of Control: A Robot Invasion of the Solar System." This is, of course, a play on the old engineer's adage that consumer products can be typically characterized by any two—but not three—of the following adjectives: fast, cheap and reliable. With many individuals, the failure of one matters little.

Brooks was prophetic in his interpretation of this concept to robotics. Provided you can make many simple things that effectively work together, who cares if the individuals fail periodically? The only way to ensure the success of robotic explorers is to make it okay for them to occasionally fall out of the sky. SA

MORE TO EXPLORE

Kilobot: A Low Cost Scalable Robot System for Collective Behaviors. Michael Rubenstein, Christian Ahler and Radhika Nagpal in *2012 IEEE International Conference on Robotics and Automation (ICRA)*, pages 3293–3298; May 14–18, 2012.

Progress on "Pico" Air Vehicles. R. J. Wood et al. in *International Journal of Robotics Research*, Vol. 31, No. 11, pages 1292–1302; September 2012.

Harvard Microrobotics Lab YouTube channel: **www.youtube.com/MicroroboticsLab**

SCIENTIFIC AMERICAN ONLINE
Watch RoboBees take flight at **ScientificAmerican.com/mar2013/robobees**

ANCIENT SCOURGE: Smallpox scarred this child for life in 1915.

Sonia Shah is a science journalist and author of *The Fever: How Malaria Has Ruled Humankind for 500,000 Years.* She is currently writing a new book on emerging diseases.

EMERGING DISEASES

NEW THREAT FROM POXVIRUSES

Smallpox may be gone, but its viral cousins—monkeypox and cowpox—are staging a comeback

By Sonia Shah

TEN THOUSAND YEARS AGO, WHEN SMALLPOX FIRST EMERGED, HUMANKIND COULD do little more than pray to the gods for succor. Later known as variola, the virus that caused the disease first attacked the linings of the nose or throat, spreading throughout the body until a characteristic rash followed by virus-filled blisters developed on the skin. Over the course of recorded history, the "speckled monster" killed up to a third of the people it infected. During the 20th century alone, it felled more than 300 million men, women and children.

IN BRIEF

When smallpox was eradicated 35 years ago, people stopped getting vaccinated against it.

In the intervening years the general population has lost immunity not only to smallpox but also to other poxviruses that were formerly held in check by the smallpox vaccine.

The number of cases of monkeypox and cowpox has started to climb, raising the possibility of a new global scourge spreading in smallpox's place.

CORBIS

By the late 1970s, however, the deadly scourge had been eliminated from the face of the earth thanks to mass vaccination campaigns that protected millions and left them with a small scar on their upper arm. With nowhere to hide in the natural world—humans are the virus's only host—variola was beaten into extinction. Today the only known viral samples are locked in two specialized government laboratories, one in the U.S. and the other in Russia. Absent a catastrophic lab accident, deliberate release or the genetic reengineering of the virus, smallpox will never again spread death and misery across the globe.

The World Health Organization, which had organized the eradication campaign, sounded the official all clear in 1979, two years after the last sporadic case was recorded, in a Somali hospital worker. Since then, no country has routinely vaccinated its citizens against smallpox, although the U.S. began inoculating certain health personnel and selected members of its armed forces after the terror attacks on September 11, 2001. Thus, an entire generation has reached adulthood without any exposure to either the disease or the vaccine, which sometimes caused serious side effects.

And therein lies the rub. The smallpox vaccine did not protect just against the variola virus. Anyone who was vaccinated against smallpox also developed immunity to infection with variola's viral cousins—including monkeypox and cowpox. Given the much larger scale of smallpox infections at the time, this secondary protection was seen as a minor benefit.

Now that the smallpox vaccine is no longer widely given, the question becomes: Could these obscure pathogens, which, like smallpox, belong to the *Orthopoxvirus* genus, pose a new danger to humans? There are reasons to worry. Unlike smallpox, cowpox and monkeypox naturally lurk in rodents and other creatures, so they can never be fully eliminated. The number of cases of monkeypox and cowpox in humans has steadily risen in recent years. And both viruses have begun to infect different creatures beyond their normal hosts, raising the possibility that they might spread through new paths around the planet.

No one knows how monkeypox and cowpox will change over time, but virologists worry that if they mutate to jump more easily from one person to the next, they could devastate large parts of the globe. That grim possibility drives a small band of virologists to learn more about these—or any other—potential pox plagues in the making, so as to sound the alarm if they show signs of developing into more threatening forms.

VARYING SEVERITY

THE HISTORY AND BIOLOGY of poxviruses offer some clues as to what to expect from smallpox's kin in the future. Historically, 60 percent of the pathogens that plague humankind, including the orthopoxviruses, have originated in the bodies of other vertebrates. Variola's closest living relative, taterapox, was isolated from a wild gerbil in Africa in 1968. Molecular analyses suggest that smallpox's evolutionary ancestor probably got its start in an African rodent species, possibly now extinct. Similarly, cowpox and monkeypox, despite their names, live in voles, squirrels or other wild rodents.

When variola's ancestor first jumped into humans, it probably was not very contagious, says microbiologist Mark Buller of Saint Louis University. Then, somewhere along the line, he and other researchers surmise, a variant emerged that was much more transmissible. The critical change allowed the virus to broadcast itself via the coughs, exhalations or sneezes of an infected person. Meanwhile human beings started living in much closer quarters, making it that much more likely for one person to pass the infection on to another. The combination of the biological change and the altered environment gave the emerging virus the edge it needed to become a global scourge.

Just because a virus is easily transmitted, however, does not necessarily make it lethal. Indeed, scientists still cannot explain why poxviruses vary so greatly in their severity. In most people, cowpox, camelpox and raccoonpox infections trigger little more than a skin rash, with virus-filled pustules that harmlessly clear up on their own. Monkeypox infections, on the other hand, can be quite deadly in humans. Even at that, not all monkeypox viruses are equally dangerous. The worst subtype, found in the Congo Basin, kills about 10 percent of people who are infected, whereas another version, from West Africa, rarely if ever ends in death. As it happens, the West African strain in 2003 caused the first-ever recorded cases of monkeypox in the Western Hemisphere. The outbreak, which occurred in six states in the U.S., led to the hospitalization of 19 people, including a child who suffered encephalitis and a woman who was blinded, necessitating a corneal transplant. Investigators traced the infection to rodents imported from Ghana that passed the virus to pet prairie dogs, which in turn infected their owners. Such intermediary animals allow a virus that normally lives in animals with little human contact to reach potentially large numbers of people.

Subtle genetic differences may help explain the shifting severity of pox infections. For example, some poxviruses possess genes for proteins that interfere with the ability of the immune system to respond effectively to the infection. When researchers compared the genes from different poxviruses, they zeroed in on one that was found in several different kinds of poxviruses. In the most deadly strains of variola, this gene triggered the production of a protein that evidence suggests prevents some immune cells from efficiently coordinating their counterattack against the virus. But the equivalent gene in the Congo Basin strains of monkeypox (which are less deadly than smallpox) provided the hereditary instructions for a much shorter protein. When researchers looked at the milder West African version of monkeypox, the gene was missing altogether and the protein in question could not be manufactured. Thus, the evidence suggested that the shorter protein in the Congo Basin strains of monkeypox somehow made them less deadly than smallpox.

Speculation among researchers about how different species of poxvirus acquired this and other genes indicates why monkeypox and its cousins could potentially become more dangerous threats than they are now. The genes, which are not essential for poxvirus replication, appear to be faithful copies of genes the viruses acquired at some point in the evolutionary past from organisms they infected. Yet, curiously, the viruses do not in the normal course of an infective cycle come anywhere near the genetic material stored in the nucleus of the host cells.

One possible explanation, popular among pox virologists, posits the simultaneous infection of a human or other vertebrate host with a poxvirus and a retrovirus. Such co-infections are probably pretty common, researchers say. Retroviruses are known for incorporating their own genes into their host's DNA. (About 8 percent of the human genome consists of DNA that originated in retroviruses.) It is possible that the unusual biochemical activity of the retrovirus inside the cell could allow the poxvirus to capture its host's genes.

If true, this hypothesis could prove portentous. Poxviruses are genetically stable and do not usually mutate quickly. If they can steal genes from their hosts that make them more virulent, then there is no predicting what a relatively harmless, not to mention an already deadly, poxvirus might do under the right circumstances. The change from mild to dangerous threat could occur more quickly and unpredictably than anyone might have previously suspected.

SMALLPOX'S "LITTLE COUSIN"

MONKEYPOX IS BETTER poised than any of its viral cousins at present to emerge as a global threat. Virologists refer to it as smallpox's "little cousin," in part because it causes an illness that is clinically indistinguishable from smallpox. First reported in captive monkeys in 1957, the virus typically lives, evidence suggests, in African rodents, possibly rope squirrels. Outbreaks have so far occurred mostly in Central Africa, with the notable exceptions of the U.S. in 2003 and Sudan in 2006.

University of California, Los Angeles, epidemiologist Anne W. Rimoin was in Kinshasa, Democratic Republic of the Congo, in 2002, when she first heard about local residents who had fallen ill with monkeypox. She did not know how many people were infected, how they were exposed to the virus or whether the virus could spread to others. But she knew the disease was life-threatening and wanted to learn more.

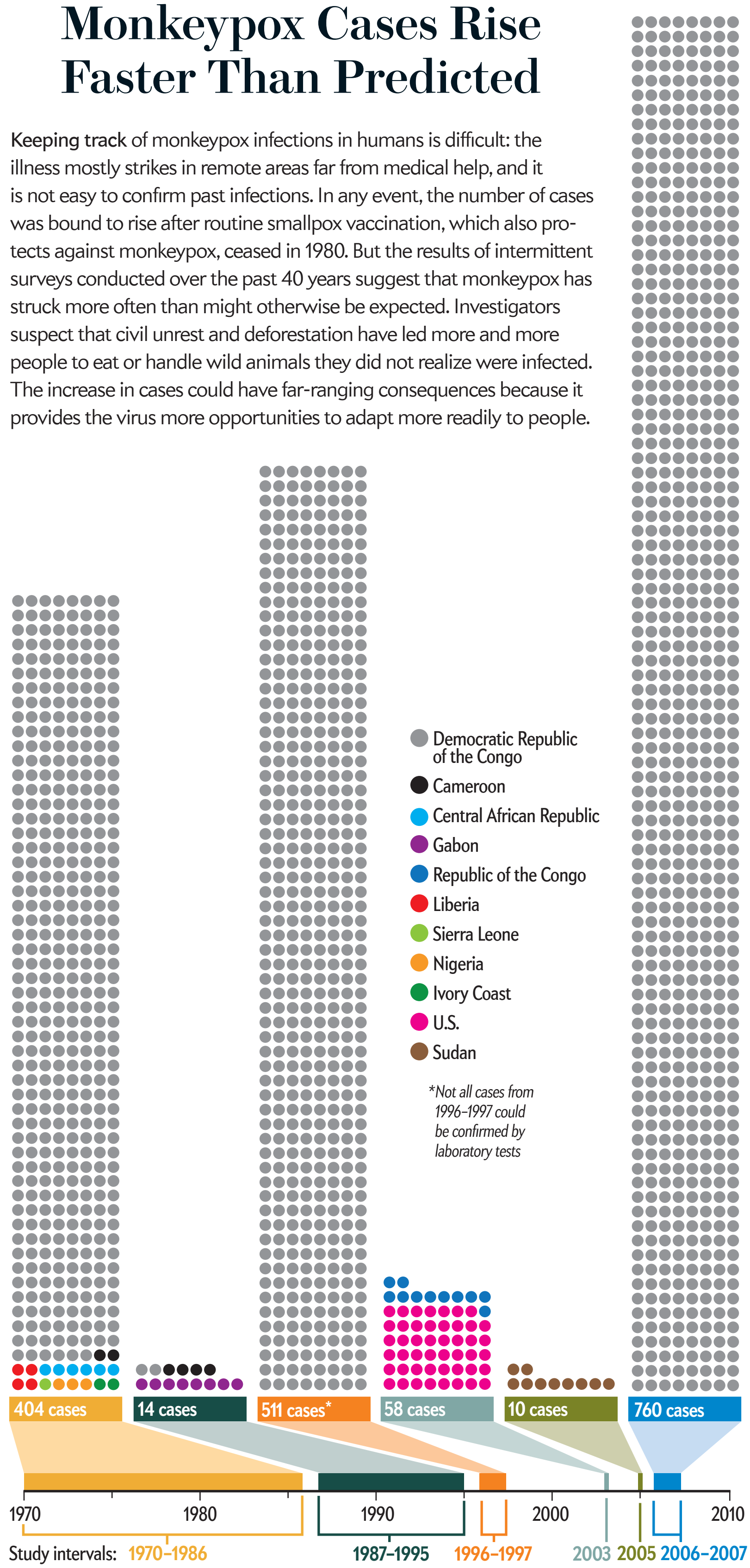
With her blond hair and buff pedicure, Rimoin could hardly be mistaken for a local in the remote Congolese jungles. Yet she had studied the country's politics as an undergraduate in African history and was fluent in French, which is still spoken in the former Belgian colony, as well as Lingala and other local languages. She started asking around. "I just clicked with the right people and asked the right questions," she says. And "it became clear to me that there were probably a lot more cases than were being reported."

But how to find them? Unsurprisingly, given the dearth of health care facilities in

WORRISOME TREND

Monkeypox Cases Rise Faster Than Predicted

Keeping track of monkeypox infections in humans is difficult: the illness mostly strikes in remote areas far from medical help, and it is not easy to confirm past infections. In any event, the number of cases was bound to rise after routine smallpox vaccination, which also protects against monkeypox, ceased in 1980. But the results of intermittent surveys conducted over the past 40 years suggest that monkeypox has struck more often than might otherwise be expected. Investigators suspect that civil unrest and deforestation have led more and more people to eat or handle wild animals they did not realize were infected. The increase in cases could have far-ranging consequences because it provides the virus more opportunities to adapt more readily to people.



SOURCES: "MONKEYPOX: AN EMERGING INFECTION FOR HUMANS?" BY JOEL G. BREMAN, IN *EMERGING INFECTIONS 4*, EDITED BY W. M. SCHELD, W. A. CRAIG AND J. M HUGHES, ASM PRESS, 2000; "OUTBREAKS OF HUMAN MONKEYPOX AFTER CESSATION OF SMALLPOX VACCINATION," BY MARY G. REYNOLDS AND INGER K. DAMON, IN *TRENDS IN MICROBIOLOGY*, VOL. 20, NO. 2; FEBRUARY 2012

Graphic by Jen Christiansen

rural Congo, few people who were sick sought out clinicians. And those who had recovered could not easily be identified with blood tests because there was no way of telling whether the presence of antibodies against poxvirus was the result of an earlier smallpox vaccination or another poxvirus infection. Assessing the incidence of monkeypox required finding people who were in the throes of an acute monkeypox infection, when it would be possible to test for the virus itself from the pustules on the skin.

Rimoin began her quest by establishing a research site deep in the forest. There were no roads, no cell-phone signals and no radio transmission. She chartered planes to get in and out and spent days walking and traveling by canoe and by motorcycle to track down monkeypox cases among the Lingala-speaking villagers of interior Congo.

The results were alarming. Compared with similar data collected by the World Health Organization in 1981–1986, Rimoin had found a 20-fold increase in the number of human monkeypox cases. Even so, she believes that her findings, which were published in 2010, are an underestimate. "It's the tip of the iceberg," she asserts. After all, the WHO had a much bigger and much better financed operation looking for monkeypox 30 years ago. Rimoin's team undoubtedly missed many more cases, relatively speaking, than that earlier, larger effort.

RISE OF MONKEYPOX

ALTHOUGH THE SPIKE in monkeypox cases was larger than anyone had anticipated, it was not unexpected. After all, most of the country's population is unvaccinated against poxviruses. (The Democratic Republic of the Congo stopped vaccinating against smallpox in 1980.)

Further research suggested that something else was going on as well. Ecologist James Lloyd-Smith, one of Rimoin's colleagues at U.C.L.A., uses computer models to study how diseases jump from animals to humans. According to his analyses of Rimoin's data, the withdrawal of the smallpox vaccine and subsequent loss of immunity to related poxviruses could not fully account for the spike in cases. There must have also been at least a fivefold increase in "spillover" events, he says, in which the virus jumped from infected rodents into humans.

With expanded opportunities to infect people, monkeypox might better adapt to humans. A few tweaks to a current viral trait may be all that is needed to make it a much more contagious pathogen.

Why monkeypox might be jumping into humans more frequently is a matter of conjecture. It could be that continued clearing of land for agricultural use and for burning wood has put more and more people in contact with infected squirrels, mice and other rodents. In addition, more local people may have been reduced to eating potentially infected animals as a result of the Congolese civil war. A 2009 survey, published in October 2011, found that a third of people in rural Congo eat rodents found dead in the forest and that, suggestively, 35 percent of monkeypox cases occur during hunting and farming season. (Most people contract monkeypox from close contact with infected animals, such as handling or eating them.)

Rimoin and other virologists worry that with expanded opportunities to infect people, monkeypox might better adapt to the human body. Buller studies the ways in which orthopoxviruses cause diseases in both humans and animals. Monkeypox "can already kill people," he says, and it can spread between individuals, too—just not that well. All that may be needed to transform monkeypox into a much more contagious human pathogen might be a few minor tweaks to a current viral trait.

SPREAD OF COWPOX

REPORTS OF PEOPLE and animals infected with rodent-borne cowpox virus are rising as well—in this case, in Europe.

Cowpox infections are mild in most people. After the virus enters cells and disarms the host's initial immune response, a fusillade of virus-hunting antibodies made by the victim prevents the pathogen from spreading to tissues throughout the body. Not so in people whose immune systems have been weakened, such as by HIV, cancer chemotherapy or treatment to prevent the rejection of transplanted organs. "They can get a smallpoxlike disease, and they can die," says Malcolm Bennett of the University of Liverpool in England. Since 1972, public health experts estimate, the number of immunocompromised people in the U.S. who are now susceptible to serious disease from cowpox and other poxviruses has grown 100-fold.

Bennett, a veterinary pathologist, studies the ecology and evolution of cowpox in wildlife. In the U.K., he says, cowpox normally resides harmlessly in bank voles, field voles and wood mice. Domestic cats pick up the virus from the rodents they hunt. They then expose the people who care for them (often at close range) to cowpox, a chain of events that accounts for half of all human cowpox cases in the U.K.

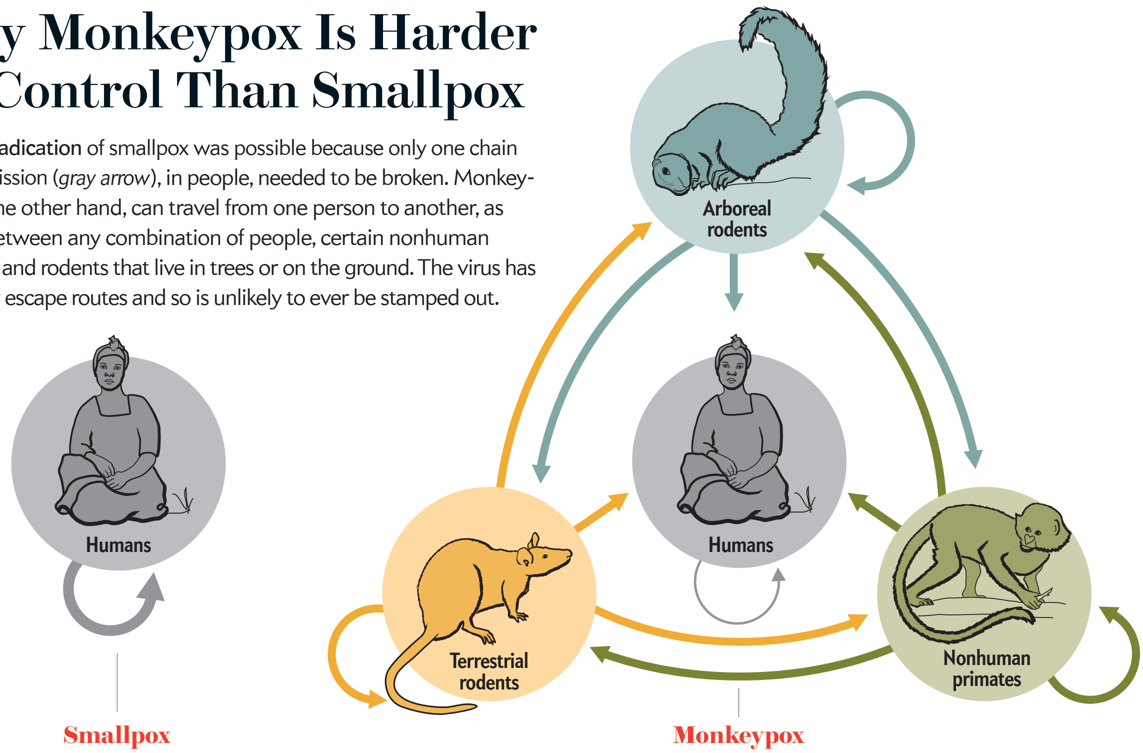
Like monkeypox, cowpox has started making forays into creatures outside its normal reservoir hosts. With bank vole populations booming thanks to mild winters and other favorable climatic conditions, rats may have started playing an intermediary role in cowpox transmission similar to the one played by prairie dogs in the 2003 American outbreak of monkeypox. "There's been a proliferation of reports, either zoo-related or pet-related, associated with rats," says Mary Reynolds, an epidemiologist at the U.S. Centers for Disease Control and Prevention. That trend "is potentially quite concerning because black and brown rats sure make their way around the globe pretty efficiently," she notes. If cowpox becomes established in rats, as opposed to just voles and wood mice, millions more people could be readily infected by, for example, being bitten or coming into contact with their droppings.

Indeed, orthopoxviruses are notoriously adept at colonizing new species. The vaccinia virus, for example, which was used to create modern smallpox vaccines, now freely propagates in dairy cattle in Brazil, as well as in buffalo in India. And there are "a range of orthopoxviruses out there that have never been isolated or fully characterized," Reynolds points out. Given the right opportunities, those less familiar pox strains could extend their ranges into new regions and species. "Some will be pathogenic to people," Bennett adds. "They just haven't managed to make the species jump yet."

MANY PATHWAYS TO INFECTION

Why Monkeypox Is Harder to Control Than Smallpox

Global eradication of smallpox was possible because only one chain of transmission (*gray arrow*), in people, needed to be broken. Monkeypox, on the other hand, can travel from one person to another, as well as between any combination of people, certain nonhuman primates, and rodents that live in trees or on the ground. The virus has too many escape routes and so is unlikely to ever be stamped out.



SOURCE: "HUMAN MONKEYPOX: AN EMERGING ZOONOTIC DISEASE," BY SCOTT PARKER, ANTHONY NUARA, R. MARK L. BULLER AND DENISE A. SCHULTZ, IN *FUTURE MICROBIOLOGY*, VOL. 2, NO. 1; 2007

ARMED AND VIGILANT

AS THE CROWD of people who have never received a smallpox vaccination grows, pox virologists expect the incidence of human cases of monkeypox, cowpox and other poxviruses to continue to rise.

Should any of these poxviruses become adept at plaguing humans, new drugs and vaccines—and the resources necessary to use them—will be needed to contain the threat. Because of post-9/11 fears of intentional releases of smallpox, a spate of new vaccines and drugs are being developed to fight smallpox. These medications will likely provide protection against naturally emerging poxviruses as well. But producing and distributing them, as well as safeguarding against their inevitable side effects, will be a complex and costly undertaking. New smallpox vaccines, such as Bavarian-Nordic's Imvamune, have been designed to be safely administered even to immunocompromised people, but they must be given in higher doses and over the course of two shots instead of one, making them more expensive than traditional smallpox vaccines. A new drug, manufactured by Siga Technologies and known as ST 246, prevents orthopoxviruses from traveling from one cell to another in a host. Despite not yet being approved by the U.S. Food and Drug Administration, the federal government has already purchased a large amount of ST 246 and added it to the national biodefense stockpile.

In places such as the rural Congo River basin, where health financing for cutting-edge new vaccines and drugs is limited, the best hope for now seems to be enhanced surveillance, combined with community education programs. For example, a monkeypox education program run by the CDC, in conjunction with local health officials and voluntary nongovernmental organizations in the Democratic Republic of the Congo, increased the proportion of local people able to recognize monkeypox cases from 23 to 61 percent. Rimoin's arduous surveillance of monkeypox continues as well, with new studies aimed at sequencing the genes in variants infecting animals and people today to see how the virus may be changing. Better detection means more opportunity to care for and isolate infected individuals, squelching chances for the virus to mutate into new forms that spread more efficiently between people.

The ancient war between poxviruses and humans may not have ended when that 21-year-old Somali hospital worker cleared his smallpox infection back in 1977. With new tools and better surveillance, scientists are better armed and more vigilant than ever before. But to prevent another pox from falling on humankind, society will need to maintain those defenses for some time to come. SA

MORE TO EXPLORE

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SCIENTIFIC AMERICAN ONLINE
Watch as Anne W. Rimoin describes her research into the spread of human monkeypox at **ScientificAmerican.com/mar2013/rimoin-video**

Illustration by Portia Sloan Rollings

FORENSICS

THE GOVERNMENT WANTS YOUR DNA

Cops can collect DNA when making an arrest, sometimes before charging a person with a crime. This practice poses a threat to the civil liberties of innocent people

By Erin Murphy

IN BRIEF

Police use of DNA initially posed only a minimal threat to privacy. But collections have expanded to include those arrested for nonviolent crimes and others taken into custody but not yet formally charged with an offense.

DNA sampling has achieved increasing sophistication as police adopt techniques that search databases for samples that only partially match those from crime scenes, a practice that can bring entire families under the spotlight of a criminal investigation.

The U.S. Supreme Court will ultimately decide whether just being arrested for a crime gives police the authority to demand a genetic sample. A variety of legal measures are needed to protect against potential abuses of gargantuan genetic repositories.


EVIDENCE BAG
Name/Rank/No.
Signed

Erin Murphy, professor of law at the New York University School of Law, is an expert on the use of DNA in criminal investigations. Her research focuses on technology and privacy in the criminal justice system, with a particular emphasis on street crime.

STARTING IN THE MID-1980S, A SERIAL KILLER MURDERED at least 10 women in the Los Angeles area. Nicknamed the "Grim Sleeper" because of the long dormancy between his crimes, he eluded capture for nearly 25 years. Then, in 2010, police arrested a man in California for what appeared to be a totally unrelated felony weapons charge. State law required the man to submit a DNA sample for a national DNA database. Typically a DNA database search looks for an exact match between a profile of DNA left at a crime scene by an unknown person and the profile of a known convicted offender. It focuses on 13 places in the genome (the full complement of our DNA) where bits of genetic material vary from person to person. If the crime-scene material differs in any of those 13 places, then the samples do not match, and investigators know that they do not have their suspect.

This time, however, the search was more subtle. It aimed to find DNA profiles that were similar, but not an exact match, to that of the Grim Sleeper. Such an inquiry was possible because in 2008 California became the first state in the nation to formally authorize a new kind of database search. Known as kinship, or familial, matching, this technique looks for partial DNA matches. It is conducted after DNA found at a crime turns up no exact hit. Because related people tend to share more DNA with one another than they do with strangers, a "near miss" in the database may suggest that the search found a person related to the actual perpetrator. Police can then investigate the relatives of the person in the database with the hope of solving the crime.

In the case of the Grim Sleeper, a familial search in 2008 turned up nothing. Two years later, however, the same inquiry generated a lead to the man who had been arrested in California for the weapons offense. Given the fellow's age and the dates of the serial killer's first attacks, suspicion focused quickly on an older relative—his father. A police officer, posing as a waiter at a pizza restaurant, surreptitiously collected genetic samples as the family ate a meal. The sample from the father matched the crime-scene evidence collected long ago, and shortly thereafter the alleged Sleeper was arrested.

This kind of DNA story is so electrifying that television shows like to copy it: a ruthless killer at last outwitted by flashy technology and dogged police persistence. Yet there is another kind of high-tech tale—also about a search for a serial killer—that is equally noteworthy but decidedly disturbing.

Take the case of Shannon Kohler, a Louisiana man approached by officers conducting a DNA dragnet—a broad sweep that netted more than 600 DNA samples from men matching the purported description of the killer. Kohler declined to volunteer a sample but proffered an array of exonerating details, including an accounting of his whereabouts at the time of three of the murders.

Nevertheless, police obtained a court order (later ruled invalid) allowing them to take his DNA and leaked his name to the press—which identified him prominently as a leading and uncooperative suspect in the case. Eventually Kohler's sample established that he was not the murderer, yet authorities never told Kohler of his exoneration. He learned that he had been vindicated only when, two months later, a newspaper printed a small item—after he had endured the dark cloud of suspicion casting him as a potential serial killer and the fear of being wrongly arrested for a capital crime.

As Kohler's saga illustrates, broadening use of DNA testing by law enforcement poses a growing threat to the civil liberties of innocent people. In the 15 years since the national database, called CODIS (*Co*mbined *D*NA *I*ndex *S*ystem), was started, it has amassed DNA signatures of more than 10 million offenders and another 450,000 unidentified people who left genetic material at a crime scene but were never found. The database contains profiles from individuals who have been charged with but never convicted of an offense. More than half of U.S. states now require cops to collect DNA after an arrest for certain offenses.

To address the threat to civil liberties, policy makers should demand answers to simple questions about the precise effectiveness of the technology—for example, finding out how many convictions have come about as a result of DNA database searches

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and what percentage of searches turn up useful information—before, as some have suggested, a national database of DNA from everyone in the country is established, allowing any sample collected from a crime to be compared against DNA from the entire U.S. population.

For more than 200 years we have required the police to get a warrant when officers wish to search or seize evidence from individuals in connection with a crime; DNA evidence should be no different. The government should also put in place stricter controls over the use of DNA databases, by taking steps such as forbidding partial matches. Also, it should enact rules to ensure that stored DNA samples are not subject to new tests without court permission and that police databases become available to defense attorneys for exonerating the wrongfully accused. Such changes are not just essential to preserve civil liberties, they are also needed to ensure public safety.

An increasing number of states require that a person provide a DNA sample immediately after being arrested.

THE SLIPPERY SLOPE

AT ONE TIME, the threat posed by compulsory DNA testing was minimal. The practice began in the late 1990s with the passage of state laws compelling people convicted of the most serious felonies, such as murder and sex crimes, to supply blood samples containing DNA. Now these samples are obtained by simply swabbing the inside of the cheek, and the information that is recorded comes from stretches of DNA that vary from person to person but do not reveal anything else about the donor's traits.

In the 2000s states increasingly began to require samples from offenders convicted of less serious felonies or even misdemeanors. Today the federal government and every state mandate compulsory testing of some convicted offenders. Noting that convicted criminals have fewer privacy rights than other citizens, courts have universally upheld such laws.

Yet fresh concerns about civil liberties have been raised by the trend among states in the past five years to require that people arrested for certain crimes give DNA samples. More than half of states and the federal government have arrestee sampling laws in place, some of which authorize the police to take a genetic sample immediately rather than waiting to see if a prosecutor actually files charges. Some states require automatic removal of genetic data collected from a person whose case is later dismissed, but others put the burden on the person wrongly arrested to file a petition to get the DNA record expunged. Finally, some laws provide for the destruction of the biological sample (not just the record), but others allow the government to retain the sample indefinitely.

In the coming months, the U.S. Supreme Court will decide whether DNA samples taken from someone arrested violates the Fourth Amendment of the Constitution. No one disputes that a person arrested for a crime should be required to give a genetic sample if one is needed to compare with evidence found at the alleged scene of the crime. But taking samples from everyone arrested for the sole purpose of expanding the database is a different matter. With more than 14 million arrests annually, a huge fraction of which end in dismissals, arrestee collection statutes could result in many innocent people having their DNA information loaded into police databases and then checked weekly against all the nation's unsolved crimes.

Familial searching, in contrast, has yet to be decided by any court. Like the compiling of arrestee databases, the guidelines for familial searching vary greatly state to state. Yet unlike the rules about whose DNA must go in the database, which are set by democratically elected legislatures, the rules about how police can use the DNA database are often put in place internally by high-level federal or state officials, administrative agencies, or even the heads of individual state or municipal crime laboratories. In fact, the situation is so muddy that it can be difficult even to discern which states engage in what practices. Current data indicate that at least 15 states actively undertake familial searches, although the most prominent users are law-enforcement officials in California, Virginia, Colorado and Texas. Unquestionably, other states have informally conducted occasional searches, and a handful of states are now weighing authorizing legislation. Some states do recognize the potential for abuse. Maryland and the District of Columbia both forbid intentional familial searches by law, and more than 15 states in addition to Maryland prohibit it through written or unwritten policy.

NOT YOUR FATHER'S FINGERPRINT

ADVOCATES of the widespread collection and matching of DNA for crime solving often argue that DNA is no more than a glorified fingerprint and thus raises no new legal issues. Indeed, the handful of courts that have upheld arrestee collection statutes have likened DNA sampling to the routine taking of fingerprints at arrest, a practice long sanctioned by both the courts and the public. Although this analogy has superficial appeal, it is misleading: DNA can potentially provide more information about a person than a fingerprint and can open the door more widely to breaches of privacy.

What is more, even fingerprinting is more invasive than it used to be. Courts have long viewed fingerprinting at arrest as just a minimal encroachment of individual privacy, and for most of the history of the technology it was: a print was taken at a local precinct and then stored in a musty drawer. It was seldom seen again unless police had a new reason to suspect a person of a crime. Today fingerprints, like DNA profiles, are loaded into electronic databases, where they may be automatically searched not just locally but globally. To be sure, access to a common database aids in crime solving. Yet when mistakes occur—and they do happen—the consequences can be shocking. Just remember Brandon Mayfield, the Oregon attorney arrested and held in custody for two weeks as a suspect in the 2004 train station bombings in Madrid because of a faulty fingerprint match.

A false match is the only way to misuse a fingerprint, which simply cannot reveal as much as a person's DNA does. Fingerprints do not tell law enforcement that you have a brother or that you were adopted. They cannot identify you by ethnicity or sex or reveal whether you are predisposed to cancer. There is no expectation with fingerprinting, as there is with DNA, that it will accurately predict hair and eye color, height, age, bone structure or skin color, not to mention a range of genetic predispositions such as tendencies toward violence, substance abuse or mental illness.

Right now the DNA that is examined and recorded for forensic purposes does not reveal the most personal of these details. But the technology for doing so either already exists or likely will in the future. And the law does not clearly forbid this testing. Courts have consistently interpreted the Constitution to say a great deal about how the police acquire information, but they have exercised very little control over what police then do with that information. If police lawfully obtain a sample, are there then no limits or restrictions on how long that sample can be kept, how long it may be used or what kind of tests can be run on it?

DNA crime tech extends beyond futuristic invasions of privacy. Erroneous IDs are more possible than TV crime shows suggest.

If police examine only DNA fragments that do not reveal personal details, these questions may seem frivolous. Yet because police currently use DNA to make family connections, and in light of ongoing research into using DNA to reveal physical traits, disease and other predispositions, the present legal distinction between the mere acquisition and storage of genetic material and its use for analysis of personal information may quickly turn dangerously antiquated.

It is not hard to imagine that one day police may learn from crime-scene DNA that the unknown criminal is a man of Eurasian descent with blue eyes who is perhaps highly muscular and has a predisposition to alcoholism. Officials may then identify people with a similar profile and investigate those individuals or make their private information public even if many of those under suspicion will end up having nothing to do with the crime. Law-enforcement officials may simply use DNA as a starting point. Information about possible facial characteristics or physical build hinted at through a genetic profile may then be compared against other databases that store photographs of faces and other biometric information, thereby enabling the police to use highly sophisticated and potentially intrusive data mining of personal information on a vast number of the U.S. populace.

The issues raised by the use of DNA technology in law enforcement are not limited to futuristic invasions of privacy or possible harassment of those who happen to be family members of a possible suspect. Even today the potential for mistaken matches is greater than TV crime shows would have you think. The comparison process is far from perfect, especially as smaller and smaller quantities of DNA are tested. Crime-scene samples are generally not in pristine laboratory condition but contain a mix of material from multiple individuals. Analyzing those mixtures is a highly subjective process. One of the few empirical studies of the subjectivity inherent in DNA comparisons recently uncovered alarming possibilities for error: researchers submitted the results of DNA tests in an actual case to 17 experienced analysts; they received significantly divergent reports, ranging from inclusion of the defendant as a possible contributor to the crime to, on the contrary, definitive exclusion.

Finally, one very disturbing aspect of forensic DNA typing is the disproportionate impact that it has on minorities. Because blacks and Latinos make up a greater share of those arrested and convicted in our society, it is their DNA that is most likely to be collected and searched. Yet that is not necessarily because those groups commit more crime. For instance, studies show that across the country, the arrest rate for marijuana possession for blacks and Latinos is double, triple or even quadruple that for whites even though the first two groups do not use marijuana at any higher rate than the third. If police make arrests in a racially skewed way, then DNA databases will also be racially skewed. And it will be those groups whose relatives and family members will be most likely to fall under suspicion as a result of familial-match methods.

The need to more closely regulate law enforcement's use of DNA collection and analysis goes beyond rules and policies related to mandatory collection and familial searches. So far the discussion has centered on the cases in which a person is ordered to give a DNA sample after arrest or conviction. It is also possible, however, for police to obtain DNA surreptitiously, as was done in the Grim Sleeper investigation. In such cases, Fourth Amendment law points in conflicting and often counterintuitive directions. Constitutional protection has traditionally not extended to discarded material—if you throw your bloody shirt in the trash, you cannot complain that your rights were invaded when law enforcement snatches it up as evidence. But should the same reasoning apply to DNA, which is "discarded" routinely, albeit unintentionally? It is simply not possible to live in the world and not shed DNA. Given the myriad ways that DNA can be revealing of intimate personal details, does its ubiquity mean you have no grounds for complaint if the police pick up your discarded soda can and try to match your DNA profile with records in CODIS or store your information in a database or spreadsheet?

FORENSICS OUT OF VIEW

WHAT SHOULD BE DONE to protect the right to privacy of innocent people as DNA use in law enforcement expands? It would be logical to expect that popular sentiment would serve as a check against government abuse of the right to obtain and store DNA from suspects. Yet nearly every aspect of investigative DNA forensics can and does take place behind the scenes, with little public accountability. Investigators have collected samples surreptitiously from people under investigation. New law-enforcement technologies used to analyze those samples are almost always deployed without official comment. Retesting of old samples using new methods happens without prior notice or legal permission. Even government research to determine the effectiveness of DNA methods is shielded from true, scientific peer review. For example, when a list of more than 40 prominent scientists and academics (disclosure: I was among them) published a letter in *Science* requesting controlled access to the national database to verify the accuracy of government claims about the statistics used to determine how rare certain DNA profiles are, FBI administrators simply refused. The FBI has also threatened to cut off access to states that allow defense attorneys to request to search a government database in an attempt to find the true perpetrator.

The issues that accompany the building of massive DNA databases are only exacerbated by an industry that stands to gain financially from the unchecked embrace of these methods by police and law-enforcement agencies. For-profit companies manufacture the kits used to collect DNA, the instruments required to test it and the software necessary to interpret the results. Private interests benefit every time a new mandatory collection law is passed or a different search technique is approved, especially arrestee laws that will very likely spur demand from every police precinct in the country. It is no coincidence that some of the most vocal proponents of DNA fingerprinting have been employees of lobbying firms promoting their clients' interests, many of whom were previously employed by government labs. For instance, Gordon Thomas Honeywell, a firm that represents Life Technologies, maintains a Web site on legislation aimed at "moving DNA programs forward," and one of the most popular training conferences for law-enforcement analysts is sponsored by Promega, a private technology corporation involved with DNA testing.

NAME, ADDRESS, CHEEK SWAB

STEADY EXPANSION of forensic DNA programs is unlikely to stop with the collection of genetic material from people suspected of crimes or with familial searches. Members of the military are already required to provide DNA samples, although surprisingly, most police officers are not. Soon DNA collection may be considered a reasonable request in exchange for any benefit for which accurate identity is important. Perhaps the government will one day demand a DNA sample from student-loan applicants, government employees, or Social Security or Medicare recipients. And perhaps one day testing will disclose information about more sensitive personal traits.

Some officials and policy analysts have proposed the creation of a population-wide database to which every person would simply contribute at birth. Victim advocates and law-enforcement officials note that a truly national database would go a long way toward solving and controlling crime. Even civil-rights advocates reluctantly note that despite the potential for invasion of privacy, putting everyone's DNA in the ring may be the only way to ensure fairness and accuracy in the use of forensic DNA.

In this age of Google and instant credit checking, of routine bag and body searches at airports, buildings and schools, it is easy to anticipate that our genetic code could soon become just one more piece of currency to trade for a safer society. Yet thin as the line may seem at times, the Constitution has always distinguished between what the government may ask you to do and what it may force you to do.

The Supreme Court has upheld the right of the police to ask you your name, but it has also found that the Constitution prohibits officers from arresting you if you refuse to tell them that information, absent a reasonable suspicion that you were engaged in criminal activity. A threshold has also been set for taking fingerprints: we do not have compulsory national fingerprint programs for crime control. A universal DNA database thus initially strikes legal scholars as patently unconstitutional. If everything short of a population-wide database is on the table, however, how can we best use this powerful forensic tool?

Officials in the U.K. recently answered that question by passing the Protection of Freedoms Act. That law demands the destruction of physical DNA samples taken from arrestees—rather than keeping them for a century, as had been the previous practice—and the purging of innocent persons from the database after a certain period. The U.S. would benefit from similar legislation as well as laws requiring that the efficacy of DNA databases in criminal investigations be evaluated and that rules be put in place to curtail the uses to which biological material collected by law-enforcement officials can be put.

In addition, the government should forbid familial searches that risk casting suspicion on innocent people who have done nothing wrong but are simply related to a criminal offender. At the same time, it should allow access to DNA databases by individuals who are qualified to assess whether the government is abusing this enormous compilation of data. Defense lawyers, too, should be able to search a government database to establish the innocence of a client, as should neutral experts in statistics and population genetics who can check the accuracy of the databases. Laws are also needed to unambiguously clarify which kinds of genetic typing will and will not be allowed—detection of a suspect's physical or personal traits, for instance, might be deemed unacceptable to a society that values civil liberties.

Finally, I would stick to the Constitution's original commitment to freedom from government intrusion into the lives of innocent people by forbidding the indiscriminate taking of DNA samples from anyone arrested. I suggest this step not only out of concern for individual rights but also from a desire to preserve community safety. The tremendous energy directed toward collecting and storing the DNA of arrestees should instead go toward filling an enormous deficit of crime-scene investigators and lab technicians. Emphasis should be on increasing the rate of collection of evidence because as few as 10 to 20 percent of crime scenes for most serious offenses are examined for evidence.

Before the government devotes still more funding to expand its repository of citizen DNA, it should be required to report to the public in detail about the successes achieved so far. We have amassed millions of gene profiles, but no one can say how many arrests have resulted from collecting this information, much less how many convictions or for what offenses. Are these infractions for second-degree murder or merely for marijuana busts? Before we expend more resources and compromise personal liberty still further, we need a concrete accounting—not just anecdotal case reports—of how much the vast investment in DNA collection and recording has already cost taxpayers and society as a whole. SA

MORE TO EXPLORE

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SCIENTIFIC AMERICAN ONLINE
Listen to an audio recording of a conference on familial searching at ScientificAmerican.com/mar2013/dna-sampling

A bottlenose named Winter lost her tail to a crab trap. So scientists built her a new one

By Emily Anthes

BIOENGINEERING

A DOLPHIN'S TALE

IN DECEMBER 2005, WHEN WINTER THE BOTTLENOSE DOLPHIN WAS JUST A FEW MONTHS OLD, SHE WAS swimming with her mother in Mosquito Lagoon, along central Florida's Atlantic coast. Somehow she got herself tangled in a crab trap. An eagle-eyed fisherman spotted her struggling and called in a wildlife rescue team. The volunteers gently positioned the dolphin on a stretcher, carried her out of the water and drove her across the state to the Clearwater Marine Aquarium.

She was in bad shape when she arrived—exhausted, dehydrated, and sporting numerous cuts and abrasions. She could barely swim, and trainers stood in the tank with her, holding her little body up in the water. No one knew whether she would make it through the night. But she was a survivor, enduring that first night and the next one, too.

Adapted from Frankenstein's Cat: Cuddling Up to Biotech's Brave New Beasts, *by Emily Anthes, by arrangement with Scientific American/ Farrar, Straus and Giroux, LLC (North America), Oneworld (UK/Aus).*

Slowly, with bottle-feeding and round-the-clock care, the team nursed the calf back to health. As Winter began to stabilize, though, other problems emerged. A line from the crab trap had been wrapped so tightly around her tail that it had cut off the circulation. The tissue was necrotic: the dolphin's skin started peeling off, and the tail itself began to decay. One day Winter's caretakers found two of her vertebrae at the bottom of her pool. Winter was getting her strength back, but her tail was clearly a goner.

Although she didn't know it, in one way, Winter was lucky—she was born in the 21st

century, and there has never been a better time for an animal to lose a body part. Materials ranging from carbon-fiber composites to flexible, shape-shifting plastics are making it possible for us to design artificial appendages for patients that fly, trot or swim, and prosthetists have succeeded in creating a new beak for an eagle, a replacement shell for a turtle and a false foot for a kangaroo.

Whereas sensors and tags affixed to animals' bodies could help save entire species, by informing conservation strategies, artificial tails and paws represent the other end of the spectrum: a way to provide a (sometimes literal) leg up to unlucky individuals. Prosthetic devices are not appropriate for every animal—indeed, one of the challenges prosthetists face is determining what is in the best interest of bodies that look nothing like our own—but when we get it right, our custom-designed and individually engineered devices are helping us aid animals one life and limb at a time.

STUMPED

THE CLEARWATER MARINE AQUARIUM is located on an island just off Florida's Gulf coast. A few stairs lead from the main lobby to an open-air deck, where two dolphins frolic in a large tank. It is easy to pick out Winter—instead of a long full tail, she has a little curled stump that hangs off her torso like a comma.

Even with her abbreviated tail, Winter looks at home in the water, gliding and playing just like her fellow cetaceans. She has adapted to her unique body by adopting some unusual swimming techniques. Dolphins typically use their pectoral fins for balance, but Winter "cheats" and uses hers as little oars. And without the pair of flukes that typically adorn the end of a dolphin's tail, Winter lacks a dolphin's normal system of propulsion. So she taught herself to swim like a fish, moving her body from side to side, rather than up and down, as dolphins normally do. Unfortunately, this fishlike swimming posture puts unusual pressure on Winter's spine, causing it to curve unnaturally.

In the months after the dolphin's rescue, her caretakers began to worry that her strange method of swimming would cause permanent injury. In September 2006 an aquarium official mentioned this concern in an interview with National Public Radio, which was airing a segment about Winter. A prosthetist named Kevin Carroll happened to hear the broadcast while driving to his Orlando office. As he listened to Winter's saga, he thought: "I could put a tail on that dolphin."

Carroll grew up near a hospital in a small Irish town, where seeing the ailing and injured children come and go inspired an interest in fixing the human body. Today Carroll is vice president of Hanger, based in Austin, Tex., and one of the world's leading prosthetists. Every once in a while, someone will walk into his clinic with a three-legged dog or a beakless bird and ask for his help. As an animal lover, Carroll finds himself unable to resist donating his weekends to the cause. Over the years he has

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worked with his Hanger colleagues to make prostheses for a veritable menagerie of animals: dogs, ducks, sea turtles, "whatever comes our way," he says. "I've sort of become the Doctor Dolittle of prosthetics."

When the aquarium agreed to let Carroll take a crack at a prosthetic dolphin tail, he began recruiting his team. He knew whom he wanted for a partner: Dan Strzempka, a prosthetist in Hanger's Sarasota, Fla., office. Strzempka, who has worn a prosthetic leg since he was run over by a lawn mower at age four, is a Florida native with a passion for the ocean and its creatures.

Carroll and Strzempka have agreed to meet me at the aquarium and walk me through how they tackled the task. They are an odd pair: Carroll is slight and cue-ball bald, with a white beard; Strzempka is tall, tanned and solidly built. When we get to the dolphin tank, Strzempka leans up against the railing and calls to Winter: "Hey, girl! What's up, buddy?" "Good marnin'!" Carroll shouts out to her in his Irish brogue.

Over the past five years the men have spent countless hours standing here beside this tank. Winter was unlike any other patient they had treated before, so the first task was understanding her body. Carroll and Strzempka began a crash course in dolphins, reading up on their anatomy and physiology and watching slow-motion videos of swimming cetaceans to understand their biomechanics. Although animal prosthetists can draw on human medicine, success often requires a degree of ingenuity; knowing how to build a leg for a human amputee won't get you far if you want to replace an elephant's missing foot or outfit a dog with a faux paw. So prosthetists often MacGyver each animal appendage, custom-designing and individually engineering it.

In Winter's case, the basic plan seemed easy enough—Carroll and Strzempka decided to create a plastic tail that would slip over what remained of Winter's peduncle, the muscular back half of a dolphin's body that normally runs from the dorsal fin to the tail flukes. The challenge, they realized, would be figuring out how to keep the prosthesis on. Winter would be putting an incredible amount of force on the tail while swimming, but she would not be pressing the entire weight of her body into it, as a human does with a prosthetic leg. "Water," Strzempka reminds me, "is a totally different environment." What is more, dolphin skin is slippery, sensitive and delicate—and very easily injured.

Human amputees commonly use soft liners to cushion their stumps and shield their skin, and Carroll and Strzempka decided

IN BRIEF

A bottlenose dolphin named Winter lost her tail after getting tangled up in a crab trap. She was forced to swim from side to side like a fish, which warped her spine.

Two prosthetists decided to build Winter a whole new tail, something that had never been done before. In the process, they invented a new kind of gel.

Today Winter's false tail is helping to straighten her spine, and "dolphin gel" cushioning has proved useful for human athletes who have lost limbs.

PRECEDING PAGE: COURTESY OF HANGER, INC.

that Winter would need something similar. The standard human liner would not do—for Winter, they would have to create a brand-new material, soft enough to protect her skin, sticky enough to stay put on a slick surface, and strong enough to withstand daily use and abuse in a tank full of saltwater.

They enlisted the help of a chemical engineer, who tinkered with the recipe for a gel liner common in human prosthetics, trying to create a version more suitable for a dolphin. The first few prototypes he made were promising, but their performance was inconsistent, and there were several dramatic failures, including a fire that burned a warehouse to the ground. ("It was a small warehouse," Strzempka assures me.) Finally, the engineer nailed it.

"It's incredible material," Carroll says, as we sit inside the trainers' office at the aquarium. He hands me a sheath of the rubbery gel, which is white, jiggly and slightly gummy to the touch. It resembles nothing so much as a supersized piece of calamari. Technically, the material is a thermoplastic elastomer—a mixture of plastics that begins as a liquid and can be molded into a variety of shapes when heated—but everyone just calls it the "dolphin gel." Eager to show off its properties, Carroll takes a two-foot strip of the gel and hands the other end to Strzempka. He starts walking backward. Two, five, 10 feet—the material just keeps stretching. Finally, Carroll lets go. His end whips back across the room. Strzempka holds up the gel; it looks as good as new, neither distended nor deformed. The men beam, and I get the sense that this is a well-rehearsed stunt. The gel also provides serious cushioning, which Carroll demonstrates by wrapping his hand in the liner and beating it furiously with a heavy mallet, before breaking into a grin and pulling out his unharmed hand.

KEEP SWIMMING

WINTER IS AN OLD PRO now, happily wearing a full-size, anatomically correct prosthetic tail. To put the device on, a trainer balances on a platform suspended in Winter's tank. With one swift command, Winter gets into position, pointing her head down toward the bottom of the pool and sticking her peduncle up out of the surface of the water. A trainer rolls a sleeve made of the dolphin gel onto Winter's stump. Then comes the prosthesis itself, which Carroll and Strzempka carefully constructed after taking a series of three-dimensional images and scans of Winter's body. The prosthesis has a flexible, rubberized plastic "socket" that slips on over the gel liner, hugging what remains of the dolphin's peduncle. The socket tapers into a thin carbon-fiber strip, which is bolted onto a pair of fake flukes. Suction keeps the entire apparatus on.

Although the device is modeled on a dolphin's natural tail, it is made of all sorts of unnatural materials, and Winter has to be supervised while she is wearing it. Winter's caretakers need to make sure that the tail does not suddenly start to slip off, for instance, or catch on something in the pool. So Winter does not wear the tail all the time. Instead it is reserved for her daily therapy sessions, when trainers lead the prosthesis-wearing dolphin through a series of drills designed to build up her muscles and reinforce proper swimming posture. The artificial tail helps keep Winter's spine in proper alignment, and with it on Winter does, indeed, flick her tail up and down rather than from side to side. "It's just beautiful to see her swim with it," Carroll says. Winter's scoliosis has improved since she started wearing the device, and Carroll hopes the prosthesis, combined with regular therapy, will help the dolphin lead a long, healthy life.

Despite the progress she has made, Winter will spend the rest of that life in an aquarium; a dolphin without a tail, or with a human-fashioned one, is not a great candidate for survival in the wild. There is no telling how her prosthesis would hold up to years of constant use. And Winter will need continuing access to trainers to reinforce proper swimming posture and doctors to monitor her spinal alignment. Carroll and Strzempka are still making several new tails a year for Winter, who has not yet reached her full adult size, tweaking the design as her body changes. They also dream of making more dramatic improvements to the prosthesis. Strzempka would love to figure out how to incorporate a vacuum device that pumps air out of the tail whenever Winter moves it up and down. The result would be an even tighter seal and a self-adjusting prosthesis.

Winter has become an ambassador for prostheses.

Winter's tail has earned her celebrity status. There are books, video games and documentaries about her, and in 2011 Warner Brothers released *Dolphin Tale,* a 3-D movie based on her story. (The prosthetist, or "mad scientist character," as Carroll calls him, is portrayed by Morgan Freeman.) The aquarium's Web site and gift shop are chockablock with Winter gear: T-shirts, postcards, magnets and toy dolphins that are also missing their tails.

But Winter has become much more than a powerful marketing tool—she has also become an ambassador for prostheses. Children with prosthetic arms and legs regularly visit the aquarium, and many are invited into the tank with Winter. The encounter can do wonders for a kid's psyche, Carroll tells me.

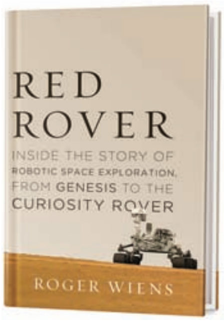
Winter has helped human amputees in more concrete ways, too. As word spread about the so-called dolphin gel, prosthetists began ordering it for their human patients. The material, which grips the skin better than the liners commonly used with people, has proved especially useful for amputee athletes, whose replacement limbs start to slide off when they sweat. Strzempka, an avid golfer, became a convert the first time he tried the gel in his own artificial leg. "The stickiness is a huge benefit, especially in Florida," he says. "If you're golfing 36 holes a day, your skin becomes like a dolphin's—slippery." It did not take long for Hanger to start selling "WintersGel" liners to everyone from seasoned triathletes to 11-year-old girls. "Animals give back to us all so much," Carroll says. "We learn so much from working with them." SA

MORE TO EXPLORE

Winter's Tale: A Dolphin in Distress. John Barry in *Tampa Bay Times,* December 7, 2008. www.tampabay.com/features/humaninterest/article927462.ece

Winter: The Dolphin That Could! A documentary produced and directed by David Yates and Steve Brown. On DVD. Clearwater Marine Aquarium, 2010.

SCIENTIFIC AMERICAN ONLINE
To read about other animals for whom researchers have designed and built unique prostheses, visit **ScientificAmerican.com/mar2013/animal-prostheses**



Red Rover: Inside the Story of Robotic Space Exploration, from Genesis to the Curiosity Rover

by Roger Wiens. Basic Books, 2013 ($25.99)

The principal investigator for the ChemCam—the Curiosity rover's rock-vaporizing laser—recounts his experiences working at the frontier of space exploration. Tight deadlines and budget constraints pushed mission teams to exercise their creativity and find D.I.Y.-style solutions to problems that threatened to halt projects. Wiens offers a backstage tour of the delights and disappointments of working on missions—including the Genesis mission to collect solar-wind particles, which wound up crash-landing in the Utah desert.

—Marissa Fessenden

The Bonobo and the Atheist: In Search of Humanism among the Primates

by Frans de Waal. W. W. Norton, 2013 ($27.95)

Building on his 2009 book *The Age of Empathy,* primatologist de Waal argues that human morality comes not from religion but from our animal ancestors—that it is not "top-down" but "bottom-up." For evidence, he looks to chimpanzees, which adopt others' children, amend broken relationships and comfort one another in times of stress. He makes the case that humans, like other social primates, are essentially good (though capable of evil) and motivated by the survival benefits of living within a group.

> *"Morality is not as much of a human innovation as we like to think."*
> —Frans de Waal

Storm Kings: The Untold History of America's First Tornado Chasers

by Lee Sandlin. Pantheon Books, 2013 ($26.95)

The geography of North America's Great Plains is ideally suited to the strange storm phenomenon of tornadoes. Collisions between masses of wet, warm air from the Gulf of Mexico and cool, dry air from Canada and the Rockies over the wide-open space create the kind of intense thunderstorms that lead to twisters, which early eyewitnesses dubbed "Storm Kings."

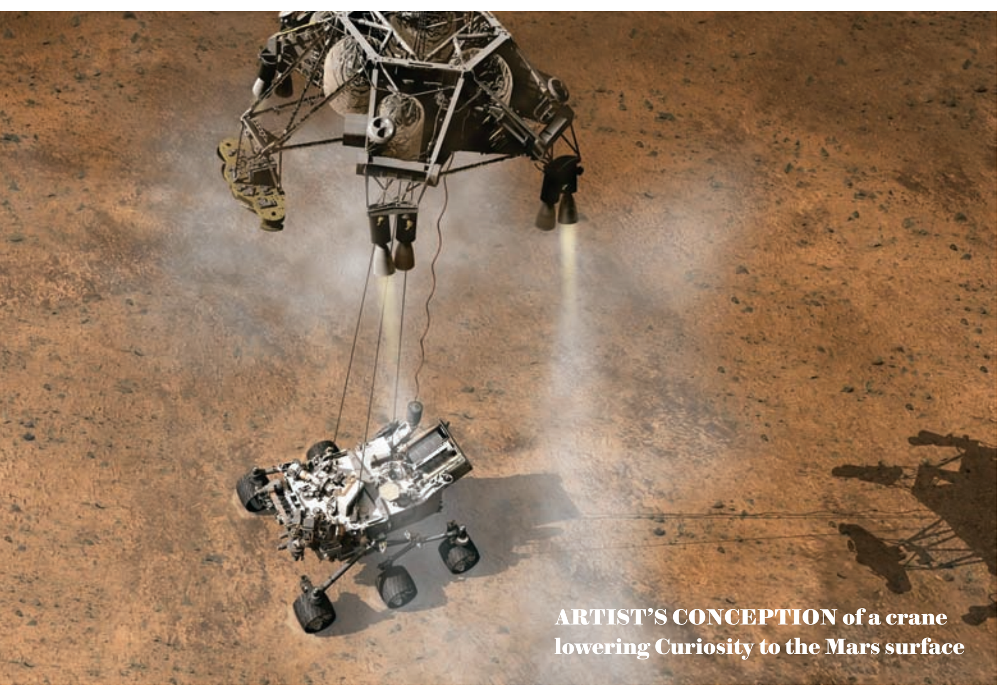
Sandlin's history of tornadoes in America includes lively debates about storm science in the mid-1800s between America's first meteorologist, James Espy, and his contemporaries, as well as the first successful twister forecast in 1948 by meteorologists at the Tinker Air Force Base in Oklahoma City.

—Marissa Fessenden

To Save Everything Click Here: The Folly of Technological Solutionism

by Evgeny Morozov. PublicAffairs, 2013 ($28.99)

In his first book, *The Net Delusion,* published in 2011, Morozov showed how social media could be harnessed by authoritarian dictators just as effectively as freedom fighters. Here he turns his acerbic pen to the seductive hopes of the Silicon Valley do-gooders—those who claim that clever digital technologies will solve systemic problems of politics, policing and personal behavior. In doing so, he explains why this techno-solutionism, far from offering a pain-free way of improving lives, may leave us culturally impoverished instead. *—Michael Moyer*



ARTIST'S CONCEPTION of a crane lowering Curiosity to the Mars surface

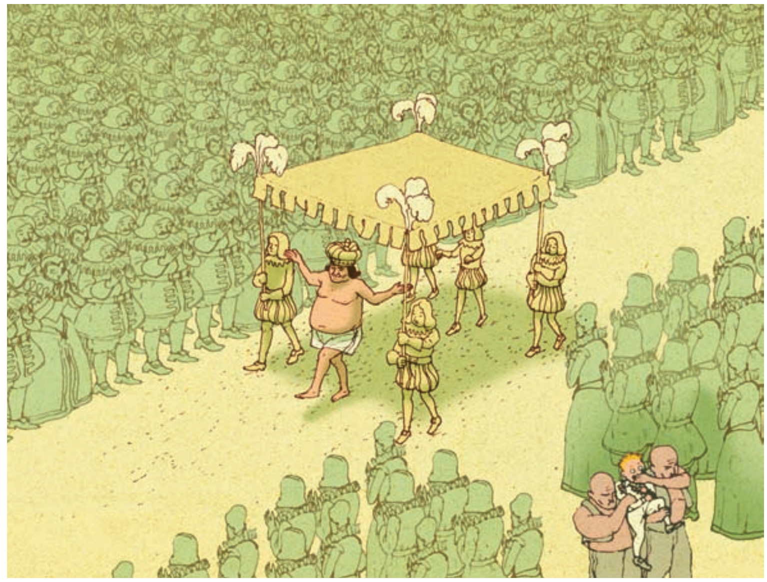
COURTESY OF NASA/JPL-CALTECH

SCIENTIFIC AMERICAN ONLINE
For more recommendations, go to ScientificAmerican.com/mar2013/recommended

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

Dictators and Diehards

Pluralistic ignorance and the last best hope on earth



In Tyler Hamilton's 2012 book *The Secret Race* (written with Daniel Coyle), the cyclist exposes the most sophisticated doping program in the history of sports, orchestrated by Lance Armstrong, the seven-time Tour de France winner now stripped of his titles after a thorough investigation by the U.S. Anti-Doping Agency. Hamilton shows how such an elaborate system was maintained through the "omertà rule"—the code of silence that leads one to believe everyone else believes doping is the norm—and reinforced by the threat of punishment for speaking out or not complying.

The broader psychological principle at work here is "pluralistic ignorance," in which individual members of a group do not believe something but mistakenly believe everyone else in the group believes it. When no one speaks up, it produces a "spiral of silence" that can lead to everything from binge drinking and hooking up to witch hunts and deadly ideologies. A 1998 study by Christine M. Schroeder and Deborah A. Prentice, for example, found that "the majority of students believe that their peers are uniformly more comfortable with campus alcohol practices than they are." Another study in 1993 by Prentice and Dale T. Miller found a gender difference in drinking attitudes in which "male students shifted their attitudes over time in the direction of what they mistakenly believed to be the norm, whereas female students showed no such attitude change." Women, however, were not immune to pluralistic ignorance when it came to hooking up, as shown in a 2003 study by Tracy A. Lambert and her colleagues, who found "both women and men rated their peers as being more comfortable engaging in these behaviors than they rated themselves."

When you add an element of punishment for those who challenge the norm, pluralistic ignorance can transmogrify into purges, pogroms and repressive political regimes. European witch hunts, like their Soviet counterparts centuries later, degenerated into preemptive accusations of guilt, lest one be thought guilty first. Aleksandr Solzhenitsyn described a party conference in which Joseph Stalin was given a standing ovation that went on for 11 minutes, until a factory director finally sat down to the relief of everyone. The man was arrested later that night and sent to the gulag for a decade. A 2009 study by Michael Macy and his colleagues confirmed the effect: "People enforce unpopular norms to show that they have complied out of genuine conviction and not because of social pressure."

Bigotry is ripe for the effects of pluralistic ignorance, as evidenced in a 1975 study by Hubert J. O'Gorman, which indicated that "in 1968 most white American adults grossly exaggerated the support among other whites for racial segregation," especially among those leading segregated lives, which reinforces the spiral of silence.

Fortunately, there is a way to break this spiral of ignorance: knowledge and communication. Tyler's confession led to the admission of doping by others, thereby breaking the code of silence and leading to openness about cleaning up the sport. In the Schroeder and Prentice study on college binge drinking, they found that exposing incoming freshmen to a peer-directed discussion that included an explanation of pluralistic ignorance and its effects significantly reduced subsequent student alcoholic intake. Moreover, Macy and his colleagues found that when skeptics were scattered among true believers in a computer simulation of a society in which there was ample opportunity for interaction and communication, social connectedness acted as a prophylactic against unpopular norms taking over.

This is why totalitarian and theocratic regimes restrict speech, press, trade and travel and why the route to breaking the bonds of such repressive governments and ideologies is the spread of liberal democracy and open borders. This is why even here in the U.S.—the land of the free—we must openly endorse the rights of gays and atheists to be treated equally under the law and why "coming out" helps to break the spiral of silence. Knowledge and communication, especially when generated by science and technology, offer our last best hope on earth. SA

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Illustration by Izhar Cohen

Steve Mirsky started writing the Anti Gravity column the year after the low-flow flush law went into effect for new toilets in homes. He also hosts the *Scientific American* podcast Science Talk.

Getting to the Bottom

An analysis of old customs makes us privy to a slice of ancient life

The last time I visited Boston's Museum of Fine Arts was in 2004 to see a Rembrandt exhibition. But I might have wandered away from the works of the Dutch master in search of an ancient Greek artifact, had I known at the time that the object in question, a wine vessel, was in the museum's collection. According to the 2012 Christmas issue of the *BMJ* (preacronymically known as the *British Medical Journal*), the 2,500-year-old cup, created by one of the anonymous artisans who helped to shape Western culture, is adorned with the image of a man wiping his butt.

That revelation appears in an article entitled "Toilet Hygiene in the Classical Era," by French anthropologist and forensic medicine researcher Philippe Charlier and his colleagues. Their report examines tidying techniques used way back—and the resultant medical issues. Such a study is in keeping with the *BMJ*'s tradition of offbeat subject matter for its late December issue—as noted in this space five years ago: "Had the Puritans never left Britain for New England, they might later have fled the *British Medical Journal* to found the *New England Journal of Medicine*."

The toilet hygiene piece reminds us that practices considered routine in one place or time may be unknown elsewhere or elsetime. The first known reference to toilet paper in the West does not appear until the 16th century, when satirist François Rabelais mentions that it doesn't work particularly well at its assigned task. Of course, the ready availability of paper of any kind is a relatively recent development. And so, the study's authors say, "anal cleaning can be carried out in various ways according to local customs and climate, including with water (using a bidet, for example), leaves, grass, stones, corn cobs, animal furs, sticks, snow, seashells, and, lastly, hands." Sure, aesthetic sensibility insists on hands being the choice of last resort, but reason marks seashells as the choice to pull up the rear. "Squeezably soft" is the last thing to come to mind about, say, razor clams.

Charlier et al. cite no less an authority than philosopher Seneca to inform us that "during the Greco-Roman period, a sponge fixed to a stick (*tersorium*) was used to clean the buttocks after defecation; the sponge was then replaced in a bucket filled with salt water or vinegar water." Talk about your low-flow toilets. The authors go on to note the use of rounded "fragments of ceramic known as 'pessoi' (meaning pebbles), a term also used to denote an ancient board game." (The relieved man on the Museum of Fine Arts's wine cup is using a singular pessos for his finishing touches.) The ancient Greek game pessoi is not related to the ancient Asian game Go, despite how semantically satisfying it would be if one used stones from Go after one Went.

According to the *BMJ* piece, a Greek axiom about frugality cites the use of pessoi and their purpose: "Three stones are enough to wipe." The modern equivalent is probably the purposefully self-contradictory "toilet paper doesn't grow on trees."

Some pessoi may have originated as ostraca, pieces of broken ceramic on which the Greeks of old inscribed the names of enemies. The ostraca were used to vote for some pain-in-the-well-you-know to be thrown out of town—hence, "ostracized." The creative employment of ostraca as pessoi allowed for "literally putting faecal matter on the name of hated individuals," Charlier and company suggest. Ostraca have been found bearing the name of Socrates, which is not surprising considering they hemlocked him up and threw away the key. (Technically, he hemlocked himself, but we could spend hours in Socratic debate about who took ultimate responsibility.)

Putting shards of a hard substance, however polished, in one's delicate places has some obvious medical risks. "The abrasive characteristics of ceramic," the authors write, "suggest that long term use of pessoi could have resulted in local irritation, skin or mucosal damage, or complications of external haemorrhoids."

To quote Shakespeare, "There's a divinity that shapes our ends." Sadly, for millennia the materials used to clean our divinely shaped ends were decidedly rough-hewn. SA

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Illustration by Matt Collins

50, 100 & 150 Years Ago

compiled by Daniel C. Schlenoff

Innovation and discovery as chronicled in *Scientific American*

March 1963

Anxious Times

"Ours is said to be the age of anxiety. But what exactly is anxiety and how can it be measured? Sigmund Freud wrote much about anxiety but was content to fall back largely on introspection and semantics for its definition. He pointed to the solid distinction in his native language between Furcht (fear) and Angst (anxiety), and most psychologists have followed him in considering anxiety to be quite different from fear. Theorists from one U.S. school of learning would have us consider anxiety as being the main drive to action. Almost in polar opposition to this view of anxiety as the effective mover is the clinical view expressed by Frank M. Berger (who discovered the chemical that led to the tranquilizer meprobamate) that anxiety is a disorganizer of effective action. Related to this disorganization concept is the psychoanalytic view that anxiety is the central problem in neurosis. In looser thinking this often degenerates into the notion that anxiety and neurosis are synonymous, with the result that people with a high anxiety level are treated as neurotics. —Raymond B. Cattell"

March 1913

Heike Kamerlingh Onnes

"Lowering of resistance by extremely low temperatures in recently reported experiments of a Dutch investigator have gone far to confirm the theory that the electrical resistance of all conductors would be reduced to zero by cooling the conductors to the absolute zero of temperature. By boiling liquid helium in a partial vacuum a temperature of only three degrees above the absolute zero was attained. At this temperature the resistance of mercury was found to be only one ten millionth as great as at zero Centigrade."

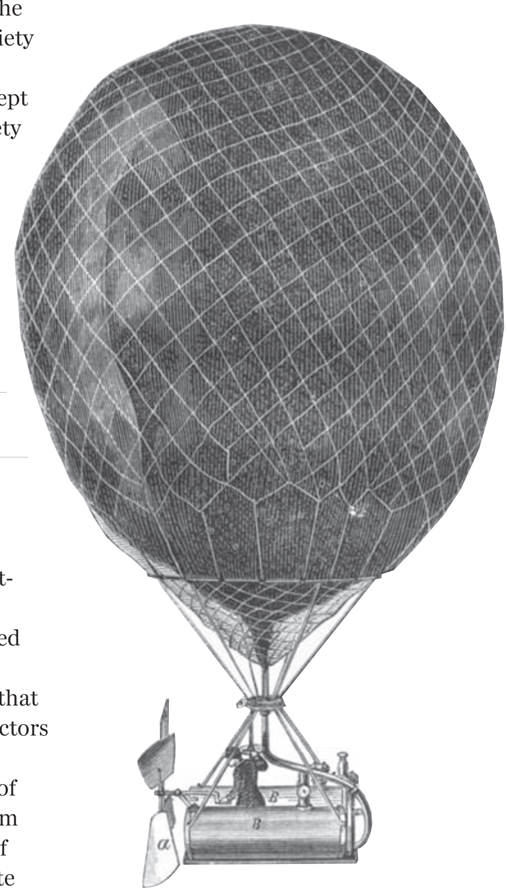
Police and Thieves

"It is reported that a Washington city policeman profiting by his experience in connection with stolen automobiles, has invented a lock for automobiles for application in the ignition circuit in such manner as to form a part of such circuit. The improved device is said to comprise a rotary electrical switch with which is combined a mechanical locking device. The insertion of any key other than the proper one will not permit the operation of the lock."

March 1863

Steerable Balloon

"The only practical benefits yet derived from balloons have been those from



FLIGHT TESTING: A more useful aerostat (at least in theory), 1863

SCIENTIFIC AMERICAN, VOL. VIII, NO. 13; MARCH 28, 1863 experiments which the Government has instituted in military operations for observing the position of the enemy. Mr. Thomas L. Shaw, of Nebraska Territory, has been engaged in making experiments with serial machines, and thinks he has discovered a method by which he can control the direction of the balloon and move wheresoever he listeth [wants]. Our engraving represents his device. There is a fan or propeller at the stern of the balloon, which is to be worked by the aeronaut."

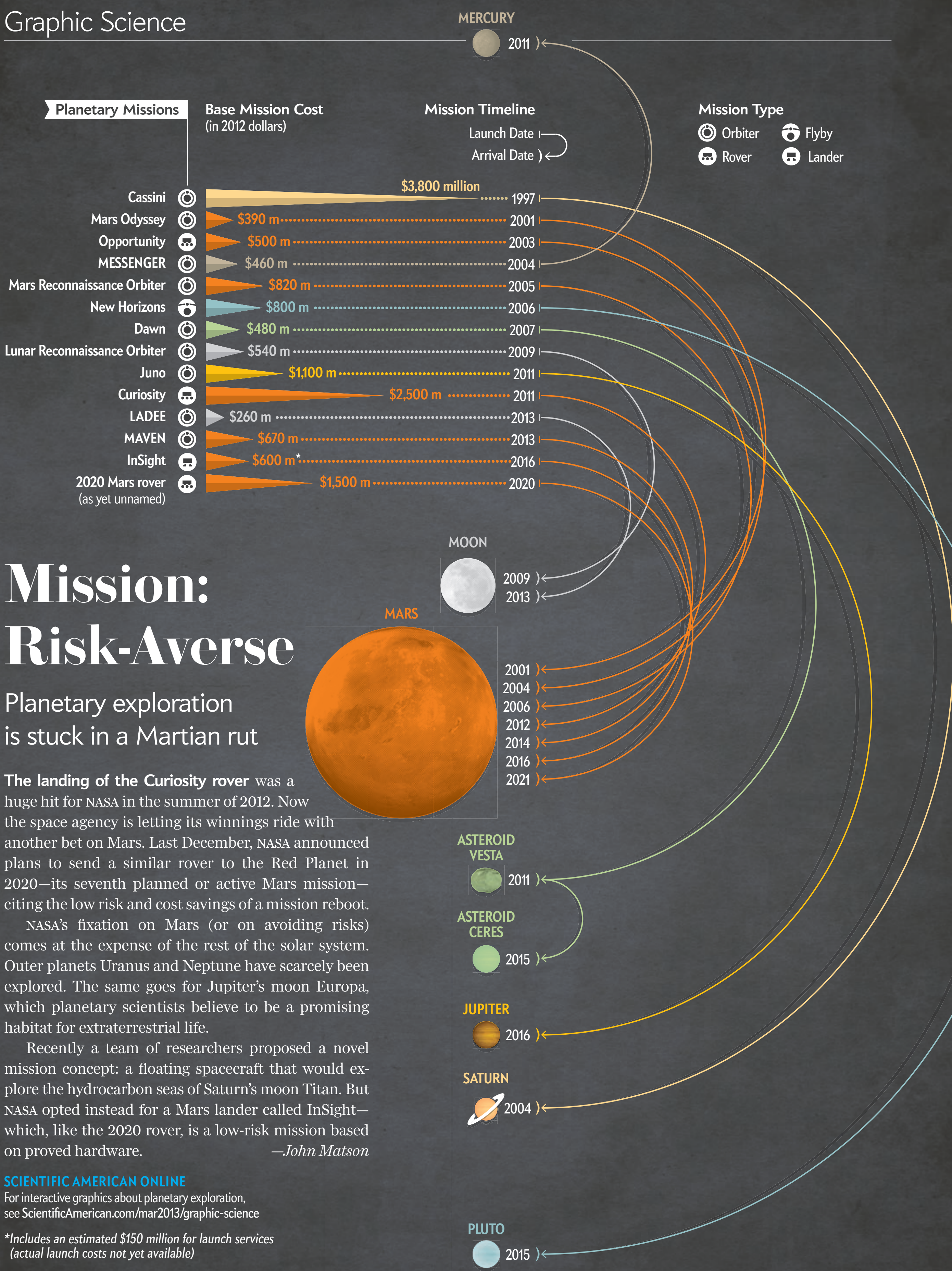
*For a slide show on inventors and warfare in 1863, see **www.ScientificAmerican.com/mar2013/weapons***

Egyptian Astronomy

"The purpose for which the colossal pyramids of Egypt were erected has always been a subject of dispute among archaeologists. Were they tombs of kings, or observatories, or sun-dials? Were they erected as barriers against the sands of the desert, or were they mere granaries? Mahmoud Bey, astronomer to the Viceroy of Egypt, now explains the matter in a novel manner. In his opinion, founded on personal observation, the pyramids were devoted to a divinity having Sirius, the Dog-star, for its emblem. Among the ancient Egyptians the stars were the souls of innumerable divinities emanating from Ammon Ra, the Supreme Being. Sirius represented the dog-of-the-heavens, Sothis, who judged the dead, so that it was perfectly rational to devote the pyramids, considered as tombs, to the star Sirius."

The Working Stiff

"The hours of labor exacted by some of the Brooklyn railroad companies are so many and the work is so severe that it is astonishing that men can perform the labor and live. The Brooklyn Central Railroad Company requires seventeen and a half hours of labor per day, and allows no time for procuring meals; the food necessary to sustain life being eaten in the cars. The compensation for conductors and drivers is $1.35 per day."



Mission: Risk-Averse

Planetary exploration is stuck in a Martian rut

The landing of the Curiosity rover was a huge hit for NASA in the summer of 2012. Now the space agency is letting its winnings ride with another bet on Mars. Last December, NASA announced plans to send a similar rover to the Red Planet in 2020—its seventh planned or active Mars mission—citing the low risk and cost savings of a mission reboot.

NASA's fixation on Mars (or on avoiding risks) comes at the expense of the rest of the solar system. Outer planets Uranus and Neptune have scarcely been explored. The same goes for Jupiter's moon Europa, which planetary scientists believe to be a promising habitat for extraterrestrial life.

Recently a team of researchers proposed a novel mission concept: a floating spacecraft that would explore the hydrocarbon seas of Saturn's moon Titan. But NASA opted instead for a Mars lander called InSight—which, like the 2020 rover, is a low-risk mission based on proved hardware. *—John Matson*

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For interactive graphics about planetary exploration, see ScientificAmerican.com/mar2013/graphic-science

**Includes an estimated $150 million for launch services (actual launch costs not yet available)*

Graphic by Section Design