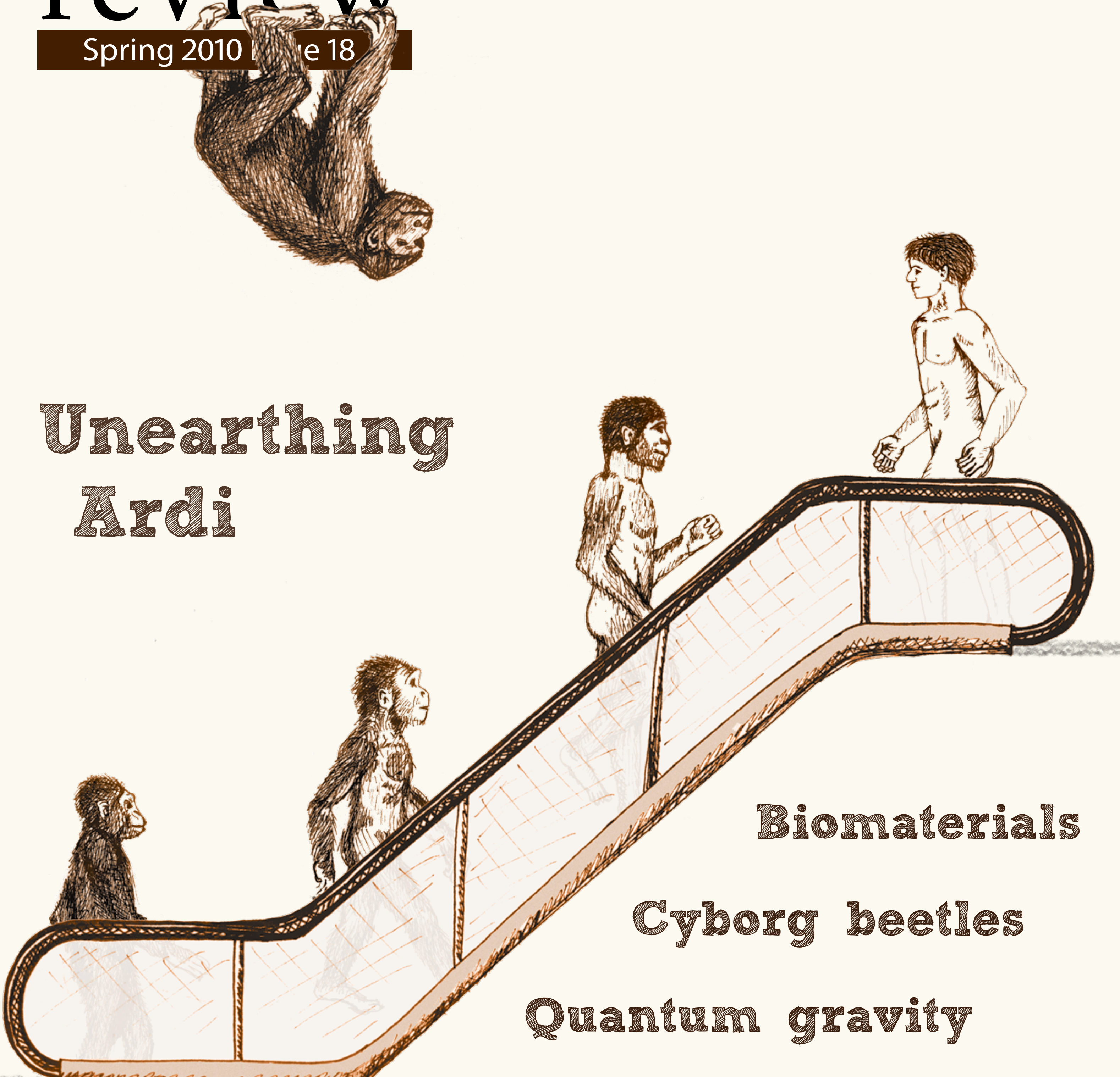
# BERKELEY science review

Spring 2010 Issue 18



## Unearthing Ardi

## Biomaterials

## Cyborg beetles

## Quantum gravity

*Molecular movies • An epic explosion • Art and the brain • Discovering planets • The Compass Project*

# BERKELEY science review



Dear Readers,

Welcome to the first issue of a new decade. While we can't foresee what the next ten years will bring, one thing is certain: UC Berkeley scientists are setting out with ambitious projects and high hopes for the future. In the physics department, particle theorists are on a quest for a "Theory of Everything:" one that reconciles the currently conflicting theories of gravity and quantum mechanics and reduces all of physics to one single, elegant idea— Phuongmai Truong takes you through it on page 32. Meanwhile, researchers in the astronomy department are trying to answer the age-old question "Are we alone?" by searching for Earth-like planets as part of NASA's Kepler mission—Linda Strubbe explains how on page 14. Could there be life on other planets? It might not take much: scientists at Lawrence Berkeley National Laboratory have discovered an organism that can survive all by itself without light, oxygen, or most nutrients (p. 13). And speaking of weird creatures and unfamiliar life forms, Michel Maharbiz and his colleagues in the electrical engineering department are developing remote controlled "cyborg beetles" as part of a DARPA-funded project—Sisi Chen surveys military involvement in insect research on page 35.

While some UC Berkeley scientists are pursuing ambitious futuristic ideas, others are delving deep into the past, yielding surprising new insights about our origins. In a project that has taken almost 20 years to reach completion, researchers have unearthed Ardi, our 4.4 million-year-old ancestor and the oldest hominid skeleton ever discovered. Among other things, Ardi calls into question the widely accepted idea that we evolved from chimpanzees—Rachel Bernstein has the full story on page 18. Further insights into evolution come from research in the integrative biology department—on page 12 Robert Gibboni explains how scientists can use fly genetics to learn about the mechanisms of evolution at the molecular level.

Besides designing the future and dissecting the past, UC Berkeley scientists are also spending their time making the present a better place. Reporting from the field on page 28, Richard Novak describes how a group of UC graduate students and San Francisco–based engineers traveled to the Amazon to teach kids about science. On a more local level, three physics graduate students have founded a program to help underrepresented students in the physical science navigate academic life—read about it on page 9. And in the bioengineering department, scientists are using their knowledge of biomaterials to develop new avenues for stem cell therapy (p. 24).

Putting together this issue of the *BSR* has been incredibly fun and rewarding. The magazine would not be possible without the dedication and enthusiasm of the student volunteers who write, edit, design, and illustrate its articles, and I'm very grateful to have worked with such a talented set of individuals. I would like to especially thank Rachel Bernstein for her continued support and Marek Jakubowski, together with his layout team, for making it all come together so beautifully.

Enjoy the issue,

Hania Köver

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**Cover:** UC Berkeley researchers unearth the oldest hominid skeleton to date, shedding new light on humanity's evolutionary past. Front and back cover drawing by Colleen Kirkhart for *BSR*; design by Marek Jakubowski.

Berkeley Science Review

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## Departments

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## Features

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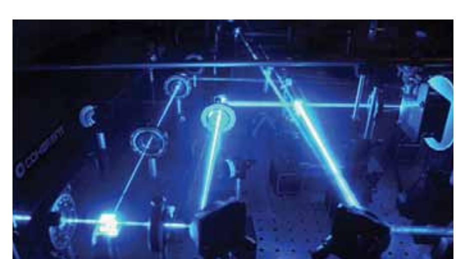
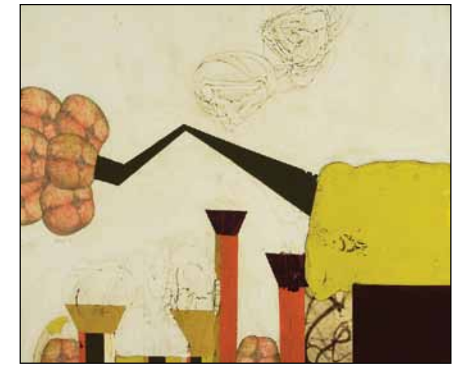
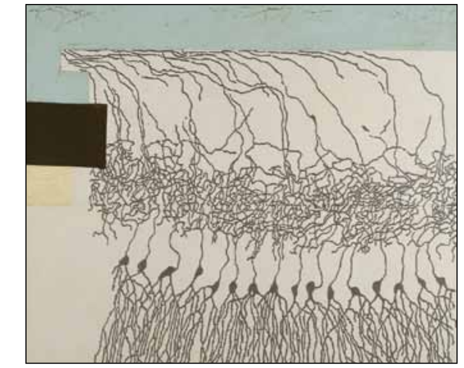


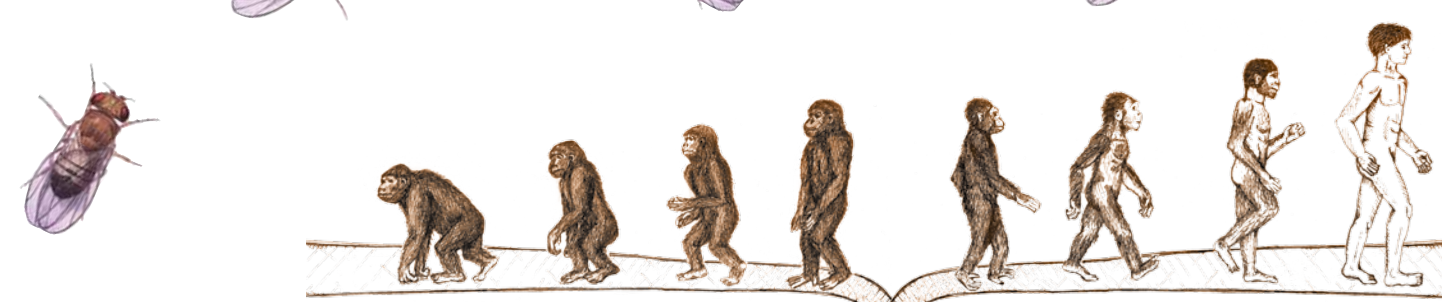






## Current Briefs



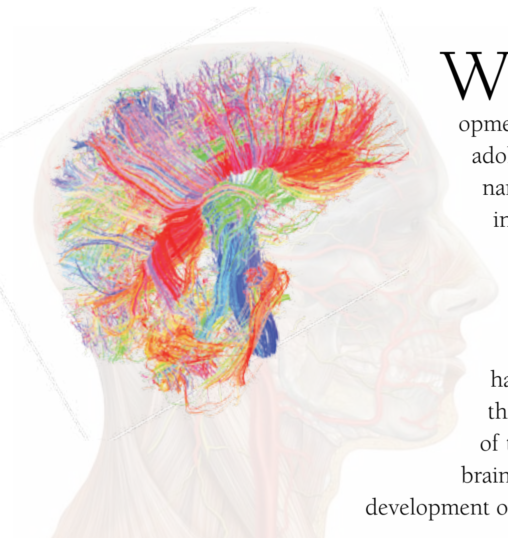


COUNTERCLOCKWISE FROM TOP LEFT: ARDI-TIM WHITE; BEE-JON SULLIVAN; SENSOR-NASA; LASER-ZHIGANG CHEN; FLIES-NASA; EVOLUTION-COLLEEN KIRKHART; BOY-RICHARD NOVAK; HEAD-PATRICK J. LYNCH / MRI-SUDHIR RAMANNA & DAVID FEINBERG; ART-KATHERINE SHERWOOD

# labscopes

LABSCOPES

## In the blink of an MRI



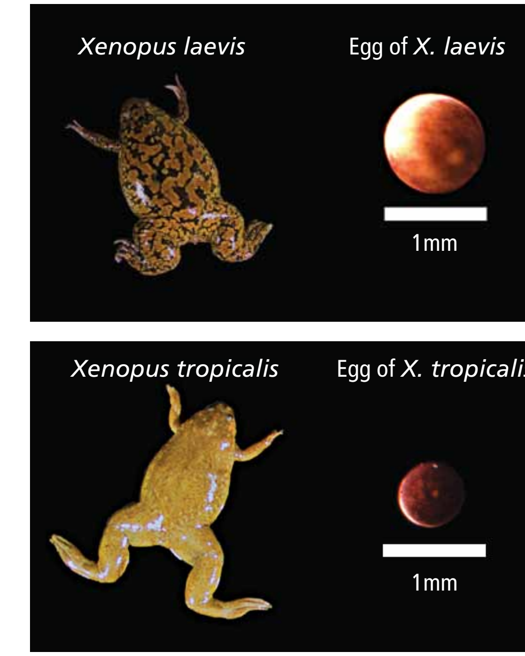
Why can't kids just do as they're told? Many a hapless parent will testify that not following directions is a simple case of naughtiness. The answer, however, may lie in the development of fiber tracts in the brain, which mature slowly over the course of childhood and adolescence and connect areas involved in goal-directed behavior. Diffusion Magnetic Resonance Imaging (Diffusion MRI) allows fiber tracts to be visualized by measuring differences in water molecule diffusion rates in the brain. Until recently, this technique wasn't easily applicable to children because subjects were required to remain still for long scan times. "Try telling an eight-year-old to stay perfectly still for 45 minutes," says Kirstie Whitaker, a neuroscience graduate student studying cognitive development in children. Now, David Feinberg, adjunct professor at the Helen Wills Neuroscience Institute at UC Berkeley, has invented a Diffusion MRI technique that cuts the time it takes to perform a scan by two thirds. This remarkable improvement utilizes signals detected from different cross-sections of the brain at the same time, speeding up the process of obtaining a picture of the whole brain. Through detailed snap-shots of a child's brain we can now begin to understand the development of fiber tracts—and how it relates to both good and "naughty" behavior.

—Gary Clark

## Size matters

Size varies widely between species—from arm span to brain size to the length of our intestines, all the way down to the size of individual cells and nuclei. Professor Rebecca Heald in the Department of Molecular and Cell Biology is interested in studying the molecular mechanisms underlying size scaling in our cells. "It's a fundamental question in biology," says Heald, and despite its apparent simplicity very little is known on the subject. In a recent experiment, her lab transferred DNA from the large frog *Xenopus laevis* into cytoplasmic extracts from its smaller relative, *Xenopus tropicalis*. Surprisingly, they found that the *X. tropicalis* extracts now produced smaller mitotic spindles and nuclei than their *X. laevis* brethren—despite their shared genetic source. Mixing cytoplasmic extracts from both species produced intermediate-sized intracellular compartments, suggesting that cytoplasmic factors present in the extracts, rather than DNA or other nuclear factors, regulate cell scaling. Heald hopes that learning more about the processes underlying size regulation will improve our understanding of cancer pathology, which often leads to dramatic changes in cell scale. Try that on for size.

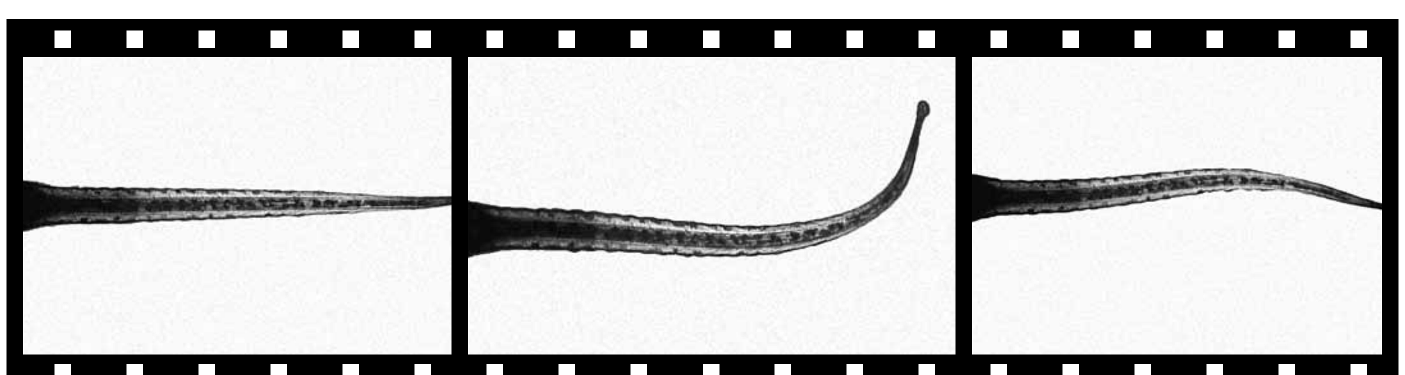
—Azeen Ghorayshi




## Lights on locomotion

Neuroscientists have been trying to understand how neurons affect behavior for decades, but until recently it was difficult to tease apart the roles of individual cells. A new technique developed at UC Berkeley now allows specially engineered light-sensitive channels to be genetically expressed in specific types of neurons. Shining light on these channels causes the neurons to be activated, permitting direct investigation of how activity in a single type of neuron affects behavior. Zebrafish are particularly well suited for these optical techniques because their transparency allows for the activation of the neurons in question by simply shining light on freely moving animals. By expressing light-activated channels in the enigmatic Kolmer-Agduhr cells of the zebrafish spinal cord, Claire Wyart, a postdoctoral fellow in the Isacoff Lab at UC Berkeley, showed that activity in this neuron type initiates spontaneous swimming in young zebrafish. "The classical method [electrical stimulation] cannot target a single cell type," says Wyart. "Activating these neurons and only these neurons remotely was the only way we could tell that they were able to trigger locomotion in a freely moving animal." Could a similar technique be used to study the function of neurons in other vertebrates? Wyart responds with an enthusiastic "Yes!"

—Monica Smith



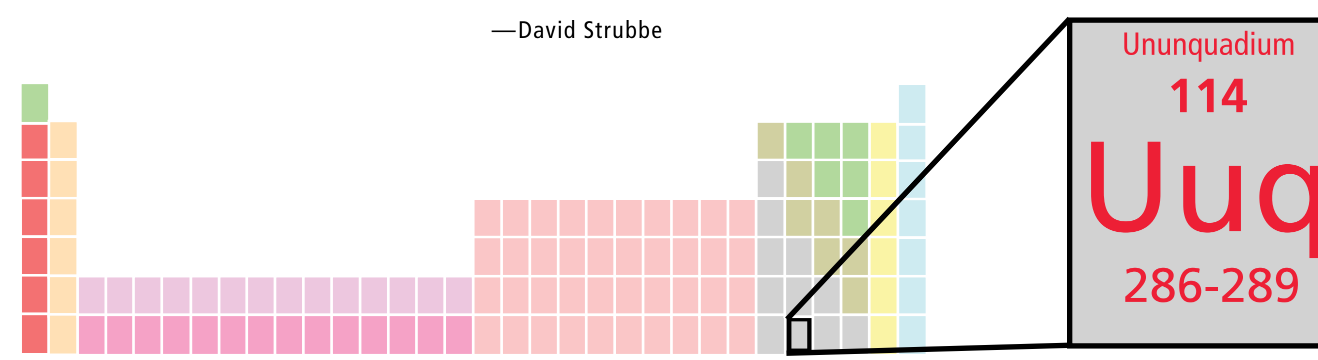
FROM TOP: PATRICK J. LYNCH (HEAD); SUDHIR RAMANNA AND DAVID FEINBERG (MRI OF BRAIN); CLAIRE WYART

## Now presenting ununquadium

Continuing in the proud tradition of groundbreaking nuclear science at Cal, where elements including berkelium and californium were discovered, researchers from the chemistry department and Lawrence Berkeley National Laboratory's (LBL) Nuclear Science Division have now confirmed the existence of element 114 (known provisionally, from its atomic number, as ununquadium or Uuq). The team, led by Heino Nitsche and Ken Gregorich, bombarded a plutonium target with calcium ions accelerated by the LBL cyclotron. Out of a continual stream of radioactive debris from the target, the team observed two nuclei with 114 protons during an eight-day run, each of which decayed in less than a second. This work independently verifies the first observations of element 114 in 1999 in Dubna, Russia. Confirmation is crucial because of the difficulty of the experiments, the very low rates of production of super-heavy elements, and even the specter of fraud: reports of elements 116 and 118 at LBL in 1999 had to be embarrassingly retracted after the data were found to be fabricated. Now, however, the existence of element 114 is on a secure footing, bringing nuclear scientists a step closer to the hypothesized "island of stability" around atomic number 120, where longer-lived elements may exist. Now you can confidently add Uuq to your periodic table—and make sure there's still some space at the bottom.

—David Strubbe

FROM TOP: REBECCA HEALD; TERRY YEN




LABSCOPES

# current briefs

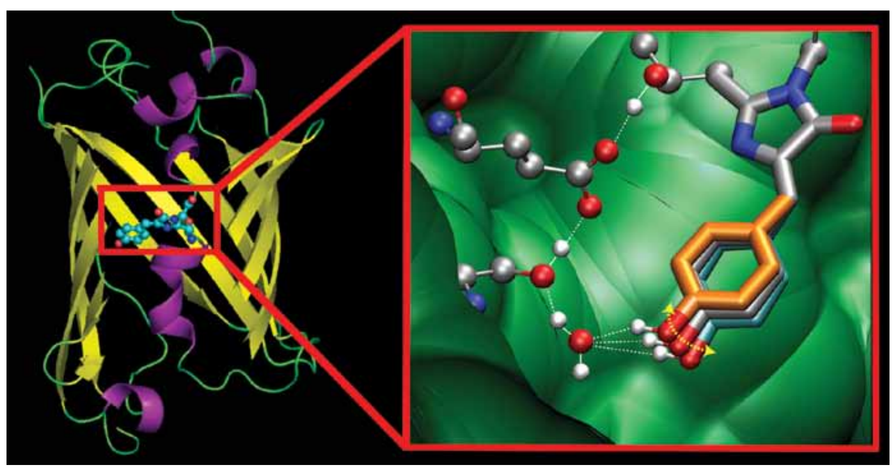
lights, camera, laser • the compass project
an epic explosion • shades of ebony • going it alone
twinkle, twinkle, little star • art and the brain

## Lights, camera, laser

### *Making molecular movies*

When molecular biologists want to look at proteins, individual cells, or intracellular structures not visible to the naked eye, they often use fluorescent proteins as easily visible tracking devices. The most commonly used fluorescent marker is green fluorescent protein (GFP), which glows bright green under blue light. GFP was first isolated from jellyfish 50 years ago, and has since become an essential tool for modern molecular biology. Although GFP is widely used, researchers still don't understand exactly how it generates its characteristic green hue. The molecular movements necessary for fluorescence occur during its excited state, which lasts only five to ten picoseconds (millionths of a millionth of a second), making it exceptionally difficult to monitor them. Scientists can determine the starting and ending configurations, but until very recently have been unable to resolve the very fast transitions occurring during fluorescence activation.

To gain insight into molecular movements that occur on a picosecond timescale, Professor Richard Mathies and his lab in the Department of Chemistry have developed an innovative technique known as femtosecond stimulated Raman spectroscopy, or FSRS. The technique is an extension of traditional Raman spectroscopy, which involves shooting a laser pulse through a sample and then collecting bands of photons, or light particles, once they have passed through. As the laser pulse passes through the molecule of interest, a small fraction of photons transfer energy into the molecule, causing vibrations of chemical bonds that in turn alter the wavelength of the photons themselves. Because specific shifts in wavelength correspond to unique chemical bonds, the scattered photons coming out the other end can be analyzed to determine which chemical bonds are present in the sample.



*Left: A cartoon of GFP's protein structure, showing the photoactive chromophore in the center. Right: Using femtosecond stimulated Raman spectroscopy, scientists can begin to understand how the chromophore moves to initiate fluorescence.*

FROM LEFT: RAYMOND KELLER; NATURE PUBLISHING GROUP

Traditional Raman spectroscopy provides excellent information about chemical structure but no information about time—the long laser pulses used make it impossible to discern which chemical bonds are present at which times. Mathies' innovation lies in the use of three laser pulses, adding two femtosecond pulses (one femtosecond is a thousandth of a picosecond) that are separated by a specified time interval, before and after the initiation of the original Raman pulse. The first femtosecond pulse excites a molecule like GFP, while the second pulse stimulates the Raman transitions to happen at a well-defined time interval after initial activation. These femtosecond pulses can be repeated at differing time delays, yielding individual snapshots of specific bonds in time that are later combined, like pictures in a flip book to provide a detailed animation of molecular movements accurate to one femtosecond. By using pulses at different energy levels, as well as different time delays, different chemical bonds can be studied individually, and again the information can be assembled after the fact to get a complete picture of all chemical bonds present.

Chong Fang, a postdoc who joined Mathies' lab to work on FSRS, saw GFP and related fluorescent proteins as the perfect test subjects for the novel technique. Fang explains, "The first time we studied GFP with traditional Raman spectroscopy, we only saw a lot of green photons and very little structural information, let alone time resolution. We wanted to see how these green photons are emitted. When you excite GFP, what happens immediately after?" By using FSRS, Fang was able to determine how the movements of the photoactive part of the molecule, or chromophore, facilitate fluorescence.

Fluorescence starts when GFP takes in energy from photons of blue light and uses this energy to initiate the transfer of protons and electrons from one of its atoms to another along molecular bonds, emitting a lower-energy green photon along the way. During this process, GFP undergoes a series of rapid conformational changes and interactions between the chromophore and its encasing beta barrel, a protein structure that looks like a Chinese finger trap. The structure provided by this protein sheath keeps the two halves of the chromophore in position to allow the proton transfer that underlies fluorescence; without the beta barrel, the chromophore does not produce any light. By combining a three-dimensional model of GFP with information provided from FSRS about the movement of key atoms, Fang can show that certain arms of the chromophore wag back and forth to facilitate proton transfer, providing the first step in fluorescence activation.

This new knowledge might allow researchers to design customizable fluorescent proteins that could change color multiple times or switch on and off in response to a specific input. Fang explains that understanding how GFP works when activated could enable new fluorescent proteins to be designed for cell imaging. "If we can change some residues in the protein pocket surrounding the chromophore," he says, "we could potentially tune emission wavelengths or vary fluorescence timescales." FSRS has broad potential as well: light-activated protein constructs being developed in labs at Cal and elsewhere could provide kinetic information for a wide variety of proteins. Though they won't be showing up at the Oscars anytime soon, the molecular "movies" produced by FSRS are sure to star in upcoming research in a variety of fields.

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Allison Berke *is a graduate student in bioengineering.*

## The Compass Project

### *Steering students toward success*

"Why is it warmer in the summer?" It's a question for class discussion during "Physics 98: Cultivate Your Inner Physicist." Students enroll in the course as part of an outreach program called the Compass Project. Most answer that the Earth nears the Sun during its elliptical orbit, but this answer doesn't explain the seasonal differences between the Earth's hemispheres. Another response is that it's warmer because of the Earth's axial tilt. For that, "I make an analogy," says Angie Little, graduate student in science and mathematics education. "If I'm the Earth, and a heat lamp is the same relative distance from me as the Sun from the Earth, we can calculate how much closer my knees might be to the lamp than my shoulders, given the tilt. Students immediately see that this small difference couldn't explain the dramatic differences in temperature between seasons and hemispheres."

Summer temperatures actually result from longer days and a more direct angle of sunlight. So the temperature change involves the orbit and the tilt of the Earth, but not the distance between the Earth and Sun. The difficulties of this thought exercise reflect those in real-world physics problems. The issues are complicated and counterintuitive, and require careful and critical thinking. Handling these challenges involves education, communication, and collaboration, skills a group of graduate students are passing on to the next generation of scientists.

The Compass Project is a recruitment and retention program for underrepresented undergraduates in the Departments of Physics, Astronomy, and Earth and Planetary Sciences at UC Berkeley. It has a progressive approach based on collaboration. "I think there's a real misconception that physicists are solitary and reclusive," says physics graduate student and cofounder Hal Haggard. "But physics is fundamentally collaborative—you need other people to make the leaps and bounds necessary to solve the big problems." The Compass Project's community focus creates a strong support network for its undergraduate and graduate student participants.

Along with physics graduate student Badr Albanna, Little and Haggard cofounded the project in 2006. Through an application process, the Compass Project brings 10 to 15 undergraduate students to campus before the start of their freshman year. For one to two weeks, the students live together, eat together, and attend classes designed and taught by graduate students. After the summer, all participants maintain contact through a lecture series, a mentorship program, group activities and, most recently, Physics 98, a semester course on scientific problem-solving.

Compass classes focus on analysis and communication. Self-reflective questions teach clear thinking, while group work and class discussions engage a variety of perspectives. In

YUKI TAKAHASHI

*Students and teachers in the Compass Project create a human compass on a campus lawn. The outreach program builds community while teaching physics problem-solving skills.*

a typical session, discussion generates hypotheses, small groups test those hypotheses, and then the class collectively shares and evaluates conclusions. Throughout, students stay focused by asking themselves Schoenfeld questions, developed by science education expert and professor in the Graduate School of Education, Alan Schoenfeld. "What am I doing, why am I doing it, what's the point—these questions get people to be more thoughtful, organized, and accountable to their own thought process," says Little. The goal of each Compass class is interaction, collective progress, and critical thinking.

Project participation has a profound effect. "The Compass Project provided me with resources that I would otherwise have overlooked," says Harjit Singh, a freshman majoring in astrophysics and earth and planetary science. "So saying 'It's too hard' is no reason to leave the discipline I love. There's plenty of support to help me be successful in the physical sciences." All undergraduate interviewees, even those who have left science, commented that they are buoyed through various struggles by their Compass experience.

Compass also helps its graduate student mentors. Regular meetings provide space for intellectual engagement with teaching. "The graduate students start to recognize how Compass makes them better teachers, and how it impacts their students across the board," says Haggard. "It's really wonderful." A shared passion for education provides a crucial support network that sustains Compass teachers and managers. The Compass ethos of interactive learning greatly benefits both its students and administrators.

Keeping the Compass Project afloat through their PhD programs, as well as logistical and funding issues hasn't been easy, but Compass coordinators have an impressive enthusiasm. "I really think you can teach science in a way that makes you want to change the world," says Albanna. "It shouldn't be a hierarchy, from professor to student or scientist to the public; it should be an exchange, a dialogue." With luck and continued hard work, their enthusiasm for education and outreach will spread and, as Albanna believes, make for a more collaborative world.

Crystal Chaw *is a graduate student in integrative biology.*

# An epic explosion

## *Observing an exotic supernova*

Somewhere in the universe, a star exploded today. Yesterday, too; tomorrow will likely bring the same. Tomorrow, however, probably won't bring a supernova like the one discovered on April 6, 2007 by a group of astronomers in the Nearby Supernova Factory collaboration, based at Lawrence Berkeley National Laboratory. Too bright for its britches and slower-evolving than any previous blast of its kind, supernova SN 2007bi (07bi for short) inspired nearly two years of intense scrutiny, challenging our current understanding of how stars die, and how they live.

Supernovae are some of the brightest events in the universe—so bright they can outshine the hundreds of billions of stars that make up the galaxies in which they live. Unlike the short flash of a camera bulb, supernovae can remain visible for weeks to months, usually powered by radioactivity. The extremely high temperatures produced in stellar explosions lead to a short period of rapid nuclear reactions, producing a significant amount of a radioactive form of nickel. As these nickel atoms decay to a more stable state, they emit high-energy light called gamma rays. Material from the outer layers of the star that is thrown off in the explosion absorbs these high-energy rays and then emits the glow that we detect with our eyes and telescopes. Thus, the brightness of a supernova and how it changes with time is directly related to the amount of radioactive nickel produced and the amount of material in the expanding outer layers.

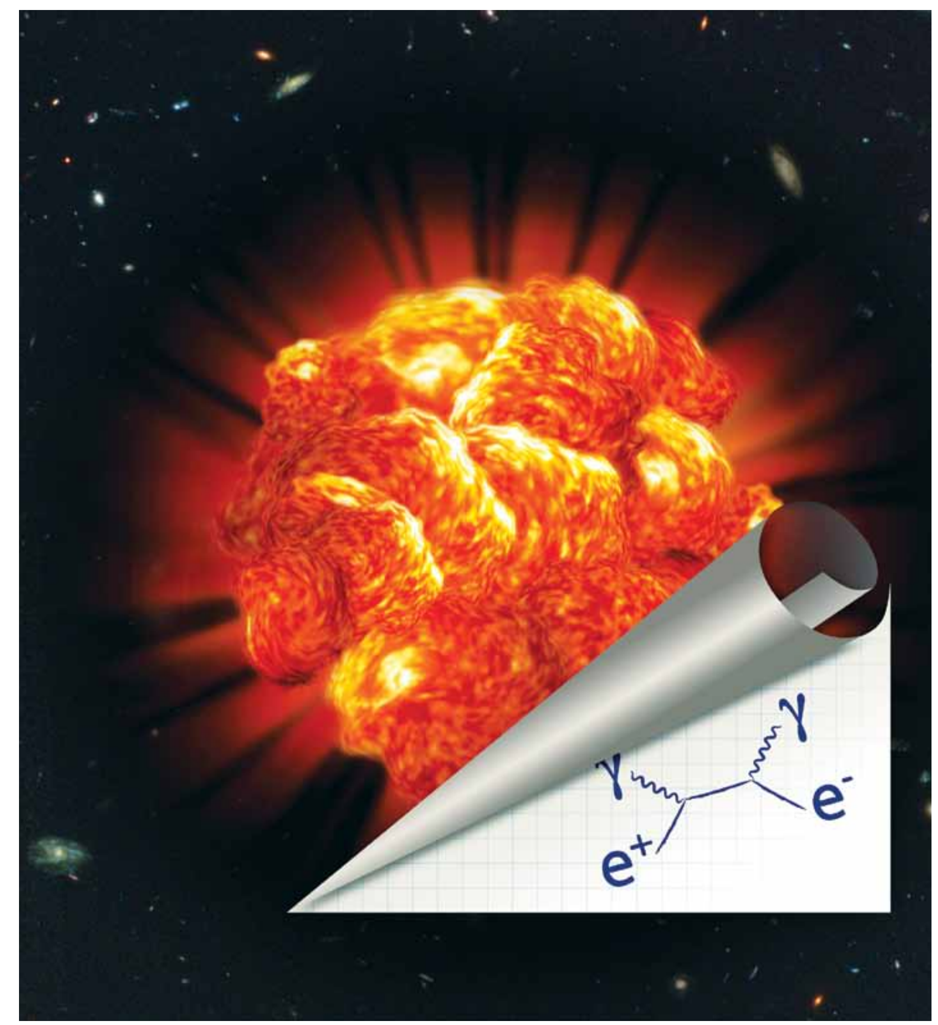
It is thought that all the previously identified supernovae come from two basic types of stellar explosions. In one case, a star more than 10 times the mass of the Sun fuses successively heavier elements throughout its life until it builds an inert iron core that grows until it reaches a critical mass. Above this threshold, the core's internal pressure cannot support it against the force of gravity, and the resulting collapse to an ultra-dense neutron star or black hole releases so much energy that much of the overlying material is violently blown away. In the other case, a white dwarf, the remnant of a less massive star like our Sun, gains material from a close by companion star until it exceeds its own critical mass and collapses on itself. Because less massive stars never get hot enough to fuse atoms into iron, a white dwarf consists primarily of carbon and oxygen. As the white dwarf starts collapsing, the carbon and oxygen get hot and dense enough to ignite an uncontrolled nuclear fusion reaction, a so-called thermonuclear runaway, which releases enough energy to blow apart the entire white dwarf, leaving nothing behind.

Ideally, astronomers would like to classify a supernova based on how it exploded, but the mechanism underlying the cataclysmic event is hidden behind all that ejected material. Instead, astronomers classify a supernova based on its observable properties and use their observations to build a case for what type of explosion took place. The wealth of supernovae identified in the last two decades has revealed a staggeringly wide variety of observable manifestations of what astronomers thought were just two types of explosions. Astronomers still believe they can usually assign a supernova to one of the two basic explosion mechanisms, but this is not always possible. Thus the question becomes, are there more than just exploding white dwarfs and collapsing iron cores behind all these brilliant blasts?

When Dr. Avishay Gal-Yam of the Weizmann Institute, lead author on the study of 07bi, and his team identified a supernova in a small, faint galaxy far, far away, there was little reason to suspect it would be anything special—as cataclysmic astronomical events go, that is. "With the earliest observations, we were able to identify SN 2007bi as part of a known observational class with just a few peculiarities," says UC Berkeley astronomy professor and co-author Alex Filippenko. But as Gal-Yam remembers, "For me the turning point was as we continued to follow it, the object just would not go away—it decayed very slowly and remained bright for months and months." Having caught the supernova as it was already fading, the team went back and found old data showing that 07bi had brightened just as slowly, taking nearly three times longer than similar supernovae to reach an unparalleled peak brightness for its type.

Gal-Yam and his team concluded that such a brilliant, slowly evolving supernova must have resulted from an explosion that produced about ten times the typical amount of radioactive nickel. Furthermore, ejected stellar material totaling more than 50 times the mass of the Sun would have been required to trap the majority of the radioactive energy and convert it to the bright signal they observed. Once the stellar debris had cleared out sufficiently, an unheard of 16 months after the supernova was discovered, further observations revealed a large reservoir of leftovers from the decay of nickel and an excessively large mass of ejected material, confirming their suspicions.

"That much ejected mass and radioactive nickel certainly pointed to an extreme configuration," says UC Berkeley astronomy professor and study co-author Josh Bloom, "something we've maybe never seen before." To Gal-Yam and his team, the picture slowly coming into focus looked like a rare, as yet only theoretical type of stellar explosion called a pair-instability supernova. This type of stellar explosion is theorized to occur when some of the most massive stars in the universe, probably those about 150 times more massive than the Sun, reach a critical stage in their evolution. Before fusing their fuel into iron, these stars' cores may become so hot that photons, or light particles, in the core have enough energy to spontaneously convert to electrons and their opposites, positrons, in a process called pair production. This spells doom for these behemoth stars because those photons are largely responsible for holding the star up against its own gravity.




AVISHAY GAL-YAM

*An artist's conception of a pair-instability supernova, shown against a background image of galaxies. Hidden deep within the expanding outer layers shown here, the trigger for such a supernova is the conversion of high-energy photons (denoted by γ) into electron and positron pairs (denoted by $e^-$ and $e^+$, respectively), which robs the star of its pressure support.*

Like a crowd-surfer who finds himself over a group of middle schoolers, the star's outer layers find themselves without the photons' support. The resulting collapse causes the core to heat up and ignite in a runaway thermonuclear explosion, blowing apart the entire massive star.

While a pair-instability supernova is capable of producing the observed properties of 07bi, it is not the only type of stellar explosion that does so. "You can't wiggle out of the fact that 07bi came from a very massive star, and the explosion produced a lot of nickel," says Bloom. "But none of that is a 'smoking gun' for anything. We can say that the trigger was pulled, but how and by whom are other questions all together." For this reason, the article published in *Nature* declares 07bi the most likely candidate for the first pair-instability supernova, but is careful to point out that, as Filippenko says, "the uniqueness of the pair-instability explanation has not yet been demonstrated."

The popular media coverage, on the other hand, has been considerably less tempered. Many stories flatly declare 07bi the first-ever example of a pair-instability supernova. When it comes to these overstatements, Filippenko considers, "Do you want people to hear about this at all? Or do you want them to get some of the details wrong? Most people aren't going to remember the details anyway!" But there is still the worry that the media robs its audience of an appreciation for the uncertainties inherent to science by overstating scientific results. Ultimately, Filippenko says, "I get a lot of messages and emails from people saying they heard about this cool story, and it got them really excited. And in the end they're not focusing on the details. They're just getting excited about science and astronomy, and that's a good thing." Gal-Yam and his team hope that this excitement about astronomy will help continue to fund current and future surveys that will scan more of the sky more often than ever before. Bloom describes events like 07bi as "bookends that teach us about the library," and these surveys are needed to extend the bookshelves and put 07bi in its proper context.

Josh Shiode *is a graduate student in astronomy.*

# Shades of ebony

## *Flies elucidate subtle mechanisms of evolution*



John Pool was a graduate student collecting fly samples in Africa when he came across something unexpected: flies in the highlands tended to have darker abdomens than those in the lowlands. One possible explanation was that the differences were simply due to random variation that was amplified as populations drifted apart. However, the trait didn't seem to split along family lines, as you would expect if genetic drift were at the heart of it all. "You could have closely related populations where one was lighter and another was darker," says Pool, now a postdoctoral fellow working with UC Berkeley professor Rasmus Nielsen. "That was the first hint that natural selection was governing the geographic distribution." Pool had discovered evolution in action, and an opportunity to study it in the fruit fly, *Drosophila melanogaster*, a genetically well-characterized and tractable organism for which an impressive genetic toolkit exists. Along with collaborators at the University of Wisconsin, Madison and Cornell University, Pool teased apart the precise nature of the genetic changes causing the coloration differences, showing that evolution at the molecular level can progress by much more interesting routes than initially expected.

From the start, the outward appearance of Pool's flies hinted at the underlying genetic cause—a gene called *ebony*, which codes for a protein (also called ebony) in the pathway that converts brown pigment to yellow pigment. As it turns out, ebony is responsible for more than just cuticle coloration; it is also utilized by the nervous system and has an important role in vision. Biologists refer to such multitasking proteins as pleiotropic. Although being versatile has its advantages, it renders ebony a tricky subject for evolution's tinkering. Consider a mutation that gives rise to a different version, or allele, of ebony that produces a slightly different protein. Any such tweak that allows ebony to perform one function better is likely to impair its other functions. Pool explains that, in ebony's case, "the argument is that if you did something kind of extreme to the protein then you maybe don't have a healthy nervous system or visual system." This phenomenon is known as antagonistic pleiotropy, and steering clear of it requires a more nuanced route for change. To this end, each protein in the vast cellular workforce has its own host of DNA with one purpose: administration. These so-called regulatory regions come in several flavors, including enhancers, which step up production, and repressors, which turn it down. In concert, the various types of regulatory regions allow for exquisite control over when, where, and in what quantity specific proteins are produced. While it is clear that natural selection can act on both protein-coding and regulatory regions, when pleiotropic proteins are involved it is hypothesized that evolution in regulatory regions is much more likely since it allows for more fine-tuned control.

To answer the question definitively, the group swapped the regulatory regions of the light and dark alleles and found that the colors of the resulting flies were determined entirely by the regulatory region they possessed. Importantly, the presumed regulators were specific for expression in the abdomen, avoiding potentially harmful pleiotropic effects elsewhere in the body. Using the same splitting-and-swapping method with smaller and smaller pieces, the team was able to pinpoint the functionally important differences between the multiple alleles. In the end, they were left with five sites at which differences in the genetic code exerted a significant effect on abdominal pigmentation, three enhancer mutations, and two in a nearby repressor. The diversity of functional mutations was a surprising find. "If you wanted to turn down abdominal enhancer expression, perhaps the simplest hypothesis would be that there was just one mutation that kind of messed up the abdominal enhancer," notes Pool. "It turned out to be more complicated than that."

Having worked out how genetics gave rise to the present coloration differences, the group turned their gaze back in time to trace the evolutionary origins of the trait. The five sites provided a chance to test a question with important theoretical implications for evolutionary biologists: what is the relative importance of standing genetic variation (the existing genetic variability in a population prior to natural selection) versus that of new mutations (genetic changes that arise *de novo* and are selected for)? If standing variation were responsible, the mutations would be present across a large part of the species' range, both in the high and lowlands. Alternatively, the mutations could have arisen from scratch, enabling the flies to conquer the higher altitudes in the first place. In this case, the mutations should be confined to the high-altitude populations. As it turned out, the group found evidence for both evolutionary paths. Three of the mutations associated with dark pigmentation were also found in more moderately pigmented individuals collected at sites on opposite ends of the continent. These were very old mutations that had evolved some 400,000 years ago. The remaining two mutations were found only in the mountains of Uganda and nearby Rwanda, and appeared to have arisen much more recently, within the last 900 years.

Combining advanced genetic manipulations and population genetics allowed the group to develop an amazingly rich and detailed case study of evolution. The surprisingly complicated molecular biology and evolutionary history that underlie this apparently simple trait should make us wonder just how unique ebony's history is. Asked about the impact of the work, Pool is hopeful. "Right now we're still just talking about whether this story is going to represent a general pattern, but I think there's a chance that certain elements might become recurring themes in enhancer evolution. One aspect is just evolution working in a more delicate way than we might have imagined."

**Robert Gibboni** *is a graduate student in neuroscience.*

NASA



# Going it alone

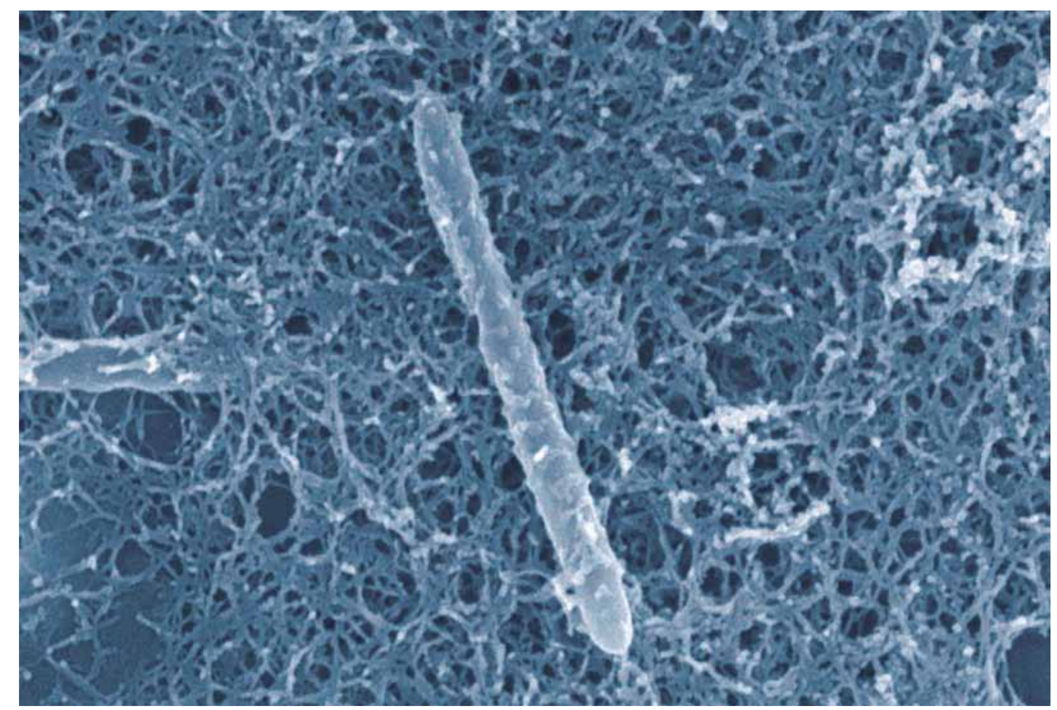
## *Scientists uncover a single organism ecosystem*



In Jules Verne's classic novel *A Journey to the Center of the Earth*, the protagonist, Professor Lidenbrock, is challenged by a cryptic text to "*descende, audax viator, et terrestre centrum attinges*" (descend, bold traveler, and attain the center of the earth). Much like the characters in the novel, researchers at the Lawrence Berkeley National Laboratory (LBL) and their collaborators have recently descended three kilometers into a South African gold mine in search of interesting life forms, naming the fascinating microorganism they found there in honor of Verne's bold travelers. *Desulforudis audaxviator* is the first identified example of a microorganism that can survive in complete isolation, independent of any other life forms. "This is exciting because one of the questions that comes up when you're considering the possibility of life on other planets is whether or not life can live alone," says Dylan Chivian from LBL, one of the scientists involved in the study. "Until now that's been purely speculation." Their work, supported by the Department of Energy and the NASA Astrobiology Institute, was published in *Science* in October 2008.

The journey taken by the scientists to characterize the organism was not easy. A team of researchers from many different institutions all over the world descended deep into the Mponeng gold mine in South Africa, and extracted over 5,000 liters of water by drilling into fluid-filled fractures. The water was filtered, and the DNA was extracted and sequenced at LBL's Joint Genome Institute. "The expectation was that there would be DNA that corresponded to a mixture of species, such as has happened every other time anyone studied a community," says Chivian. "But instead, what we got back was DNA corresponding to just a single organism."

Further inspection revealed that all components required for the organism's survival, growth and reproduction are encoded by its own genome. Thriving in an extremely hot habitat (60ºC, or 140ºF) completely devoid of light, oxygen, and most nutrients, *D. audaxviator* is capable of independently carrying out many complex life functions. While most organisms on the surface of the Earth obtain energy directly from light emitted by the Sun, *D. audaxviator* has no access to sunlight and instead generates energy by reduction of sulfate that is available as a consequence of radioactive decay of uranium. Its genome contains genes encoding the necessary apparatus for fixing carbon and nitrogen from the environment, which are essential building blocks for life. It also possesses all the genes required to synthesize all amino acids, the building blocks of proteins. This discovery tells us that it is possible to pack everything necessary for maintaining life into one organism. "This is philosophically exciting," says Chivian "in that it's the blueprint for an entire ecosystem."



*The rod-shaped bacterium* D. audaxviator *was discovered three kilometers below the surface of the earth in a South African gold mine. It can survive without sunlight, oxygen, or most nutrients.*

GREG WANGER AND GORDON SOUTHAM

The components of *D. audaxviator*'s genome provide clues about its origins. Its oxygen intolerance, for example, suggests long-term isolation from oxygen. Some of its genes appear to have come from exchange of genetic material with other organisms, suggesting that *D. audaxviator*'s ancestor was not always alone. The ability to fix nitrogen and carbon, for example, seems to have been at least partially acquired from archaea, a domain of life distinct from bacteria, which is known to often exist in harsh environments. Likewise, *D. audaxviator*'s viral defense systems are found in archaea as well. Unlike archaea, but like many other bacteria, *D. audaxviator* can form endospores (tough structures that shield it from heat and chemicals) and possesses flagella, tail-like structures that help it swim towards nutrients. This bold traveler has thus succeeded in surviving all by itself by taking good bits from the different organisms it has encountered throughout the course of its evolution.

"Life is everywhere on this planet!" muses Dylan. UC Berkeley scientists and the NASA Astrobiology Institute continue their painstaking efforts to explore and understand unknown life forms in every possible locale. Further research into the workings of this and other similar organisms (if found) might offer a glimpse of how life could exist or evolve under the extreme conditions of an extraterrestrial environment.

**Sharmistha Majumdar** *is a postdoctoral fellow in molecular and cell biology.*

# Twinkle, twinkle, little star

## *Discovering planets from afar*

At a table with an umbrella to shade the hot Greek sun, Aristotle, Democritus and Epicurus down glasses of strong ouzo as their heated discussion builds—UC Berkeley astronomy professor Geoff Marcy imagines the scene vividly. Aristotle argues "with some venom" that our planet Earth is unique in the universe; the others contend that the universe is infinite and must contain other worlds like ours. It's astonishing, Marcy points out: "Here we are 2,400 years later, and we still haven't resolved that debate!" But NASA's new Kepler mission is bringing resolution much closer.

Kepler is a space observatory that was launched on March 6, 2009, aboard a Delta II rocket from Cape Canaveral, Florida. The observatory is named for Johannes Kepler, the 17th-century German astronomer who discovered laws describing the motion of the planets. The Kepler mission's ambitious aim is to discover other worlds in our neighborhood of the Milky Way Galaxy where life may possibly exist. For all we know, life can arise from an enormous diversity of conditions. But for the only life we've ever seen, liquid water on a small rocky planet seems to be required. To start close to home, scientists designed Kepler to look for Earth-sized planets orbiting Sun-like stars at a distance where temperatures should be right for liquid water—a region optimistically dubbed the "habitable zone."

Simply photographing a distant planet is beyond today's technology, so astronomers have had to develop less direct planet-finding techniques. The Kepler mission's technique is surprisingly simple: the telescope is staring at a single patch of sky and patiently measuring the brightnesses of 150,000 stars every half hour, over and over for the next three years and beyond. Kepler's pay dirt is a small fraction of those stars—stars that harbor planets that happen to orbit in perfect alignment with Earth. During most of a planet's orbit around its parent star, the planet is invisible to us, too small and dark to be seen beside the brilliant star. But for a few special hours each orbit, such a planet travels directly between the star and us, blocking a little bit of starlight in an event called a "transit." Kepler's careful surveillance can pick up the tiny repeating dips in stellar brightness that announce a planet's presence. Only a small fraction of star-planet systems will align with us just so, but Kepler makes up for that by watching an awful lot of stars, giving the mission a good chance of finding many planets.

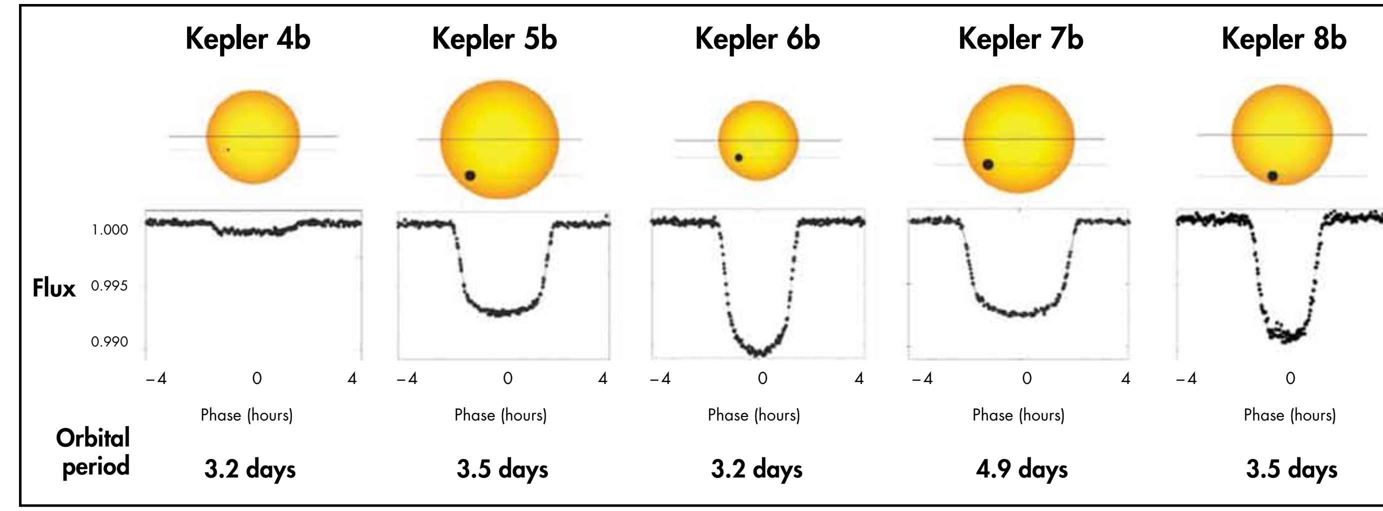
Engineers from Ball Aerospace, the firm that built the Kepler spacecraft, inspect the back side of Kepler's primary mirror assembly. The mirror is backed by a honeycomb reinforcement structure which is both sturdy and lightweight. You may recognize the Ball logo; Ball Corporation is also one of the largest makers of household glass jars and soda cans!

NASA

Although Marcy, a Kepler Co-Investigator, jokes that Kepler is "utterly the most boring and simple space-borne experiment you could ever imagine," making the idea work is a substantial challenge, technically and scientifically. Earth-sized planets are very small compared to the stars they attempt to eclipse: the starlight dims just barely, like four houses in all of Berkeley turning out their lights. For an earth-bound telescope, such a subtle change would be overwhelmed by atmospheric fluctuations and temperature variations as the telescope moved between night and day. So Kepler was launched into orbit around the Sun and is now more than four times as far from us as the Moon.

Surface features of the stars Kepler monitors also provide a challenge. The faces of many stars do not appear as simple blank backdrops behind planetary transits, but rather are blemished by transient darker regions called "starspots." As stars spin, some starspots come into view while others rotate away, more like 100 houses in Berkeley switching their lights on and off. Finding the four-house signal of an earth transit should be difficult but possible; a starspot typically takes a few weeks to appear and rotate out of view, producing a smooth rise and fall in brightness, while a planetary transit lasts only a few hours and affects the stellar brightness more sharply. UC Berkeley astronomy professor and Kepler Co-Investigator Gibor Basri, along with postdoctoral researcher and Kepler Fellow Lucianne Walkowicz, are devising detailed models of starspots to help isolate the dimming caused by planets and to learn more about how stars work along the way.

Starspots are produced by the interplay of two processes inside stars, magnetism and convection. Although the details are not fully understood, a magnetic field is generated by a star's spinning—magnetic compasses rely on a similar process in the Earth. Blobs of hot material deep inside a star normally rise up by convection, just as bubbles rise in a pot of boiling water. Sometimes, though, hot blobs trying to ascend get tied down by knots of strong magnetic field. Cooler, darker blobs of gas fill in above, appearing as starspots on the stellar surface.




These curves show the periodic dips in the light intensity from stars due to the passage of planets. The shapes of these curves provide valuable clues about the planet's characteristics. For example, the orbital period corresponds to a planet's distance from its star, and hence its temperature. Also, the degree to which it eclipses its sun's light is an indicator of its size.

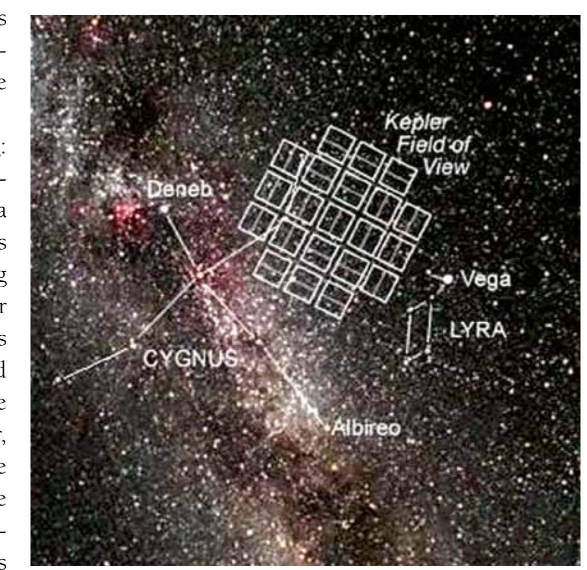
Most of our understanding of starspots comes from studying spots on the Sun, where close-up measurements are easy to do. The nagging worry, Walkowicz explains, "is the long-standing question: how typical is the Sun?" With a laugh, she rephrases, "Is the Sun a weirdo?" Now, Kepler's precise data allow a comparison of spots on the Sun with spots on a large number of other stars. Basri and Walkowicz are analyzing the stellar brightness measurements to estimate starspot sizes and relative locations, and to compute how long starspots live. Also, because stars with stronger magnetic fields tend to have more starspots, the team plans to use starspots as a way of learning about magnetic field strengths in different types of stars, perhaps providing further insight into how the fields are generated.

Their first results look promising: they compared the area of the Sun covered by spots with the spot-covered area for each of Kepler's stars, and found, as Walkowicz says, that "the Sun is not a big weirdo and so it's actually not a bad star to study." Only one third of Kepler's stars are more spot-covered than the Sun, and most of those are not more than twice as covered. As an early test for Kepler, astronomers simulated stellar data on the basis of the Sun's spot coverage and were able to extract a mock earth; that, together with these new results, indicates that Kepler really is capable of finding Earth-like planets amidst the starspots on many of its target stars.

Indeed, Kepler is off to a good start on its quest for planets. After the first six weeks of operation, 21 stars had brightness dips tantalizing enough to warrant further study by telescopes on the ground. Marcy measured spectra of the most promising candidates using the Keck Telescope in Hawaii. A planet-bearing star circles around and around, responding to the gravitational pull of its orbiting planet. Repeated measurements of the star's spectrum reveal Doppler shifts due to the star's wobble and thus confirm what Kepler suspected: the star hosts a planet.

Marcy's observations have already yielded five planets—no Earth analogs yet, but that's expected. The "low-hanging fruit" planets are big, so that they block lots of starlight, and orbit their parent star every few days, so that Kepler has had time to watch them transit many times already. Four of the five new planets are gas giants larger than Jupiter, and all have "years" only three to five days long. Such quick orbits mean the planets are very close to their parent stars, and so are much too hot for liquid water. These planets may sound strange, having no analogs in our solar system, but astronomers have actually found many planets like these already over the past decade. "Frankly, they're boring," Marcy laughs. But they illustrate that Kepler's data is as beautiful as expected, and that discovering earths near the "habitable zone" might well be just around the corner.

NASA




Kepler is aimed at a star-rich patch of sky in the vicinity of the Cygnus and Lyra constellations. Of the 4.5 million stars in its field of view, it is examining more than 100,000 for Earth-like planets.

"Sometimes you wonder, will you know when a historic moment in science is about to happen?" muses Marcy. "And I think we know! Kepler can find earths, no question about it: when the earths cross in front of their stars, the stars will dim by an amount that Kepler will see. We're about to answer a question that folks in Ancient Greece fought about 2,400 years ago. I don't think you can name another question in science that was asked 2,400 years ago that we're about to answer now."

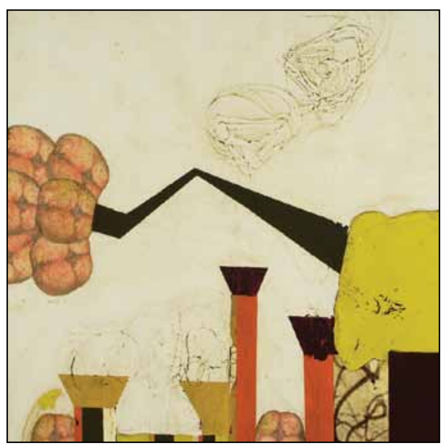
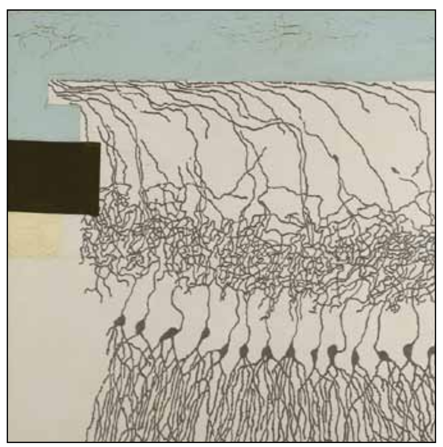
Basri adds, "It's really exciting to be at this juncture of our knowledge. The question's about to fall."

Linda Strubbe *is a graduate student in astronomy.*

# Art and the Brain

## *Painting a picture of creativity*

Artists are gifted with the ability to represent nature's forms and colors in masterpieces that delight and intrigue the world. Those of us who struggle to draw basic shapes wonder where their skills come from. Are artists born creative? Are their brains wired in ways that a non-artist's brain is not? Perhaps artists who suffer from brain injuries can shed some light on the link between the brain and artistic ability.


*Selected paintings by Katherine Sherwood. From left: "Fist," mixed media on canvas, 2008; "One in 100 Billion," mixed media on canvas, 2008; "Vesalius's Pump," mixed media on canvas, 2007.*

KATHERINE SHERWOOD

At the age of 44, Katherine Sherwood, a painter and professor in the Department of Art Practice at UC Berkeley, collapsed during a student's presentation. She couldn't speak. She couldn't move the right side of her body. Brain scans at the hospital revealed a stroke in the left hemisphere of her brain, which controls the right side of the body and is also in charge of language production and comprehension, among other tasks. Through months of depression, therapy, and hard work, Sherwood learned to talk and walk again. Previously a right-handed artist, Sherwood trained herself to paint with her left hand. Still weak on her legs, Sherwood lays her canvas horizontally and wheels around on her wheelchair as she paints.

Sherwood's first exhibition after the stroke received critical acclaim, and with recognition came speculation about the influence of Sherwood's stroke on her work. David Ross, formerly director of the San Francisco Museum of Modern Art, said Sherwood's post-stroke paintings were "more visceral, less intellectual" than her earlier work. Peter Waldman, writing for the *Wall Street Journal*, suggested that Sherwood's stroke "enhanced her powers of creativity."

Commenting on her post-stroke paintings, Sherwood says, "My work now is much less intellectualized, less figured out. Art flows through me." Curiously, these comments characterize the effects often seen with left brain damage. Damage to the left brain not only reduces the ability to perform tasks traditionally associated with that side of the brain, such as those involved in language processing, but also enhances activity in the right brain to compensate for deficits in the left brain. The right brain is involved in processing spatial information and artistic expression, so increasing its use may increase artistic ability. Sherwood's stroke may have reduced intellectualization from the left brain and enhanced artistic ability in the right brain, giving rise to a "less figured out" style. Of course, it is possible that Sherwood would have arrived at her current style even without the stroke. "There are multiple reasons why the work has changed and relegating it to the stroke doesn't do justice to the other reasons…doesn't give the 20 years of work that I had done credit," Sherwood says.

Case studies like Sherwood's cannot be generalized to everyone with left brain damage and do not speak to the role of the right brain in artistic expression. These studies lack what researchers call a control group, a second Katherine Sherwood who has not experienced a stroke and whose work can be compared with the current Sherwood's.

However, there have been studies with control groups investigating the relationship between art and the brain with respect to autism. Autistic children are born with broad linguistic and social deficits, but some children with autism have extraordinary skills that seem to arise naturally without intensive practice. In *Nadia: A Case of Extraordinary Drawing Ability in an Autistic Child*, the author describes a little girl who could not speak but was drawing pictures of roosters and horses in amazing detail by the age of five. Further studies have found that autistic children have an abnormal left brain, specifically in a region located behind the temple known as the anterior temporal lobe. Although not all autistic children are artistic, the occurrence is common enough to lead researchers to hypothesize a link between the anterior temporal lobe and art.

Additional support for the role of the anterior temporal lobe in art comes from patients with frontotemporal dementia, a neurodegenerative disease affecting the anterior temporal lobe. Bruce Miller, a neurologist at UC San Francisco, has documented cases of patients with no previous interest in art suddenly acquiring a passion for art and developing new artistic abilities after the onset of their illness.

Allan Snyder, director of the Center of the Mind at the University of Sydney, and colleagues set out to test whether damage to the left anterior temporal lobe enhances artistic ability. The group utilized a technique called transcranial magnetic stimulation (TMS; see also *BSR* Spring 2009), which directs low-frequency magnetic pulses to the brain region under study to temporarily disrupt function in that area. Healthy university students were recruited to receive TMS on their left anterior temporal lobe. Subjects were asked to complete drawing tasks before and after application of TMS. Snyder and colleagues found that drawings done after TMS were more complex and lifelike, supporting the hypothesis that damage to the left anterior temporal lobe enhances artistic ability.

Since left brain damage leads to increased activity in the right brain, it is the right anterior temporal lobe that seems to play a role in artistic expression. Snyder's study suggests that the artistic ones among us may be blessed with a more active right anterior temporal lobe. Future studies employing modern imaging techniques such as magnetic resonance imaging (MRI) could shed light on differences in the right anterior temporal lobe between artists and non-artists.

The temporal lobe is also implicated in forms of expression that go beyond visual art. In *Musicophilia*, Oliver Saks introduces the reader to Salimah, a research chemist who suffers a seizure. Subsequent brain scans show a tumor in her temporal lobe, which doctors surgically remove. Before surgery, Salimah was only vaguely interested in music. After the surgery, she can't get enough of music. She buys music CDs, attends concerts, and becomes addicted to the radio. Music now moves Salimah to tears.

Artists with brain injury provide intriguing glimpses in the complex relationship between the brain and art. Although rare, these anecdotal cases will likely continue to provide suggestive evidence to inspire researchers to dig deeper into the workings of the human brain.

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Linh Dang *is a graduate student in neuroscience.*

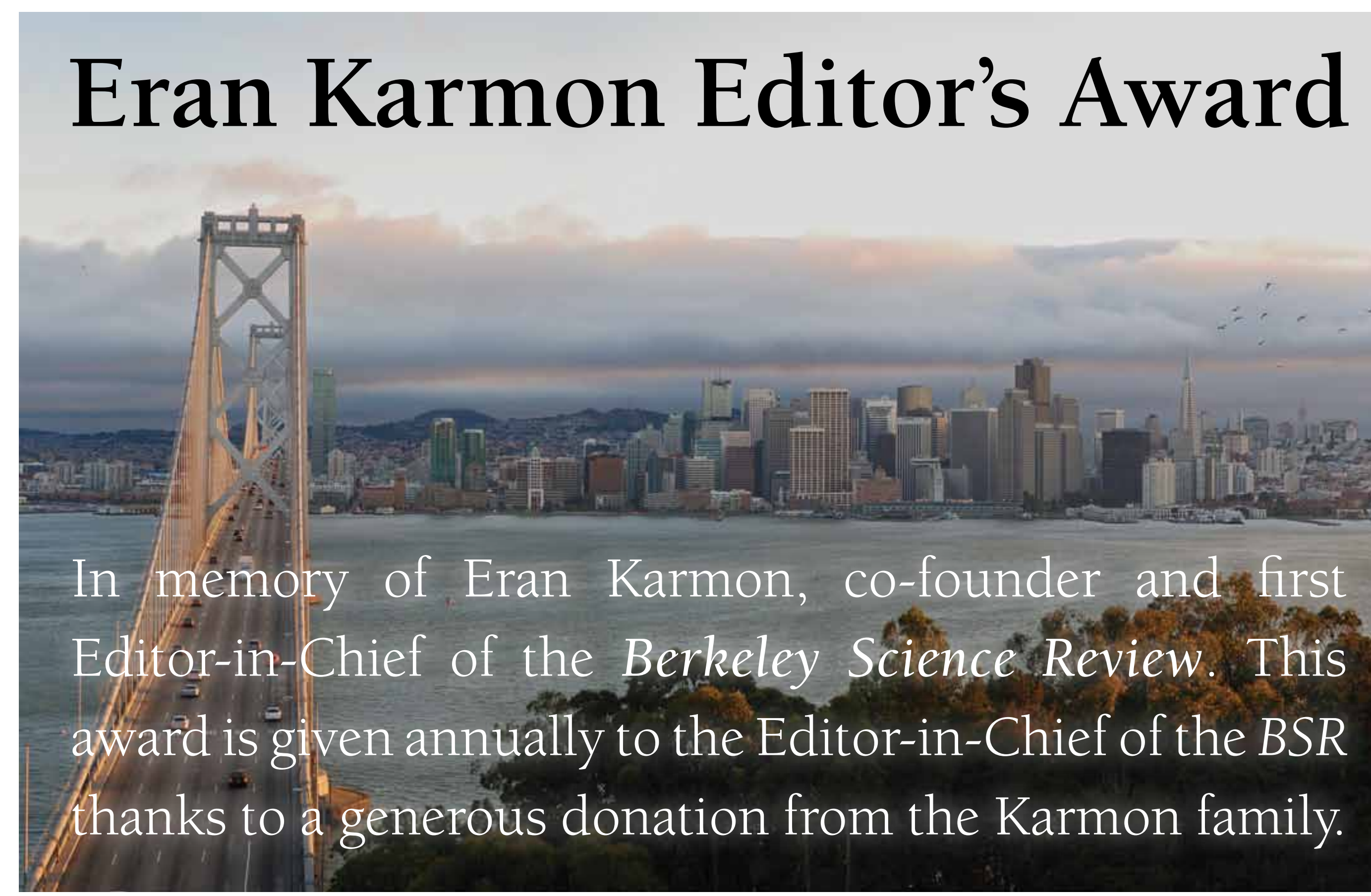
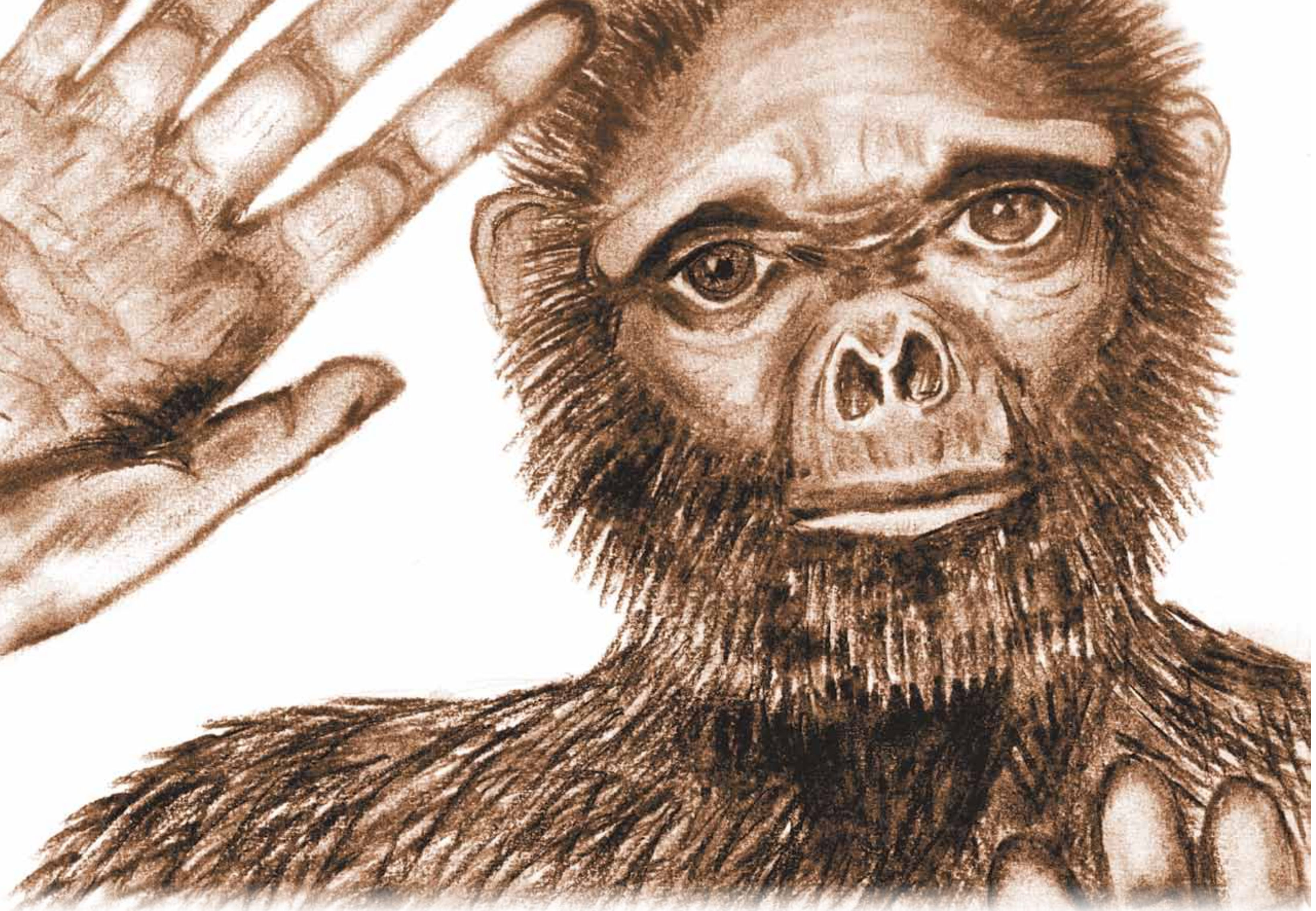



PHOTO: MAREK JAKUBOWSKI



COLLEEN KIRKHART

# Unearthing Ardi

by Rachel Bernstein

## An ancient skeleton sheds light on our evolutionary past

The cartoonist's trick for representing hominid evolution distills millions of years of change down to a few short steps from a hunched, knuckle-walking, chimp-like ancestor to an upright, smooth-skinned man. Indeed, chimpanzees are our closest living relatives, with whom we share remarkable genetic similarities, and it was long believed that the last common ancestor between humans and chimps was not far removed from the modern chimp we see in zoos today. Now, a remarkably thorough characterization of the oldest known hominid skeleton found to date turns this model on its head, suggesting a primitive, unspecialized ancestor distinctly different from modern apes and unlike anything that researchers had expected.

### Millions of years in the making

It seems appropriate that a story about a hominid that lived over four million years ago would take almost 20 years to develop. This story begins in 1992, when Dr. Gen Suwa, a former UC Berkeley graduate student who worked under integrative biology professor Tim White, discovered the first *Ardipithecus ramidus* fossils in the Middle Awash region of Ethiopia. With the help of Paul Renne, Berkeley Geochronology Center director and adjunct professor in the earth and planetary sciences department, among others, the find was dated to 4.4 million years old, making them the oldest hominid fossils discovered up to that time.

At first these fossils were characterized as a species of *Australopithecus*, which is generally agreed to be the parental genus to *Homo* and modern humans, *Homo sapiens*. As more fossils were discovered in subsequent years, however, the team decided that the find merited its own genus and named it *Ardipithecus ramidus*, which means "root of the ground ape" in a combination of Greek and the local language. Continued excavation at the site unearthed more fossils from at least 36 individuals, including more than 125 pieces of a female affectionately nicknamed Ardi. While far from complete, the Ardi skeleton includes pieces of the skull, teeth, arms, hands, pelvis, legs, and feet, providing crucial information about brain size, diet, and locomotive behavior.

Small bits of the Ardi story have been published over the years, and in October of 2009, the team published 11 papers in the journal *Science* that covered all the known aspects of Ardi's anatomy, environment, and behavior. The body of work describes the painstaking process of excavating the *Ardipithecus ramidus* fossils, as well as many other plant and animal fossils from the area used to characterize the environment, and the process of dating and interpreting the fossils to learn about Ardi's life and behavior. For example, Ardi's skull was completely crushed, likely stepped on by an animal. The team was able to reconstruct this crucial part of the skeleton using computer tomography, or CT, generally known for its use in medical scanning and 3-D imaging.

"We found Ardi 15 years ago, but the kind of work required to get to the publication stage was enormous," says Dr. Berhane Asfaw of the Rift Valley Research Service and co-director of the project since receiving his PhD from Cal in the 1980s. "I think that is how science should work. Hasty work, especially in research, is dangerous."

The scope of the project can be seen not only in the time it took to fully characterize the fossils, but also by the human involvement in the project. Hundreds of people have worked at the site since 1992, and a total of 47 different scientists representing 10 different countries and many specialties in paleontology and geology worked together to write the *Science* papers. Such a large project creates unique challenges, but also great benefits for the research, as well as for the researchers themselves. "When the participant number increases, the management part is challenging," Asfaw says. "Still, the benefit is enormous. Everybody has his own expertise, and you learn from each other."

While there have been a huge number of people involved in the *Ardipithecus* project over the course of its history, one figure has always been central: UC Berkeley integrative biology professor Tim White, who was involved in the discovery of the first *Ardipithecus* fossil and has been a co-director of the project since 1981. Earlier in his career, White was involved in analysis of the Lucy skeleton, a 3.2 million year old *Australopithecus afarensis* specimen that was the oldest hominid ancestor skeleton before Ardi's discovery (see sidebar). This research primed him for the work on Ardi that would be a focus of 15 years of his life.

Creating a cohesive picture from fossil evidence requires incredibly detailed knowledge about an extremely broad set of disciplines, including anatomy, dentition, geology, and paleontology. Furthermore, highly sensitive and complex techniques must be used to carefully extract and restore fossils, measure the composition of different samples to date them or analyze the diet of a fossilized specimen, and characterize the fossil environment. Renne describes White as the intellectual hub for the diverse team that brought together the necessary expertise to characterize Ardi. "The variety of specialists on the team is a really interesting dimension of this project," Renne says. "It has the most participants of the most diverse backgrounds of any project that I've ever worked on. It's kind of like a branching network with all these little nodes of ultra-specialists, and we channel our knowledge through people with broader knowledge who can put it all together. Tim is really the one keeping track of all of these disparate lines of evidence and integrating them into a complete story."

While White relies on a large team of specialists to help with his analysis, his own knowledge is nonetheless profound. "I regard Tim as absolutely at the height of his profession in terms of his knowledge of human anatomy and recognition of these features in fossils," Renne says. "In relation to the Ardi work, as always, Tim was very attuned to the broader context of his work. He has a keen grasp of paleontology beyond just hominid evolution."

### The dating game

*Ardipithecus* is a crucial find for elucidating human evolution because of its age, over a million years older than Lucy (see sidebar). Determining the age of these finds was thus an important first step, and according to Renne, the first part of the dating process was pretty straightforward. There was a layer of volcanic ash just under the fossil finds that was amenable to dating by argon-argon dating, which just so happens to be Renne's specialty.

Conventional argon dating relies on the natural radioactive decay of potassium to argon. This conversion was first used for potassium-argon dating, which required separate measurements of the potassium and argon content of a sample. The age of the rock can then be determined using the known rate of decay for potassium converting to argon. This technique is particularly powerful for

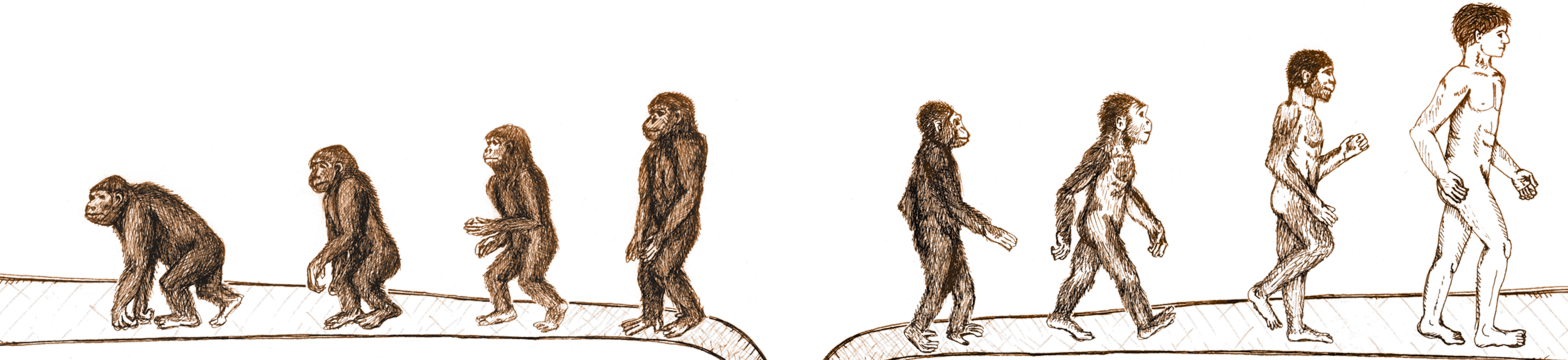


BONES THROUGHOUT THE ARTICLE: JOHANSON & WHITE

### Lucy

Before Ardi stole the spotlight, there was Lucy, a 3.2 million-year-old female of the species *Australopithecus afarensis*. Lucy was found in Ethiopia in 1974, not far from where Ardi was discovered, and showed a striking combination of hominid and ape-like features. While no older fossils had previously shown characteristics of bipedalism, fossils of Lucy's legs, feet, and pelvis indicated that she likely walked upright (although this is still a subject of debate). Her brain was quite small, only slightly larger than that of a modern chimp's. At the time, it had been thought that developing a larger brain was the driving force behind hominid evolution, so the discovery of these small-brained bipeds was quite revolutionary when the first Australopithecus finds were made in South Africa in the 1920s and 30s. Now, however, it is widely believed that hominid brains did not begin enlarging until long after bipedal locomotion had been established.

After its discovery, *Australopithecus afarensis*, with its small brain and large teeth, was taken as the model for the last common ancestor between chimps and humans until Ardi's discovery. Ardi's suite of characteristics, however, indicate that this ancestor was in fact much more primitive than expected and that it lacked many characteristics seen in modern apes. For example, Ardi's teeth are relatively small and unspecialized, indicating that Lucy's teeth were not descended from a primitive chimp-like ancestor, but instead specifically evolved to deal with hard, abrasive foods. Lucy's similarity to modern chimps may be the result of common evolutionary pressures leading to similar traits, but further characterization of the hominid fossil record in the four- to six-million-old range will be needed in order to fully understand the path of hominid development.



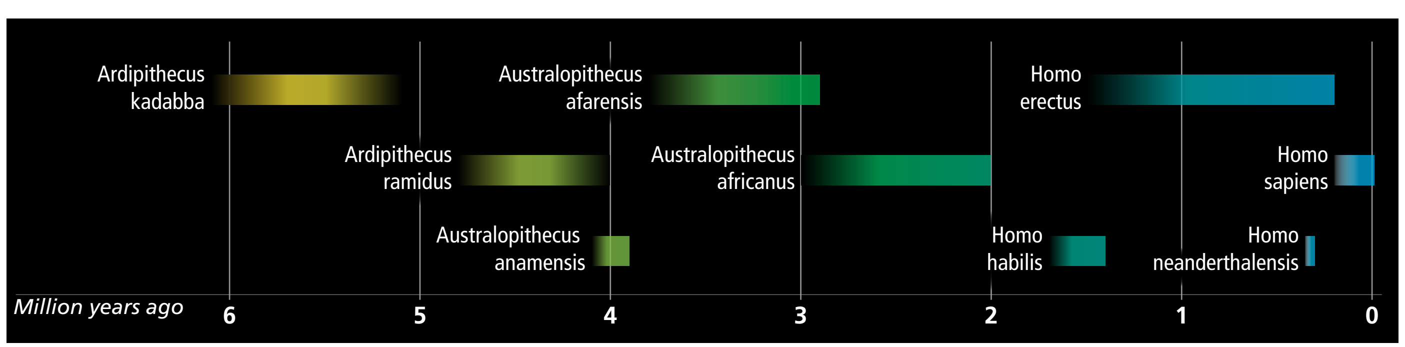
*While the last common ancestor between humans and chimps remains undiscovered, Ardi has revealed important information about the beginning of these two lineages. The typical cartoon depicts humans evolving from a hunched, chimp-like ancestor, but Ardi displays upright posture and none of the anatomical specializations that facilitate knuckle-walking or arboreal locomotion seen in chimps and gorillas. Therefore, it appears that both humans and chimps arose from a relatively upright*

dating volcanic sediment because all the argon in the magma diffuses away, so any argon present in the sample has resulted only from decay of potassium originally present when the lava first hardened into rock.

Argon-argon dating differs from argon-potassium dating by treating the sample before analysis to convert some of the remaining potassium to argon. This conversion, however, is different from the transformation that occurs naturally, creating a slightly different type of argon, argon-39 (argon-40, which has a slightly heavier nucleus than argon-39, is the result of the natural decay process). The advantage of this technique is that both types of argon can be measured in a single experiment, reducing error and greatly increasing precision. Thus, by measuring the amount of argon-40 and argon-39, the date of a sample can be determined very precisely

The layer of volcanic ash below the *Ardipithecus* finds was enriched in potassium, which made for easy argon-argon dating. However, dating just the layer below the fossils only defined an older limit. The team also needed to date a layer above the fossils to draw boundaries on an age range for *Ardipithecus ramidus*. They identified a volcanic layer above the fossils, but the quality of the rock was much poorer for argon-argon dating. While the older, lower layer was quite sandy, providing many individual crystals for analysis to confirm the date, the younger, upper layer was composed of more solid rocks. It also contained much less potassium and was mostly glass, which is very unstable over time and can result in spuriously young ages. Eventually, the team was able to find enough suitable crystals and, after extensive treatment to optimize the dating procedure, found that the upper layer was exactly the same age as the lower layer. This relatively unique 4.4 million-year-old sandwich implies that all of the *Ardipithecus* fossils were deposited in a short time and can be thought of as a snapshot of a particular time and place in our evolutionary history.

There is always uncertainty in dating samples that are millions of years old. Renne, however, is confident about his dating procedures. The argon-argon technique has unprecedented precision—Ardi's date was determined within 0.01 percent—and the accuracy can be calibrated against known historic events like the Mount Vesuvius eruption in 79 AD and the cyclical changes in the earth's magnetic field, which can be used to date rock up to a billion years old.




*Modern humans, or* Homo sapiens, *are the descendants of a long line of ancient hominids; a sampling of these species are shown on the timeline above. Scientists cannot determine exactly which ancient hominids were ancestral to other species, or to modern humans, so a complete family tree is out of reach. However, as the timeline suggests, it is likely that* Ardipithecus ramidus *gave way to* Australopithecus, *which then gave way to* Homo *and modern humans.*

FROM TOP: COLLEEN KIRKHART, MAREK JAKUBOWSKI BASED ON ARCHAEOLOGYINFO

"Here at the Berkeley Geochronology Center, we're probably more obsessed with calibration and accuracy than anyone else on the planet," Renne says. "We have the luxury to do it, and frankly we have a mandate to do it. We're the only institute in the world dedicated to geochronology. We have the freedom to really push hard and really improve techniques as we simultaneously apply them to projects that float our boats."

## The bones don't lie

At 4.4 million years old, Ardi adds almost a million years to our knowledge of hominid evolution, and the characteristics seen in this ancient hominid reveal many important details about where we come from. Fossils from 36 individuals combine to create a picture of a hominid that is unspecialized and not nearly as chimp-like as was long expected.

For many years, most paleoanthropologists assumed that the last common ancestor between chimps and hominids was like modern chimps. The main argument behind this assumption is that chimps and gorillas, which diverged earlier (more than eight million years ago) are highly similar. It was thought that chimps and gorillas have so much in common that they could not have both evolved the same characteristics in parallel. Therefore it seemed most logical that their common ancestor had developed these trademark characteristics—hand skeletal arrangements for knuckle walking, a somewhat hunched posture, their protruding mouths, and sexual dimorphism—and that they had been subsequently lost during the course of human evolution. The *Ardipithecus ramidus* fossils, however, do not show most of these highly specialized characteristics. Instead, *Ardipithecus* appears to have been a much more primitive species, indicating that similar properties did in fact evolve individually in both the chimp and gorilla lineages, but not in humans.

Teeth, which are generally quite common among fossil finds, provide one example of such evolution. Apes live in male-dominated social groups, and the males fight using their protruding canine teeth, which are constantly honed against lower teeth to maintain their sharpness. This dental characteristic is found in both apes and gorillas, but the *Ardipithecus* dentition indicates that they were not using their teeth as weapons. The teeth show no evidence of canine honing, and the male canines are not markedly bigger than the rest of the teeth, implying that there was not significant conflict among males of the species. In other words, it appears that multiple males and multiple females could live together without major male-male conflicts, a social structure that is unique to hominids relative to our ape cousins.

### Lumpers and splitters

Defining species can be a tricky business, especially when the organisms in question have been extinct for millions of years. The general definition of a species is a group that can breed to produce fertile offspring, but if the animals only exist as fossils, this test is no longer a practical barometer. Thus, assigning fossils to species can be largely a question of inference based on knowledge of modern primate species. Depending on their personal speciation philosophies, anthropologists may be referred to either as "lumpers" or "splitters," with lumpers placing many individuals in the same species despite variations among them and splitters dividing organisms into many different species based on small differences. Furthermore, there is the added complication of changes over time. If fossils are dated one million years apart but show similar features, are they the same species or not?

UC Berkeley integrative biology professor Leslea Hlusko studies variation within related baboon populations to explore the amount of variation that can be expected in a modern primate species. "You have to understand ranges of variation and ask yourself, how much variation are you comfortable with within a species?" says Hlusko. "We've looked at 632 related living baboons, and within that population, there's a lot more variation than a lot of people would be comfortable with. Ultimately, the species labels are a very static language that you apply to a dynamic process. But how else are we going to talk about it?"

*The digitally reconstructed* Ardipithecus ramidus *foot skeleton (center) shows an opposable big toe, unlike that of a modern human (right), but also lacks many of the specialized features evolved in chimpanzees (left).*

FROM LEFT: BONE CLONES; SCIENCE/AAAS; BONE CLONES

Ardi's hands, feet, pelvis, and limbs also reveal some departures from an ape-like common ancestor. Chimps have an incredibly flexible foot skeleton ideal for both climbing and grasping. Humans, on the other hand, have quite a stiff foot to act as a better support for upright walking. The *Ardipithecus* foot shows a mosaic of these characteristics, providing further evidence that the chimp is not the primitive condition but instead a highly evolved structure optimized for its environment.

The hands reveal a similar picture. While apes have developed specialized features to allow for knuckle walking on the ground and hanging and swinging through the trees, the *Ardipithecus* fossils do not display any of these traits. Instead they are rather primitive, allowing for slow climbing through the trees, but also retaining more flexibility in the hands and wrists than seen in modern apes. Furthermore, *Ardipithecus* does not have the long arms and short legs associated with knuckle walking behavior, indicating that she was probably bipedal when on the ground, clarifying a long unanswered question about our earliest hominid ancestors.

"The locomotion information we got from Ardi is very important," says Asfaw. "We were all using chimpanzees as a model to envision how the shift took place from a quadrupedal mode of locomotion to bipedal. Now we have seen from Ardi that the foot and hand bones are not transformed from those of a chimpanzee. Chimpanzees have a very specialized hand and foot for their kind of suspensory mode of locomotion in the trees. What we see from Ardi is that the common ancestor of hominids and chimps had a monkey-like hand and foot."

Finally, Ardi's pelvis confirms the picture of an arboreal climber and terrestrial biped. The team refers to the pelvis as mosaic, combining characteristics of a chimp-like pelvis optimized for climbing and the human pelvis optimized for walking upright. Compared to Lucy's pelvis, Ardi's is still quite primitive, meaning that she was not as good at walking or running long distances. However, Ardi's pelvis is also distinctly different from the modern chimp's, which should rightfully be considered a highly evolved, specialized organism and not an evolutionary relic from the days of the earliest hominids.

"*Ardipithecus ramidus* and its prevailing anatomy revolutionize the way most of us understand the earlier part of our evolutionary history," according to UC Berkeley's Yohannes Haile-Selassie, project member and curator of the Cleveland Museum of Natural History. "This is not an ordinary fossil," White elaborates. "It's not a chimp. It's not a human. It shows us what we used to be."

## Why walk?

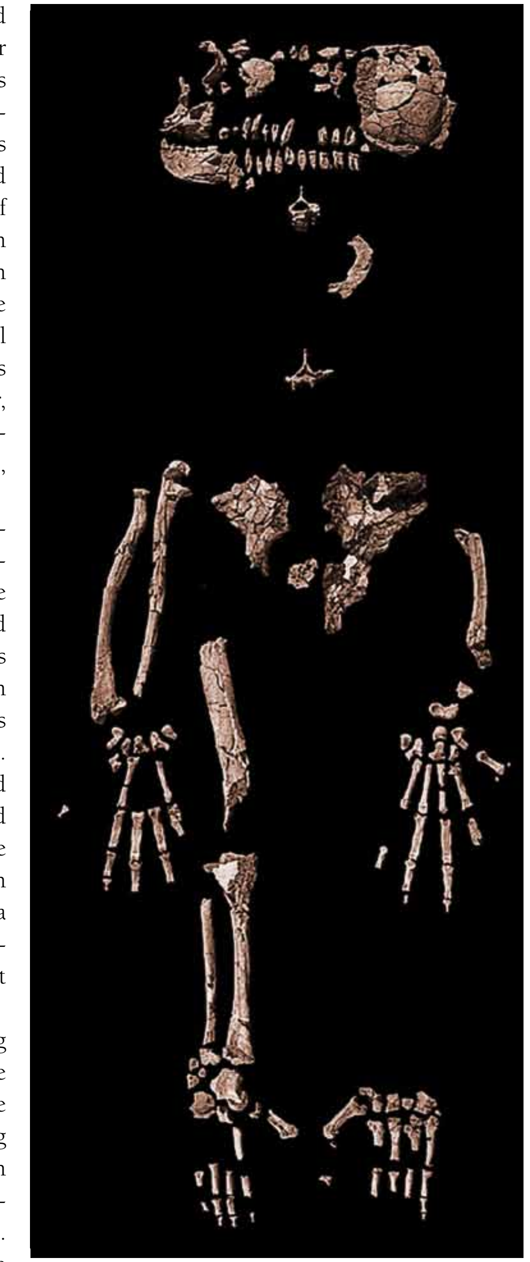
One of the big questions for bipedalism is not simply when it developed, but also why it developed. In many ways, arboreal living seems much more advantageous. Climbing into trees to nest and escape predators is vital to all non-human primates. "Most important is food," says Kent State anthropologist Owen Lovejoy. "Most of the foods consumed by most higher primates are arboreal. Becoming more terrestrial turns your world from three dimensions into two and implies a much larger searching time and range will be necessary to find various foods."

Why, then, would hominids have evolved to live on the ground? A number of explanations have been offered, including the increased ease of using tools and guarding resources on the ground rather than in the trees. The savannah hypothesis is another common justification for the origin of bipedalism. This hypothesis argues that decreased forest cover of the hominid habitat required that they venture out of trees to gather food. Terrestrial bipedalism would have been much more efficient than quadrupedalism for this purpose because it leaves the arms free for carrying. Careful analysis of fossilized plants and animals found near *Ardipithecus* fossils, however, shows that they lived in a woodland environment rather than the open savannah, discounting this long-standing hypothesis.

Lovejoy offers an alternative hypothesis in light of new evidence from *Ardipithecus*. He argues that the unique advantage for terrestrial bipedalism is directly related to reproductive fitness. Walking on two legs leaves the arms free for carrying food, which would be especially valuable to females taking care of highly dependent young. Furthermore, if the mother was occupied with caring for her offspring, she likely did not have the time to go out in search of the necessary resources. If she could depend on the child's father to provide her with extra food, she and her children would be better nourished, and they would also benefit from reduced predation.

But it wasn't quite as easy as sending her husband to the grocery store in the family minivan. The male would have wanted something in return for risking his life to bring home the bacon: a high probability that the young he was providing for were his actual biological offspring. Therefore, pair bonding, with the female consistently giving sexual preference to the male that brought her resources, might have encouraged the males to provide for their families. The idea of monogamous families was enforced by the fact that *Ardipithecus* females didn't visually advertise when they were ovulating, which is a trait relatively unique to hominids. By keeping her reproductive cycle under wraps, a female had more power over who fathered her offspring because there was no visible signal to alert dominant males and encourage them to force themselves upon her. In simple terms, the female could provide sex, and thus future offspring, as a trade for food from a specific male, creating a relatively monogamous society in which the offspring were receiving valuable resources from each parent.

TIM WHITE



*One* Ardipithecus ramidus *specimen, ARA-VP-6/500, or Ardi for short, provided a wealth of information due to the relatively completeness of her skeleton. Although her skull had been crushed, researchers were able to use the pieces to reconstruct it, and her hands, feet, limbs, and pelvis provided important details about her posture and mode of locomotion.*

Lovejoy argues that these elements of parenting were crucial in allowing for the brain growth that would eventually characterize the hominid line. "A large brain implies that selection is favoring the development of intelligence as a part of the lineage's reproductive strategy, that learning is important, but learning delays maturation because you need experience under the protection of parenting to 'program' your brain," says Lovejoy. "So when a brain begins to enlarge in the fossil record, it means that survivorship has increased and maturation is being delayed. We believe that all of the elements of advanced parenting were in place before the major advance in brain size in hominids." He does add that there are indications that Ardi already had a more advanced brain structure than living apes. Brain size is certainly an important element of hominid evolution, but other factors like bipedalism and increased female mate choice must also be taken into account in considering the sequence of the development of uniquely hominid characteristics.

## Beyond Ardi

The Ardi skeleton and associated *Ardipithecus ramidus* fossils have provided a unique snapshot of an evolutionary time and place, but the work is far from finished. More *Ardipithecus ramidus* fossils from different sites and of different ages are needed to fully determine the time and geographic range that these ancient hominids inhabited. Furthermore, while Ardi is the oldest hominid skeleton found to date, another species lays claim to the title of oldest hominid ancestor. Discovered and characterized by many of the researchers involved in the Ardi work, including White, Asfaw, Suwa, Haile-Selassie, and Renne, *Ardipithecus kadabba* is represented by teeth and a few bits of skeleton that were dated to 5.7 million years old, 1.2 million years older than *ramidus*. Originally considered a subspecies of *Ardipithecus ramidus* upon its discovery in 2001, in 2004 further fossils showed that the teeth of *ramidus* and *kadabba* were sufficiently different to merit distinction as separate species.

*Ardipithecus kadabba* highlights many of the challenges facing paeloanthropologists, including determining how much variation can be expected in a single species and characterizing our ancient ancestors based on sparse fossil evidence. *Ardipithecus kadabba* is likely *ramidus*' ancestor, but the evidence at this point is sparse. The team continues their work to further characterize both *ramidus* and *kadabba* with the hope to further elucidate our species' past the only way we know how: finding more fossils. "Ardi took us some distance closer to the common ancestor," Asfaw says, "but the record of human evolution is still full of missing data. We would like to recover those data and get a better picture of hominids' evolutionary history."

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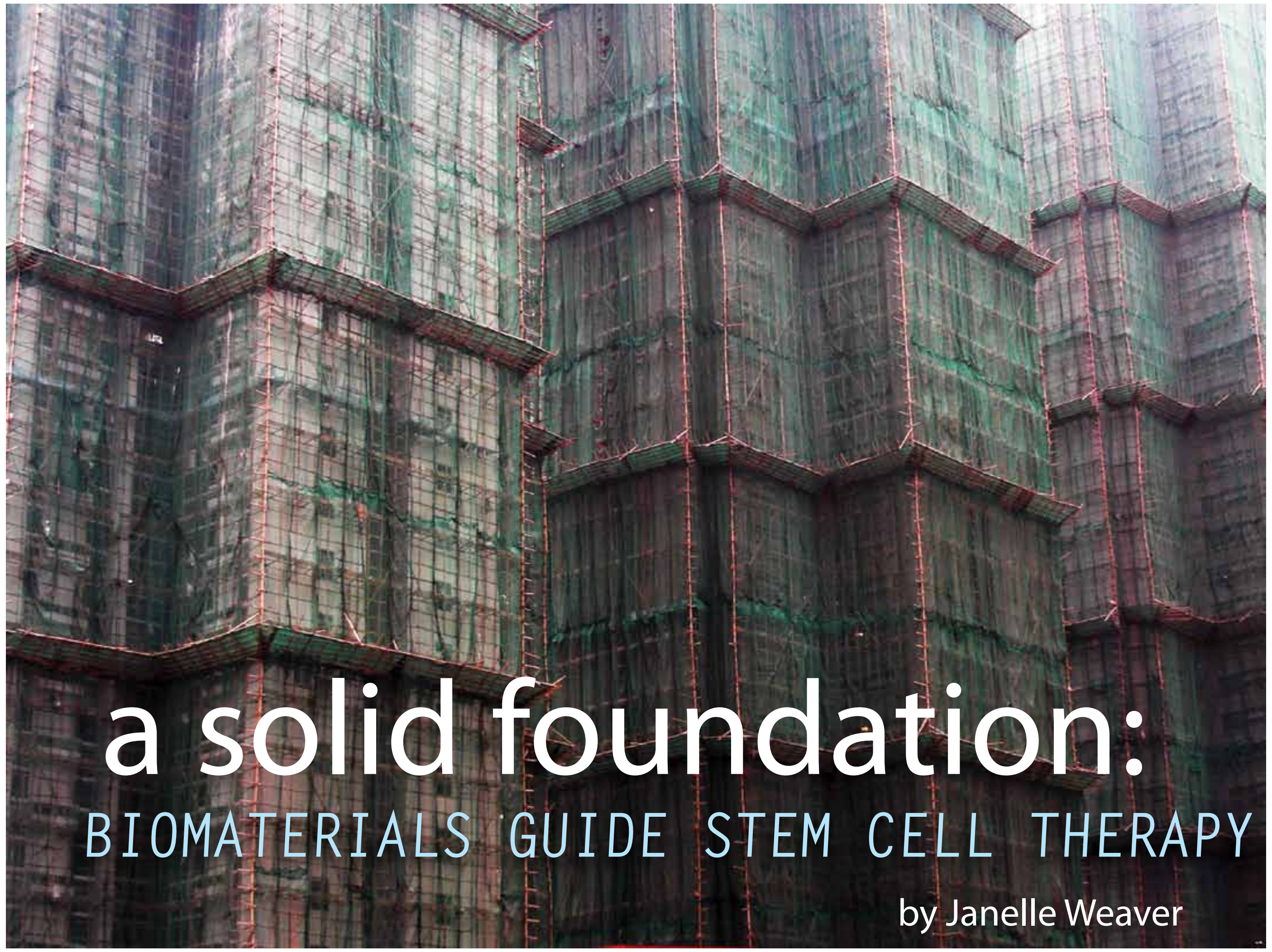
**Rachel Bernstein** *is a graduate student in chemistry.*



# a solid foundation:

## BIOMATERIALS GUIDE STEM CELL THERAPY

by Janelle Weaver

Kevin Healy is enchanted by biomaterials, right down to the props in his office. There's the vascular stent: a Teflon-covered, man-made tube that keeps arteries open. Then there's the Teflon-based vascular graft: a long tube that channels blood in patients with weakened vessels. These items are made of polymers, or large molecules consisting of repeating units, that are relatively harmless inside the body. Healy hopes to infuse them with stem cells, inject them, and repair damaged tissue in a wide range of organs, from hearts to brains.

A professor in the bioengineering and materials science departments at UC Berkeley, Healy is developing networks of polymers, called hydrogels, which act as a type of jungle gym for stem cells to grow on. Once injected into the body, they promise to restore damaged tissue without causing an immune reaction. Made of similar building blocks as cells and tissues, they're naturally broken down by the body, leaving little trace.

"Think of a hydrogel as a contact lens. It's dry—it's just a large molecule—but when you add water to it, it actually holds the water like a sponge," Healy says. A lab demo by graduate student Kimberly Kam makes that clear. When she injects a clear gel from a syringe into a flask of water, it looks stringy, like a piece of spaghetti. But when she pumps the same gel into a warmer body of water, it becomes stiff and opaque. The hydrogels are thermo-responsive "smart materials" that sense changes in their environment. If surgically injected as a liquid, they become stiffer when they warm to the body's temperature. Then they're ready to act as a scaffold for cells. By making the gel harder or softer, scientists can coax stem cells to become different types of cells.

Much past research has focused on identifying the chemicals that to determine a stem cell's fate. But the importance of mechanical forces is just starting to garner attention. Healy is one of a handful of scientists around the world who is developing materials to guide what stem cells become. Healy's lab is teaming up with chemical engineer David Schaffer and bioengineer Sanjay Kumar at UC Berkeley to pinpoint the molecules that sense mechanical properties, such as scaffold hardness, and translate these signals into a cell's fate. Together, the three labs hope to set the stage for safer, more effective stem cell therapies for a range of diseases, including heart disease, Parkinson's, Alzheimer's, retinal diseases, and spinal cord injuries.

### Healy's hydrogels

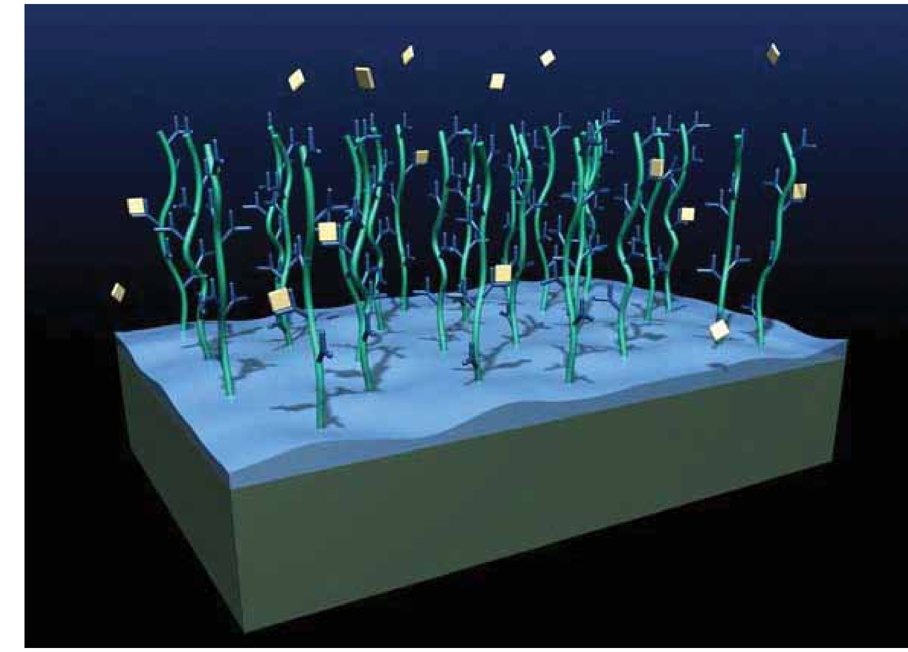
The idea behind hydrogels is to mimic the normal environment found outside cells. Cells are arranged into tissues and organs by a sort of glue called the extracellular matrix (ECM), a network of proteins that anchor cells in place. Proteins hanging off of cells connect with the ECM, like kids' arms on monkey bars. The hydrogel has little snippets of ECM glued onto it; these bind to the proteins hanging off of cells and hold the cells in place.

Once injected into the body, the hydrogel changes shape and lets cells grow into it. The hydrogel also releases chemicals that help cells recover. Eventually the artificial hydrogel is replaced by natural cells in the body. Hydrogels can stabilize damaged tissue and attract healthy cells.

Sometimes the hydrogel carries stem cells, which encourage growth of new tissue, and other times it releases drugs, which have a targeted effect at the site of injection. "We're putting the drug right at the site where the drug is needed," Healy says. One example is atropine, which is used to treat myopia, or nearsightedness. The hydrogel's structure helps hold the drug or drug delivery system in place. So far, the treatment has not been carried out in humans.

Healy's lab is fine-tuning the three-dimensional design of the hydrogel to increase the odds that it will stimulate new growth in damaged tissue. He hopes one day to translate his research to clinical applications.

IOAN SAMELI



*At the molecular scale, hydrogels are composed of long, brush-like polymers that absorb water molecules (yellow) and swell, softening the material into a gel (hence the name). Certain hydrogels absorb water at cold temperatures and expel it at high temperatures, so when they are warmed (after being implanted in the body, for example), they harden and form rigid structures ideal for tissue engineering.*

FEATURE Biomaterials

### Fickle stem cells

Human embryonic stem (hES) cells are derived from embryos and have the potential to become any cell in the body. They multiply until they are told to "differentiate" by extracellular signals and become tissue-specific cells. But this amazing ability poses a great risk: if the cells continue to divide uncontrollably after transplantation, they can lead to a tumor. Growing stem cells that are safe and effective for regenerative medicine is a huge challenge. In February 2009, scientists reported the first known case of a stem cell transplant that caused a tumor in a patient.

Hydrogels could help overcome the problems with stem cells in two ways. First, they could be used alone, without stem cells, to help repair damaged tissue. This would bypass all the ethical, medical, and technological challenges associated with stem cell research. Indeed, Healy is investigating whether hydrogels can help strengthen eye tissue in animal models of myopia. Second, hydrogels might help guide stem cells to the correct fate in a Petri dish, thereby ensuring a pure colony of cells that would not later form a tumor inside a patient. Then the hydrogels and accompanying stem cells would be injected into damaged tissue. For the latter option to work, it's essential to understand the chemical and mechanical cues that guide stem cell differentiation.

Despite some progress, stem cell research tends to advance in fits and starts. It works one day, it works for two weeks, it works for two months and then one day it stops. "You consider it a success when you can actually make differentiated stem cells in your lab, but it doesn't always mean that someone else will be able to repeat it," Healy says. Hydrogels, on the other hand, aren't as touchy because they are completely syn-

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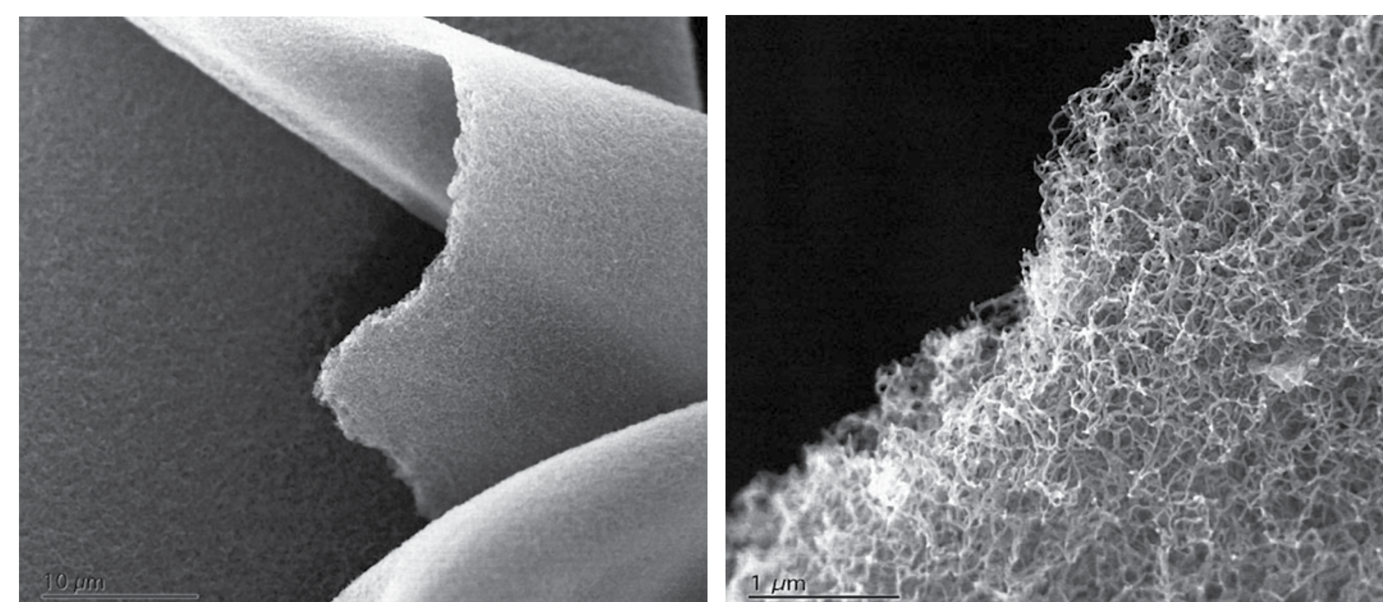
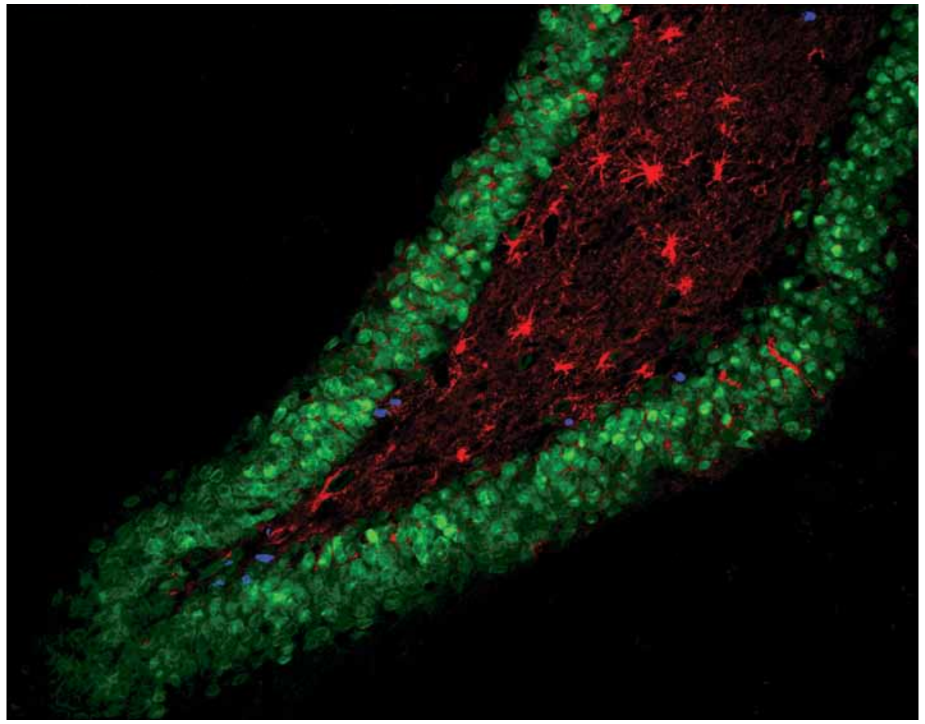



*Scanning electron microscope images of hydrogels created at UC Berkeley. The porous structure of hyrogels forms a scaffold to which cells can attach.*



*The adult brain contains neural stem cells that continually divide to generate new neurons throughout life. This image shows neurons (green), astrocytes (red), and stem cells (blue). If we learn enough about the signals that control the behavior of these cells, they could potentially be harnessed to regenerate neural tissue.*

thetic. "Now, even though there's this push for using stem cells, if you could get the job done without stem cells, it's much easier from a practical and regulatory standpoint," Healy says.

Another problem with stem cells is that they typically don't survive and integrate with existing tissue once transplanted. In the case of cardiac therapies, "they sit there isolated by themselves," Healy says. "They're not electrically or mechanically coupled to the heart. They're not doing anything. They actually could be doing more harm if they're beating off cycle." He hopes hydrogels could help stem cells integrate with surrounding tissue by providing a scaffold that holds cells in place. Research in this area might make it possible to transplant stem cells into the heart so that they beat in synchrony with other heart cells.

## Translating firmness to fate

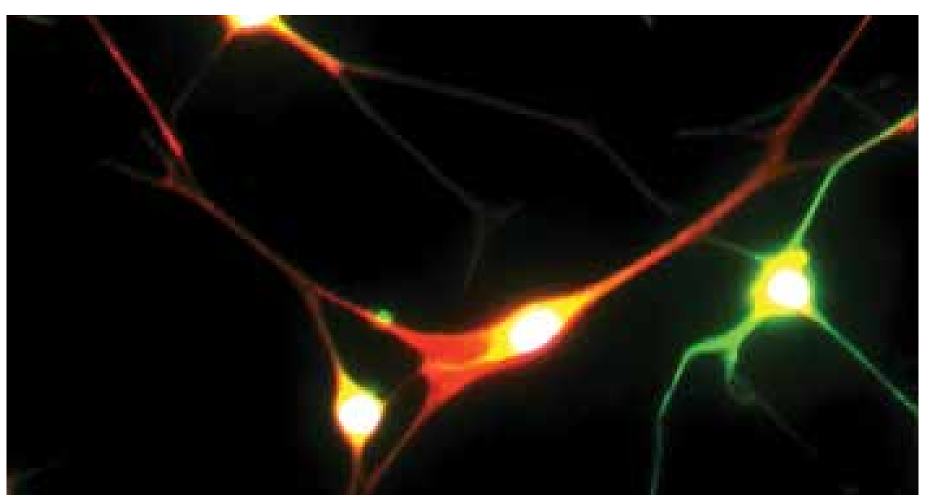
Healy, Schaffer, and Kumar are doing everything they can to get stem cells to behave. They hope one day to inject hydrogels filled with stem cells into patients with neurodegenerative diseases and spinal cord injuries. But first, they must figure out how stem cells choose their fates in a dish.

The first report that gel stiffness influences the fate of stem cells came in 2006 from Dennis Discher's lab at the University of Pennsylvania. Then, in 2008, Schaffer and Healy were the first to report that neural stem cells respond to stiffness. Harder hydrogels are more likely to produce glial cells—cells in the brain that form tough scar tissue. Soft hydrogels more often lead to neurons. How the physical environment in a dish influences the fates of stem cells sheds new light on past experiments, which typically ignored the role of mechanical forces.

The fact that stiffness affects stem cell fate may seem surprising to those outside the field, but there were previous clues in biology. You may think that cells are mechanically insulated from the environment, but even cells inside the brain pulsate as an aftereffect of a beating heart. Bones remodel in response to forces placed on muscles and ligaments. Scar tissue and tumors are harder than surrounding brain tissue. Even different cell types within a brain region have different levels of stiffness. Many cells are constantly pushing and pulling on their environment. "We think that this process of mechanical loading has something to do with what those cells will eventually become," Kumar says.

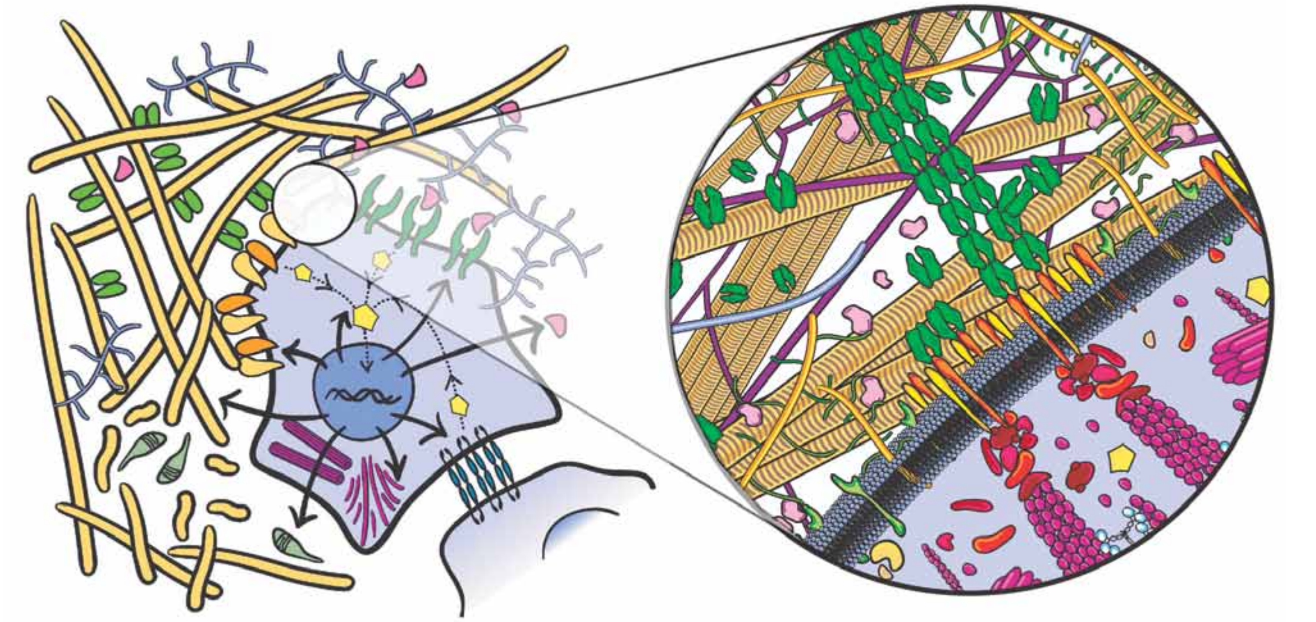
Both chemical cues and mechanical stiffness affect a stem cell's choices. If you add a chemical that tells the stem cell to become a specific type of cell, making a stiffer matrix will help tip the balance, making the differentiation more reliable. If you add another chemical that tells cells to replicate themselves, an intermediate stiffness will work best. "Just figuring out how to control cell behavior by providing the appropriate chemical cues is something that the field is working out," Kumar says. "To take the next step, to do this mechanically, is quite challenging but could potentially be very rewarding."

When it came to pinpointing which molecular pathway translates mechanical cues to fate choices, the answer was easy. Schaffer's team dug through previous studies and zoomed in on Rho GTPases because of their role in changing the mechanics and shape of the cell. "We've begun to march down the pathway on the inside of the cell and ask how mechanical information is conveyed, molecule by molecule, from the cell surface to the nucleus, where ultimately the decisions about cell fate can be made," Schaffer says.



*Neurons (green) and astrocytes (red) that were differentiated from adult rat neural stem cells grown on a peptide-grafted hydrogel surface. Neural stem cells respond to the stiffness of the medium, with harder gels generating astrocyte differentiation, and softer gels generating neurons.*

FROM TOP: DAVID SCHAFFER; LAUREN LITTLE



*By incorporating proteins for cell adhesion (green and pink) directly into the hydrogel matrix (yellow), cells can more readily attach to the hydrogel matrix via complementary proteins on their membranes (yellow and orange). These adhesion proteins also act as signals for stem cells, telling them about the tissue environment and what kind of cell to become. This causes stem cells to produce more tissue-specific proteins which are secreted into the hydrogel and help to further define the new tissue.*

JACOB POLLOCK

While most past research has focused on how freely moving chemical cues can affect stem cell fate, Schaffer and Healy look at the role of molecules, such as ECM snippets, which are fixed onto the hydrogel matrix. The advantage of such unmoving cues is that they can present the cell with spatially organized patterns. These patterns cause receptors on the cell surface to cluster differently, which changes how cells respond to signals in their environment, as well as to mechanical forces inside the cell. Schaffer and Healy are now examining how fixed patterns may help turn hES cells into neural cells. By manipulating the physical environment of the stem cells, scientists may gain more control over determining their fate and reducing the threat of tumor formation.

## The future of hydrogels

Hydrogels show great promise because they are safe—most do not trigger immune reactions—and they can easily be mass produced. But this is not the case with stem cells. Up to a billion cells might be needed for a single patient. "That's an enormous number of cells compared to what we typically deal with in the lab," Healy says. Before stem cell–laced biomaterials can reach the clinic, scientists must overcome several hurdles. "There's no real clinical output yet," Healy says. "I think we're still far away from that."

To date, most work examining the effects of stiffness on stem cell differentiation has been done in cell culture dishes, but it remains to be seen how this will translate to tissues in the body. "As scientists, we forget that cells live in the body, not in a Petri dish," says Theo Palmer, a neurologist at Stanford University. "It's really difficult to say that all the work we do in the very constrained environment of the Petri dish really represents the range of cellular responses that occur in living, behaving organisms." Clinical adoption will also require the development of new procedures that direct stem cell–laden hydrogels to the damaged tissue. "It's one thing to make a hydrogel in the lab," says Kumar, "but how do you get it to the site where it's needed? It would be nice to inject a liquid that hardens once it reaches the site of action."

Early therapies may involve the injection of hydrogels, either alone or with a drug, into diseased tissues to slow degeneration, Palmer says. Next would be to incorporate adult stem cells into hydrogels. "This therapy could be applied right away to treat stroke or spinal cord injuries," Palmer says. "The lowest hanging fruit is to deliver cells, not to restore the damaged circuitry, but to have them be healthier and happier after transplant and protect the local environment a little better."

Ideally, scientists would like to incorporate hES cells into these hydrogels because they have the potential to become myriad cell types that could restore damaged neural circuitry or tissue. That's harder, because scientists will need to make sure all the stem cells become the right cell type; undifferentiated cells can lead to a tumor. What's more, the cells would have to integrate properly with the existing circuitry. "If you pattern the stem cells first and mix them with the right kind of scaffold, that would promote neurons to survive after transplantation," Palmer says. "Then that becomes really exciting."

The idea of using hES cells to treat diseases never would have occurred to Healy when he first began his scientific endeavors. As an undergraduate, he was captivated by artificial hearts, and his project involved fabricating vessels using plastic. He pointed out to his adviser that the blood kept clotting in the plastic replica; then he asked him why. The response: "Nobody knows how to make something that will work in the human body."

By developing an innovative gel that mimics the natural cellular environment, guides the fate of stem cells, and may repair damaged hearts, Healy and his collaborators sure have brought biomaterials a long way.

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**Janelle Weaver** *is a graduate student in the UC Santa Cruz science writing program.*

# Letter from the field: Igniting scientific curiosity in the AMAZON

PAR AVION

by Richard Novak

A chlorophyll and cellulose shag carpet stretches out to the horizon, past the cauliflower thunderheads, across a land punctuated only by oxbows of ancient tributaries of the Amazon River. I look out the plane window and see a wound of bare red clay glaring up through the soggy atmosphere, a sign of a logging or mining camp; it's hard to tell which since rain and bulldozers erode the naked earth equally well here. Tin roof huts huddle in a makeshift village. As the wing flaps go down and the engines slow to a pleasant hum, the raw earth gives way to occasional patches of papaya and manioc, and later the trash heaps that go hand in hand with an outpost city. The juxtaposition of rich landscape with squalid living conditions reminds me why we, a group of graduate students, teachers, and professional engineers called Future Scientist, decided to come to the Peruvian Amazon.

The term "resource-poor" can be a misnomer for the Amazon basin: it is not necessarily the resources that are lacking but rather the knowledge of how to best utilize them. Although natural resources abound, some communities still lie in a precarious balance with disease, malnutrition, and inadequate energy. In the Amazon, it is common for over one third of a rural community to become sick with serious transmissible disease during a typical year, yet it is just as common to see adults and children collecting river water for cooking right next to floating toilets. A mother will burn firewood gathered from the forest to boil water for her children's meals, not knowing that the resulting indoor pollutants are likely to cause lung cancer and other pulmonary diseases. The presence of technology alone is not sufficient to solve existing problems. For example, a new generator donated to a town by the government will break down, with no one capable of maintaining or fixing it.

The majority of Future Scientist members had previously been involved in various science outreach programs, such as Community Resources for Science in Berkeley (see *BSR* Fall 2009), and many of us wanted to apply the principle of education as a means of change a little farther from home. We wanted to start an organization that would foster science and technical education in order to kick-start local utilization of the available resources and, eventually, sustainable local entrepreneurship.

While we are certainly not the first organization to promote sustainable development in resource-poor countries, Future Scientist is unique in that it focuses explicitly on education. Education is vital for a society's success. We decided on the following approach. First, identify a region where resources are underutilized because of a lack of science education. Next, develop low-cost solutions and lessons designed around new technologies in order to demonstrate the practical benefits of science and engineering, and encourage community participation in installation and maintenance. Finally, establish sustainable programs in local schools that couple technological solutions with financially sustainable business models.

## Building an office in the jungle

Through friends, we made arrangements to work with the Casa Girasoles Boy's Orphanage in the village of Puerto Alegría near Iquitos, Peru. The orphanage director, Gene, was interested in using solar power for lighting and other applications such as powering a laptop or a television set and radio. Because they had already identified a solution that would address their needs, we were able to focus on developing science lessons and installing solar panels rather than spending time evaluating various solution options. We brought small solar panel teaching kits to demonstrate to both students and adults how light can be turned into a practical resource. Solar electricity lessons were complemented with ones on solar heating to show how simple solar ovens can be used for cooking.

On our first day there, as the morning mist evaporated under the tropical sun, we began to collect the tools and materials for installing solar panels on the roof of the director's house. Two orphanage assistants ran off into the rainforest and returned with a custom-built ladder made out of slender tree trunks and branches nailed together. The robust acrylic panels we designed and built to withstand the demanding journey to the Amazon were unpacked and the kids watched in amazement as we showed them how the panels could power a fan to cool them off in the heat. They laughed as we clambered up the ladder for the first time, trying not to think about the precarious ladder or the searing tin roof. Once there we quickly realized that the panel installation would require equipment beyond the limited assortment of tools at the orphanage.

We set out for Iquitos the next day to purchase a drill, wood for a frame, and countless bolts, screws, nails and wiring. The whole city was a Home Depot, and we ended up visiting seemingly all of it to find the materials necessary for a solar panel installation. We got to work cutting the two-by-fours into a frame that could support the solar panels on the roof and allow them to withstand wind and heavy rain. Under the watchful eye of a group of boys, we hauled the completed frame up a makeshift ladder and bolted it to the tin metal roof. Gene urged the boys to pay attention to our work and learn what he perceived to be extremely practical skills. One of the boys climbed a nearby lemon tree to get a better view and watched as we began to wire panels together and measure the output. Our idea of introducing scientific concepts and practical engineering know-how through hands-on projects was working.

## Making sense of technology

During the day, when it was too hot to work on panel installation, we taught science lessons. Rick Henrikson, Frankie Myers, and I, all UC Berkeley bioengineering students, presented lessons to groups of curious boys and adults. We showed them how solar panels convert light into electricity, what electricity really is, and how it can be routed to a power outlet. Frances Bell, an electrical engineer, built solar ovens with the youngest boys and then did a cookie cook-off with two teams of older kids to demonstrate how solar energy can also be used for cooking. Bob Pollard, a biology and sustainable development teacher at the Indian Springs School in Alabama, brought his experience with solar panel installation and education to Puerto Alegría where he marveled at how much the kids wanted to learn. The boys were "starved of scientific exploration and had a real interest in the mechanics of what they were witnessing," Bob explained. Seeing the flash of understanding in a boy after he learned how the sun powered a hand-held fan indicated to all of us the power of knowledge and practical science education to enable local communities to become their own problem-solvers.

Of course, our solar panel installation project was not without its share of unforeseen challenges. The intense noonday heat expanded the plastic panels and caused their seals to leak, requiring additional reinforcement. We had to carefully avoid a large bat colony when installing wiring in the attic, and one day our work was interrupted by the boys chasing a neon-green vine snake through the grass. Finally, miscommunica-

*San Francisco electrical engineer Frances Bell helps a student set up a cardboard and aluminum foil solar oven for a cookie bake-off demonstration of practical solar energy.*

*Future Scientist members Tyson Kim, Bob Pollard, and Richard Novak install solar panel framing on the roof of the orphanage director's house. The panels now power a laptop and TV and reduce usage of a gas-powered generator.*

PHOTO: JERIC SANTIAGO; GRAPHICS: ASAKO MIYAKAWA

AMAZON PHOTOGRAPHS PROVIDED BY RICHARD NOVAK

*Three boys examine water samples collected at a nearby river under a microscope. Hands-on science lessons introduced children to key concepts, such as the connection between microorganisms and water-borne diseases.*

tion during the planning stage posed a problem. During the initial discussions, we were told that, above all, the orphanage needed solar lighting to avoid using the generator. We were given a rough idea of the scale of the buildings and built custom solar panels to fit those metrics. The estimates turned out to be quite inaccurate, and the primary need turned out to be food refrigeration rather than lighting. Although we were able to re-engineer the solar panel system to address some of the additional needs, the experience highlighted the importance of conducting careful needs assessments in the future. We would have been able to provide a more satisfactory result had we been able to visit the site in-person before the pilot project. Despite these setbacks, we were able to complete solar panel installation on time and provide the orphanage with a sustainable source of electricity. The night before we left the orphanage, Gene and his wife were flicking the lights on and off, testing out the benefits of solar power.

In addition to our lessons about solar energy, the rest of the team was busy with other relevant science projects. Since more than half of a typical community becomes ill during the year with various infectious diseases and parasites, we brought microscopes to show how even clean-looking water can harbor organisms that cause illness. Jana Broadhurst, an MD-PhD student at UCSF, and other team members led groups of kids to a nearby swamp to collect water and mud samples. The enthralled budding scientists examined the river water and puddle sludge under the microscope in awe. We also brought microscope slides with various disease-causing organisms, and the boys were shocked when they saw malarial parasites, roundworms, and bacteria that make them sick on a regular basis. Mei Gao, a public

> From behind his back, the older boy pulled out a toad that spanned the length of his torso and said, "Let's dissect it!"

health student at UC Berkeley, then showed that these organisms could be easily filtered using cloth. Along with the microscopy lessons, Tyson Kim, an MD-PhD student at UCSF, and Gautham Venugopalan, a third-year UC Berkeley bioengineering student, showed the boys how a microscope works and had them build their own compound microscopes using magnifying lenses. Gautham found the kids to be extremely creative and receptive to learning about optics. At one point he observed, "I saw at least two kids make compound lens systems on their own without ever being told that it would be a good idea," a sign that relatively small effort can have a great impact.

### Let's dissect this!

The curiosity and desire of the students to understand the world around them made the teaching experience truly rewarding. The boys, true orphans as well as children abandoned by their families unable to care for them, were all raised in rough urban environments and never received the rich natural history education normally bestowed upon kids growing up in rainforest villages. Despite an unfortunate early childhood, these boys never lost the innate curiosity and desire to learn, and voluntarily attended our afternoon hands-on science lessons. When asked at the end of our stay what they wanted to be, a vast majority said "scientist" or "engineer." For the rest of the students, our lessons seemed to spur a greater desire to learn. Jaime, a 15-year-old boy from the town of Caballococha, became intent on learning English and becoming a guide or English teacher around Iquitos and would use the team members for English practice.

While the children's reactions were overwhelmingly positive, our reception by adults was mixed. Teachers from the Puerto Alegría school were fascinated by our hands-on lessons and were interested in adopting the lesson plans and materials into their curricula. They had heard of our activities from the students and were keen on contributing to the excitement. On the other hand, Gene and other orphanage caretakers disapproved of the science lessons that did not have a defined and immediate practical benefit. He encouraged the kids to participate in our solar panel work, but he did not see any value in showing them microorganisms under a microscope or talking about water filtration. He felt that education should consist of agriculture, social studies, and religion—knowledge and skills that prove immediately useful in an agrarian society.

*Solar-powered fans were a big hit in the tropical heat, and allowed the kids to see the rooftop panels in action.*

Nevertheless, our relatively brief interaction with the orphanage seemed to unleash a torrent of learning and curiosity that was not so visible before our arrival. Toward the end of our stay, two boys beckoned me to join them under the dining hall building. From behind his back, the older boy pulled out a toad that spanned the length of his torso and said, "Let's dissect it!" We had never discussed dissection, surgery, or anatomy, and here were two kids wanting to see how a toad works. I ended up teaching an impromptu lesson on where toads live, what they eat, and how they are useful in pest control. They eventually let the toad go into the forest, but I could see that their curiosity to learn had been whetted.

### Looking back, looking forward

What next? Our experience during our pilot visit taught us that the science education approach to global aid would be most effective if conducted through community schools. In Puerto Alegría and other villages, the schools are the center of the community, both geographically and socially. Every child attends the local school for at least some time, and the school offers a hub of social interaction. In addition, the school we visited had a small business based on a well-established local model, raising crops on teaching farms and selling the produce in markets as a source of supplemental revenue. In each school there is a group of motivated teachers who seek above all to help their students succeed, and as a result of their social importance, schools are perfect partners for enacting meaningful and sustainable change.

We saw the desperate need for reducing the frequency of disease, often due to improper hygiene and waste disposal. In addition, farmers in the region are confronted with nutrient-poor soil and must go to great lengths to obtain fertilizer. As a result, we are developing a practical biogas digester for communities that would provide a hygienic site for disposing of human and animal waste. The biogas digester could convert the manure to nonpathogenic effluent fertilizer and methane, a sustainable source of cooking fuel from the fermentation process. We are collaborating with the nonprofit organization Project Amazonas to identify practical digester designs, test them out, and develop school lessons around maintaining digesters and the science and engineering principles behind them. Already one member of Future Scientist, Frances Bell, has returned to Peru to start this project. She and her colleagues are developing a practical biogas digester system to provide cooking fuel as well as fertilizer for a fish pond and farm. The project will soon be integrated into a series of workshops and lessons for adults to demonstrate how biodigesters can provide significant benefits to an agrarian community. We hope to build a large-scale digester system at a nearby school, develop a financial model for its operation, and organize a hands-on science lesson program relevant to the biogas digester.

Our first trip confirmed that an education-based approach to global aid and development is not only valid, but also practical and necessary. We are building on our initial findings and expanding our "experiment" to produce a new generation of Future Scientists that will effect sustainable global development on a larger scale.

Richard Novak *is a graduate student in bioengineering.*

### About Future Scientist

**What does Future Scientist do?**

We provide science education and technical training for resource-poor communities to sustainably address their own needs.

**How did it begin?**

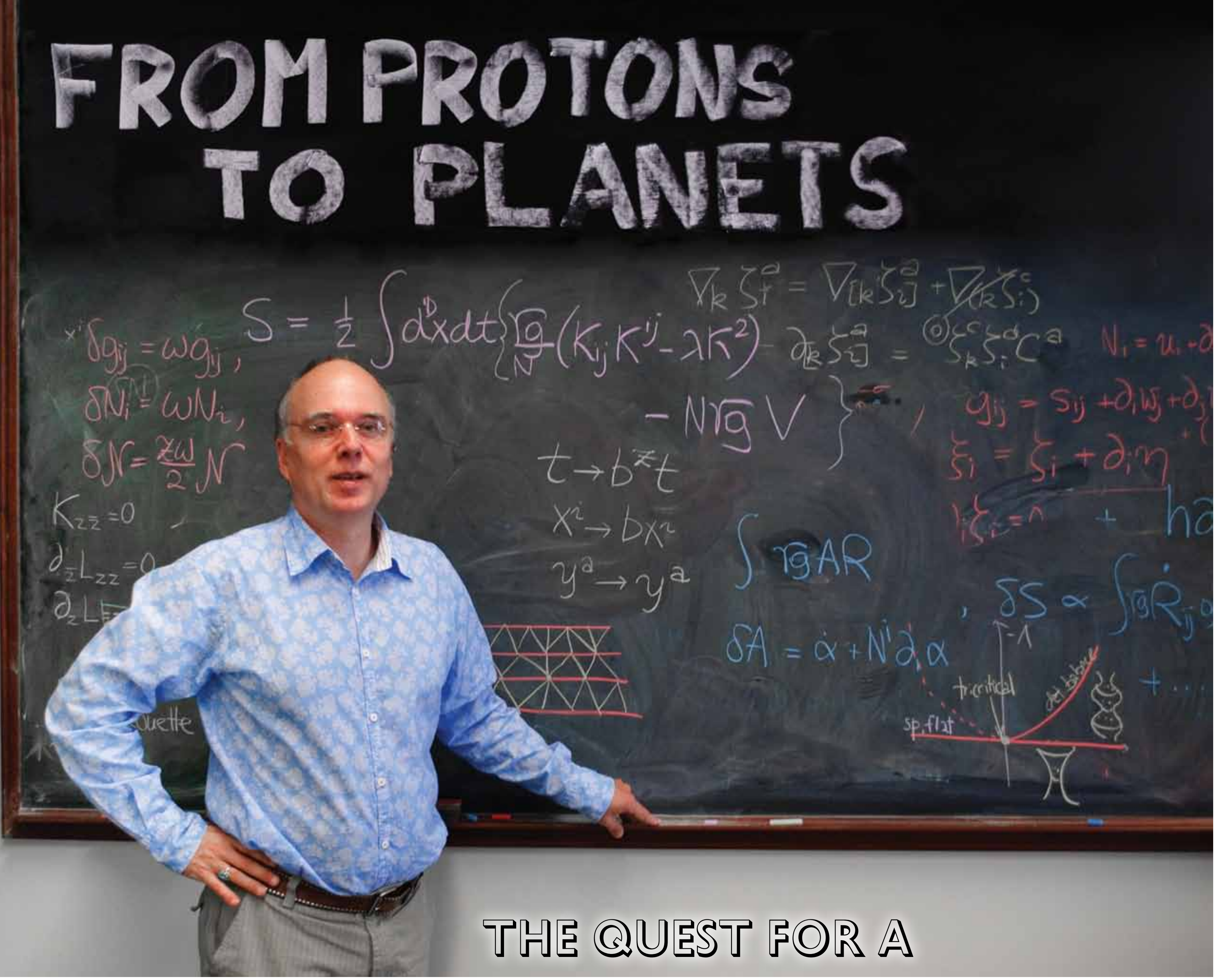
UC Berkeley and UC San Francisco engineering, medical, and public health students and several engineering and education professionals decided that practical education can provide sustainable solutions to social problems.

**What has Future Scientist done so far?**

We have begun developing a practical science and engineering education program in the Peruvian Amazon. In August 2009, we traveled to Peru as part of a pilot program to assess the science education approach and identify what works and what doesn't. We installed solar panels at an orphanage, taught hands-on science lessons, and conducted extensive needs assessments of surrounding communities.

**What is planned for the near future?**

We are collaborating with Project Amazonas, a Peruvian conservation and aid organization, to develop practical biogas digester designs as a solution to waste disposal, pathogen transmission, energy, and farming fertilizer problems. Two volunteers are testing specific digester designs and identifying ways to work with schools to develop hands-on programs that would train a generation of skilled engineers and scientists to establish, maintain, and improve biogas digesters.




PHOTOGRAPH AND GRAPHICS BY MAREK JAKUBOWSKI

# THE QUEST FOR A THEORY OF EVERYTHING

by Phuongmai Truong

Textbooks show thousands of formulas and theories for the various branches of physics—classical and quantum mechanics, astrophysics, particle physics, condensed matter, optics, and relativity, to name just a few. But can there be one ultimate theory from which *every* formula can be derived? In the quest for such a "Theory of Everything" (TOE), Petr Hořava in the UC Berkeley physics department has recently launched a new approach to characterize an elusive concept known as quantum gravity.

## The continuing search for a Theory of Everything

In 1687, Isaac Newton described the force of gravity, the phenomenon that attracts objects with mass toward each other, holding together clusters of galaxies and humans to the earth. Two hundred years later, in 1864, James Clerk Maxwell united the electric force with the magnetic force, creating the theory of electromagnetism. In the early 20th century, Albert Einstein developed special and general relativity (see sidebar) to complete the description of moving objects at the macroscopic level, while Max Planck, Paul Dirac, Erwin Schrödinger, Werner Heisenberg, and many other physicists successfully described the subatomic world of photons and electrons with the theory of quantum mechanics. The question of how protons and neutrons (the building blocks of atoms) bind together to form atomic nuclei despite the repulsive electric force between them was answered in 1970 with the discovery of the strong and weak nuclear forces.

Up to this point, everything in our daily life can be explained by one of these four main forces or a combination of them: gravitational force, which keeps us on our chairs writing and reading this article; electromagnetic force, which forms atoms and holds together molecules; strong nuclear force, the glue keeping nuclei intact and weak nuclear force, the cause of radioactivity and the burning of the sun.

While explaining all branches of physics with only four forces is a great step toward the much-desired TOE, physicists continue to strive for more simplicity. In 1967–68, Sheldon Glashow (Boston University), Steven Weinberg (University of Texas, Austin), and Abdus Salam (Imperial College, London) successfully unified electromagnetism with the weak nuclear force to make the "electroweak" force. In 1974, Glashow and Howard Georgi from Harvard University proposed the first theory to unify the electroweak force and the strong nuclear force, forming the "electronuclear" force, which can explain the behaviors of all known subatomic particles, including the lifetime of individual particles and interactions among them. Such theories combining the original three forces are called Grand Unified Theories (GUTs). Different GUTs have been developed independently by different researchers, but none of the GUTs are yet experimentally confirmed because the technology required for such experiments is not available. Nonetheless, the GUTs are theoretically fascinating because with them, only two forces, the gravitational and the electronuclear, govern the universe.

Following the pattern of combining forces, it is natural to ask whether gravity and the electronuclear force can merge. For the purpose of describing most physical phenomena, this has never been necessary because although both forces are present at all scales of measurement, the effect of gravity is only dominant at the large scale of massive objects, whereas the electronuclear force is dominant in the very small "quantum" world of fundamental particles like electrons and quarks (the particles that make up protons and neutrons). However, at the even smaller, so-called Planck scale (about $10^{-33}$ centimeters, many orders of magnitude smaller than a proton), where things are hot, dense, and tiny, as the universe may have been right after the Big Bang, both quantum and gravitational effects are important. On this scale, current physics theories completely break down, producing unsolvable equations and failing to describe the interactions between particles.

In an attempt to get past this limitation, physicists have formulated theories called "string theories". In these models, fundamental particles are described as vibrational modes of strings. The size and the energy of the string determine the mass and other properties of the particle. String theories provide the frameworks for a successful theory of quantum gravity, but they are neither complete nor tested.

**Gravity** is the governing force in spacetime when the masses of objects are significant. Because an extremely heavy mass has a gravitational field strong enough to bend the path of photons traveling near it, gravity is said to be able to bend the spacetime manifold just as a heavy object sitting on a sheet of cloth can indent the sheet. The heavier the object is, the more bent, or curved, the spacetime surrounding the object becomes. As gravity is dominant in the macroscopic world with planets and stars, the spacetime in general relativity is curved. In contrast, physicists study the behavior of particles and their interactions in quantum theory with the assumption that they are in a flat spacetime, because masses of particles are extremely small. This difference in spacetime's properties makes it difficult to reconcile the gravity-dominant regime and the quantum-mechanical regime.

**Special relativity** tells us that the speed of light is a fixed constant, but time and space can change their values depending on the viewer's perspective and the speed of the object.

**General relativity** explains how massive objects (such as the Sun) can bend the path of light, thus bending space and time via the force of gravity.

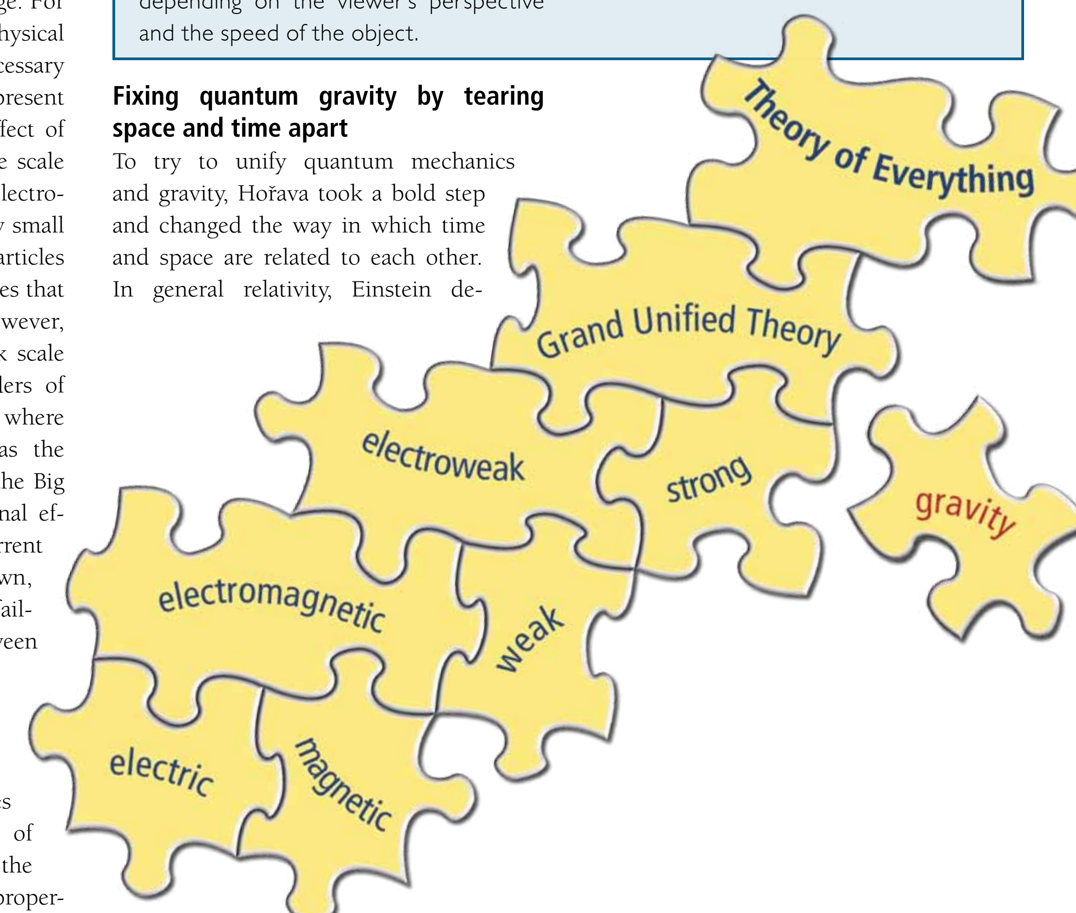
Three important constants in general relativity:

- the **speed of light** (light travels at a constant speed of $3 \times 10^8$ m/s)
- the **gravitational constant**, which enters into the formula of gravitational attraction between two massive objects
- the **cosmological constant**, which is theoretically proposed to explain the expansion rate of the universe

**Lorentz invariance** is a property of spacetime that follows from special relativity. Essentially, it means that the laws of physics are exactly the same whichever way you look and however fast you move. A consequence of Lorentz invariance is that space and time scale in the same manner.

## Fixing quantum gravity by tearing space and time apart

To try to unify quantum mechanics and gravity, Hořava took a bold step and changed the way in which time and space are related to each other. In general relativity, Einstein de-



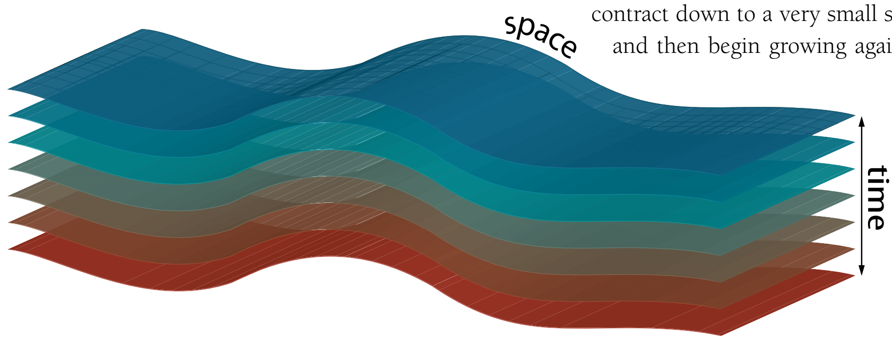

*The incomplete puzzle of physical laws. All but one of the natural forces governing the universe can be combined and described by the Grand Unified Theory. Can Hořava's theory reconcile the misfit gravity with the Grand Unified Theory to obtain the ultimate Theory of Everything?*

scribes the universe in 3+1 dimensions, called "spacetime," meaning the usual 3-dimensional space plus time are inseparably tied together to form a 4-dimensional "manifold." This spacetime manifold must obey a certain principle, known as "Lorentz invariance," which ensures that space and time scale in the same manner (see sidebar). The principle of Lorentz invariance is considered fundamental by many theoretical physicists, and previously proposed candidates for quantum gravity have usually preserved it. Hořava decided to let go of Lorentz invariance and employ a new scaling formula for spacetime: if space increases by a constant factor, then time would increase by that constant factor cubed.

Hořava calls the cubic power the "z=3 Lifshitz point," since the concept of scaling space and time differently was borrowed from the theory of Evgeny Lifshitz (of the former Soviet Union) in condensed matter physics. This new proposal for quantum gravity has been dubbed the "Hořava-Lifshitz quantum gravity" by the physics community. In the theory, space and time form a different sort of manifold, with 3-dimensional space forming a manifold by itself, and a stack of many of these manifolds on top of one another making a "spacetime foliation." The direction of stacking is the direction of time.

By tearing apart space and time in this way, both the very small and very large scales can be described using only quantum mechanics. The asymmetrical scaling factors ensure that at the very small scales, gravity is negligible, whereas at the macroscopic level gravity emerges and behaves just as it would under general relativity. In fact, solutions to Hořava's theory at the large scale resemble black holes, a major successful prediction of general relativity. The three most important constants in general relativity (the speed of light, the Newton gravitational constant, and the cosmological constant in Einstein's equations) can be described as combinations of constants introduced in Hořava-Lifshitz quantum gravity.

Current research suggests that our universe started with a Big Bang, expanded to the size we see today, and will continue expanding forever. In contrast, Hořava-Lifshitz quantum gravity "predicts that the universe will contract down to a very small size and then begin growing again," says cosmologist Robert Brandenberger of McGill University. In other words, the universe in Hořava's theory goes through phases of contracting and expanding, with quantum mechanics dominating in the contracting phase and gravity dominating in the expanding phase. This prediction matches the results of research done by Jan Ambjorn at the Niels Bohr Institute, whose computer simulations also show the universe going through phases of expansion and contraction.



*Example of a spacetime foliation in Hořava's quantum gravity. The colored surfaces represent 3-dimensional space manifolds stacked on top of one another. The stacking direction is the direction of time.*

The Hořava-Lifshitz quantum gravity theory has generated a lot of excitement because it proposes a way of unifying quantum mechanics and gravity that is different from all other string theories, the leading front-runners for the Theory of Everything. How and whether the Hořava-Lifshitz theory and string theories might relate to each other is still an open question, as is the question of whether any of the theories are correct. "When I proposed this, I didn't claim I had the final theory," says Hořava, "I want other people to examine it and improve it." Time will tell whether the Hořava-Lifshitz theory is a promising candidate for a Theory of Everything, and there is not yet any solid experimental evidence for its correctness. And, as always for a newborn idea, "there is still much work to do to smooth out the little kinks in the theory," says Hořava.

**Phuongmai Truong** *is a graduate student in physics.*



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CYBORG INSECTS

insect creepy-crawlies thrilled to discover that these six-legged crea-

# Lieutenant Bug

## Cyborg insects report for duty

by Sisi Chen

ng counter-measures in the form of a rolled up newspaper").

No doubt something like military-funded neural-controlled beetles may incite some controversy. But those who think that piddling with the stuff of life is intrinsically wrong may want to reconsider historical context. "The bioengineering is not the frightening part. After all, we've been domesticating animals forever,"

of nature, technology, and politics.

s. And that may not be such a straightforward question to answer. Those insect creepy-crawlies thrilled to discover that these six-legged creatures may soon be outfitted with more outlandish features

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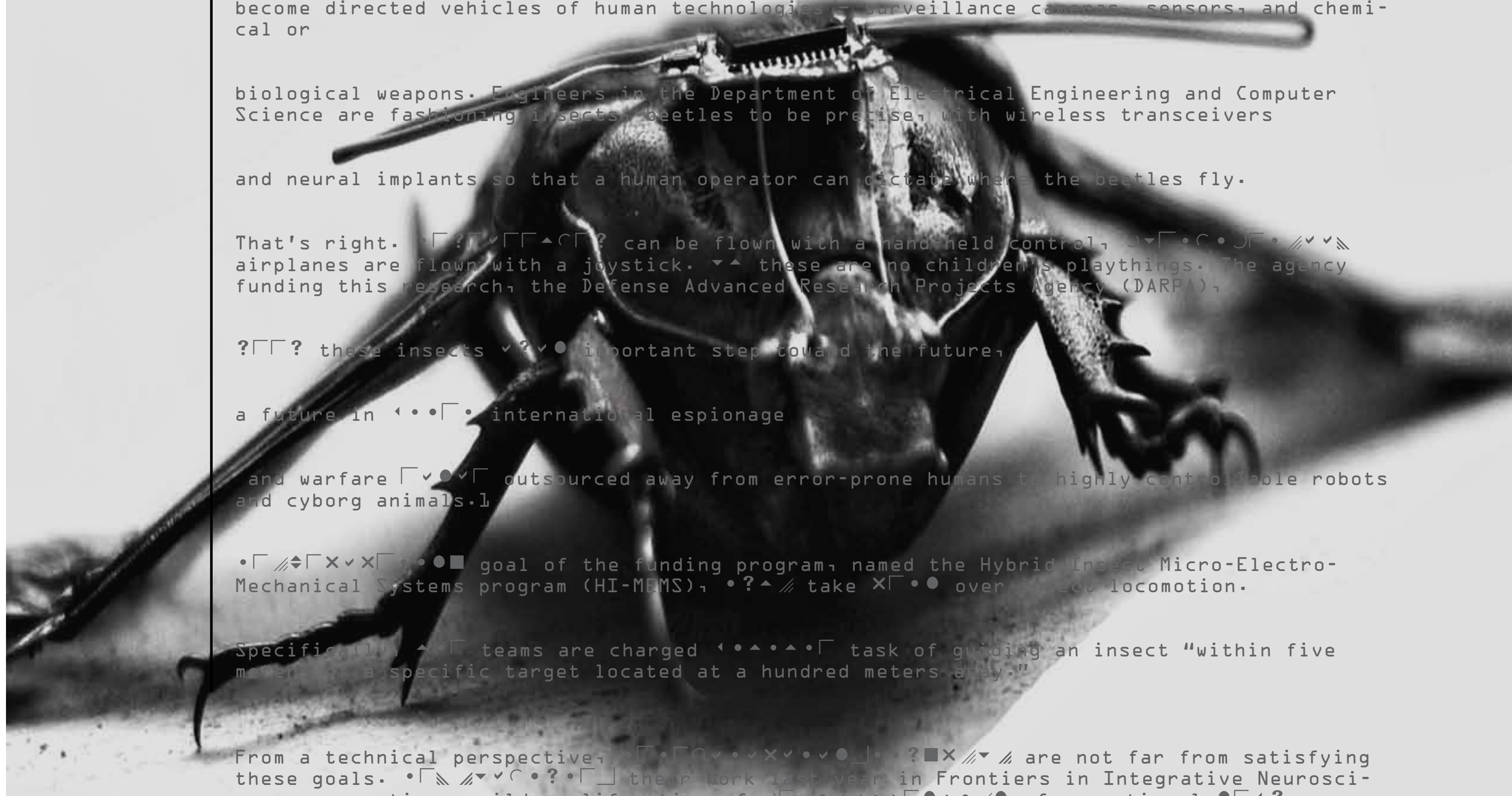

biological weapons. Engineers in the Department of Electrical Engineering and Computer Science are fashioning insects, beetles to be precise, with wireless transceivers

and neural implants so that a human operator can dictate where the beetles fly.

That's right. can be flown with a hand-held control, airplanes are flown with a joystick. these are no children's playthings. The agency funding this research, the Defense Advanced Research Projects Agency (DARPA),

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and warfare outsourced away from error-prone humans to highly controllable robots and cyborg animals.1

goal of the funding program, named the Hybrid Insect Micro-Electro-Mechanical Systems program (HI-MEMS), take over locomotion.

Specifically, teams are charged task of guiding an insect "within five meters of a specific target located at a hundred meters away."

From a technical perspective, are not far from satisfying these goals. their work last year in Frontiers in Integrative Neurosci-

Those already skittish of insect creepy-crawlies will not be thrilled to discover that these six-legged creatures may soon be outfitted with more outlandish features. Indeed, these tiny animals could become directed vehicles of human technologies, including surveillance cameras, sensors, and chemical or biological weapons. Researchers in the Department of Electrical Engineering and Computer Science are fashioning insects—beetles, to be precise—with wireless transceivers and neural implants so that a human operator can dictate where the beetles fly.

That's right. These beetles can be flown with a hand-held control, much like hobby airplanes are flown with a joystick. But these are no children's playthings. The agency funding this research, the Defense Advanced Research Projects Agency (DARPA), sees these insects as an important step toward the future, a future in which international espionage and warfare can be outsourced from error-prone humans to highly controllable robots and cyborg animals. The funding program, named Hybrid Insect Micro-Electro-Mechanical Systems (HI-MEMS), aims to take rein over insect locomotion, charging teams with the task of guiding an insect to a target with a radius of five meters from 100 meters away.

Professor Michel Maharbiz and his group are not far from satisfying these goals. They published their work last year in *Frontiers in Integrative Neuroscience*, generating a wild proliferation of media attention, from national news sources to personal blogs. Already, the beetle has been featured as one of *TIME Magazine*'s 50 Best Inventions of 2009 and the *MIT Technology Review*'s 10 Emerging Technologies of 2009. All of this press coverage has generated a hubbub of reader opinions ranging from moral outrage ("this is just plain wrong!") to wry sarcasm ("I have already rendered this technology useless by developing countermeasures in the form of a rolled up newspaper").

No doubt something like military-funded neurologically controlled beetles may incite some controversy. But those who think that piddling with the stuff of life is intrinsically wrong may want to reconsider historical context. "The bioengineering is not the frightening part. After all, we've been domesticating animals forever," says Professor Jake Kosek of the Department of Geography, whose research focus lies at the intersection of nature, technology, and politics. "The real question is how these military-funded technologies will be used in the future," Kosek says. And that may not be such a straightforward question to answer.

## Winging it

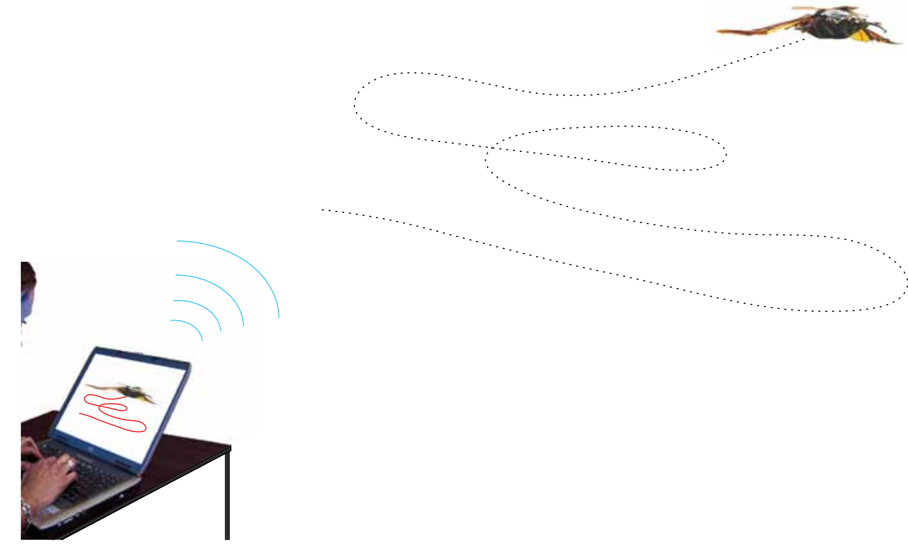
Free flight is one of nature's marvels that engineers drool over. Yes, we can ferry millions of passengers around the world each day in fat passenger planes and fly fighter jets in twirling backflips to dodge missiles. But try scaling an air vehicle to the size of an insect and you will hit major roadblocks to achieving sustained stability and maneuverability. Many engineers, including a handful at UC Berkeley (see "Robot Flea Circus," *BSR* Fall 2007) are trying to combine inspiration from nature with engineering finesse to create fully synthetic mechanical insects capable of flying and jumping. However, even the most successful examples of this have achieved mere seconds of sustained flight. Although these avenues of research have immense long-term implications in understanding the details of fine mechanical control needed to generate flapping-wing flight, their near-term applicability is limited.

Engineers like Maharbiz are instead turning their eyes towards using natural systems as starting platforms themselves. This road is also fraught with challenges, not the least of which is the choice of an appropriate insect host. According to Harvard biologist E.O. Wilson, the earth contains an estimated 10 quintillion ($10^{19}$) insects, making up approximately eight million distinct species. The sheer diversity of these insect types complicates the selection of an appropriate species. To limit the choices, Maharbiz's team made a clever decision based on flight mechanics.

The *Mecynorrhina torquata* beetle is outfitted with a tiny computer, radio receiver, antenna, and battery. Its asynchronous flight mechanism makes it a good candidate for low-power engineering.

MAREK JAKUBOWSKI

Insect flight falls roughly under two categories: synchronous and asynchronous. Synchronous flight, as seen in dragonflies, grasshoppers, and moths, is characterized by a direct correspondence between neural stimulation and wing beats. Each beat of the wing is triggered by an individual neural impulse. Asynchronous flight, in contrast, uses neural impulses to trigger the wing muscles to oscillate for many beats. These wing muscles have a resonant muscle-mechanical system, allowing the wings to flap faster than the muscles contract, thus requiring fewer muscle contractions for more flaps. This is akin to a child's swing set, in which a single push can keep the swing going for many cycles. Beetles and other insects with high wing beat frequencies possess asynchronous flight muscle systems.



By sending radio signals to circuitry on the beetle, researchers can control the beetle's free flight. Positive and negative pulses to the beetle's brain stimulate the start and stop of flight, respectively, and combining pulses controls flight altitude. Researchers are also able to signal the beetle to turn right or left by stimulating the beetle's basalar wing muscle.

ORAPIM TULYATHAN

While other HI-MEMS-funded teams were working with moths, Maharbiz reasoned that insects with asynchronous muscle systems would provide perfect platforms for low-power engineering. The motor neurons fire at much lower frequencies than the wing beat frequency, implying that the neuronal stimulus serves only to switch flight on and off, and to specify how quickly the beetle's wings are beating. Thus, if a researcher were trying to manually control flight, it would be possible to trigger a beetle brain only occasionally, while a synchronous flier would require stimulation for every wing beat. The muscles could subsequently be triggered independently to achieve turning.

The easiest beetle for the team to acquire was *Zophobas morio*, the darkling beetle, because their larvae are often used as pet food. There was just one glitch. "The problem was that the beetle naturally doesn't fly," says Hirotaka Sato, the postdoctoral researcher leading the project.

"We did find one paper," says Gabriel Lavella, another researcher in the Maharbiz lab, "showing that *Zophobas* could be stimulated to fly briefly," which inspired the group to continue testing them. However, it soon became clear that these beetles were vastly underqualified for the job, even though Sato was able to scare them into flying for about five minutes. "I think I set the world record," he quips.

Within several months, they were able to acquire a real flying beetle: the *Cotinis texana* beetle, which was readily supplied from horticulturalists in Florida looking to get rid of these garden pests. Although the neuroanatomy of insect flight control is still not well understood, the literature indicated that visual and auditory stimuli could sometimes be sufficient to initiate flight, which gave the researchers hope that direct neural stimulation could trigger the start and stop of flight. Indeed, Sato was able to show that on and off can be signaled, respectively, by applying repeated positive and negative voltage pulses to electrodes implanted between the left and right optic lobes of the insect's brain. Once the beetles were in the air, the average flight length was about 45 seconds. Furthermore, Sato found that stringing varying numbers of flight initiation pulses together allowed him to control the vertical tilt of the beetle's flight and thus control altitude.

To achieve left-right control, they turned to the muscles. An anatomical dissection of the beetle's flight muscles revealed that a muscle underneath the wing, the basalar muscle, is the most important and easily accessible muscle for controlling the turns. As Maharbiz suspected, direct stimulation of these muscles with low-frequency electric pulses acted as basic turning commands.

Despite these initial successes, the engineers were subject to another key constraint to satisfy the DARPA project goals. Wireless flight requires that the insect carry the weight of the receiver electronics. Beetles can carry up to 30 percent of their own weight, and the team needed a beetle that could carry up at least 1300 milligram of payload weight. *Cotinis*, however, weigh only one gram, and thus posed unrealistic constraints on what the beetle could carry. Enter *Mecynorrhina torquata*. Weighing in at just over eight grams, these green iridescent flower beetles, primarily reared as pets for hobbyists, were up to the task.

Each beetle is outfitted by hand one at a time. A bit of beeswax is used to hold the anesthetized beetles in place while Sato pierces small holes in the cuticle on their head and underneath their wings. Steel wire electrodes, already soldered onto the electronic control board, are then threaded through the holes to the appropriate depth in the brain. The board—including a tiny computer running control software, a radio receiver, and an antenna—and a battery are strapped to the back of the beetle like a backpack and the beetle is ready to be flown.

Although ideal for these prototypes, *Cotinis* are obviously disadvantaged by their large, bumbling size. Even Maharbiz has admitted that the technology, as it stands right now, would not be effective for stealthy surveillance. "Can you imagine," he says, "if you were in a meeting and a giant beetle half the size of your palm, completely nonnative to your environment and wearing a circuit board on its back suddenly careened in through the window and crashed onto your computer screen?" Such a scenario would certainly not be very stealthy.

One aspect of this scene could be changed easily. The circuitry could be concealed by implantation in a pupa, which has almost the same anatomical structure as a fully formed adult. Pupal implantation was one of the original contract stipulations, with the idea that neural integration would be more intimate if the neurons were able to grow around the electrode. In reality, the Maharbiz team found no functional advantage and no longer bothers with the technique because of the increased time and effort needed to coax the pupa through metamorphosis. If needed, though, the entire circuit board could be inserted into the pupa, leaving no visible traces of electrical tampering in the metamorphosed adult, whose cyborg status could thus remain undetected.

## Full throttle ahead

There are other immediate scientific questions and engineering challenges that the team aims to address in the upcoming year or two. For one, the control of beetle flight is still shaky, based only on direct user stimulation of the beetle's flight muscles. To really gain exquisite control of in-flight turning, feedback needs to be implemented directly

FEATURE Cyborg beetles

### The military's purse strings

Close to 70 percent of all engineering research in the United States is funded by the Department of Defense. Although the course of the future may be hard to predict for specific applications, the large coffers of military agencies set much of the overall tone and bias of national research efforts. In 2008, the Department of Defense commanded $6.9 billion to fund science and engineering research, significantly greater than the National Science Foundation's $4 billion. (The heaviest hitter by far, however, is the Department of Health and Human Services, which has an annual budget of nearly $30 billion, disbursed mainly through the National Institutes of Health.)

Yet the military exerts its influence through more than the heft of its wallet. For instance, DARPA is characterized by creative 'blue-sky' research ideas and tight discipline enforced in its review process. Some of its projects are indeed huge flops (think full-size mechanical elephants or Orion, the interplanetary spaceship designed to be propelled forward by launching nuclear bombs out of its rear end), but many of DARPA's success stories might have never been realized under a more conservative funding scheme. Unlike most grants, which are peer-reviewed, the DARPA contracts are zealously managed by dedicated program managers, who hold awardees to exacting standards and well-defined goals. Contracts are renewed only if stated goals are met. In this sense, other civilian funding agencies might have much to learn from this innovative and results-oriented organization. The new ARPA-E (Advanced Research Projects Agency for Energy), just launched by Energy Secretary Steven Chu last summer, may be a good first step in this direction.

on the circuit board. "What we want to do is make a synthetic control loop running in tandem with the biological control loop," Maharbiz says. "I don't think this is something that's ever been tried in free flight."

Maharbiz and Sato, along with an ever-growing group of students, postdocs, and collaborators, are now trying to fully characterize the main muscles that cause turning. That is, given some input, they would like to know exactly what the output is in terms of degrees of rotation. "We want graded behavior," Maharbiz says, "not just, I hit it and it turns some indeterminate amount." Using techniques first demonstrated by Michael Dickinson at Caltech, who specializes in fly flight, they aim to vary both the frequency (how quickly the positive pulses are applied to the muscle) and also the phase shift (at what point in the wing beat the pulse is applied) to generate elaborate descriptions of the beetle's flight response, which can then be used as programming guidelines to implement on-chip feedback.

Michel Maharbiz has garnered much media attention with his work on beetle flight, funded by the Defense Advanced Research Projects Agency.

To monitor the beetle's flight, the researchers are installing a 12-camera Vicon system, the kind used by animation companies for motion capture, in a large room at UC Berkeley's Richmond Field Station. Slap a few one-millimeter reflective stickers on the beetle, throw it into a room outfitted with Vicon cameras, and the system will automatically track the three-dimensional trajectories of the flying beetle. The centimeter-scale resolution provides the necessary precision that is not obtainable using a single camera.

Maharbiz also wants to expand his work beyond beetles. "We aim to soon be able to scale this technology down to where we can actuate a fly," Maharbiz says. "There's no reason why this shouldn't be possible." Innovations in battery technologies would drastically reduce the payload, of which nearly 30 percent is battery weight. Additionally, the flight control mechanisms of flies are well articulated in the insect literature, lowering the knowledge barrier to robust flight control of these species.

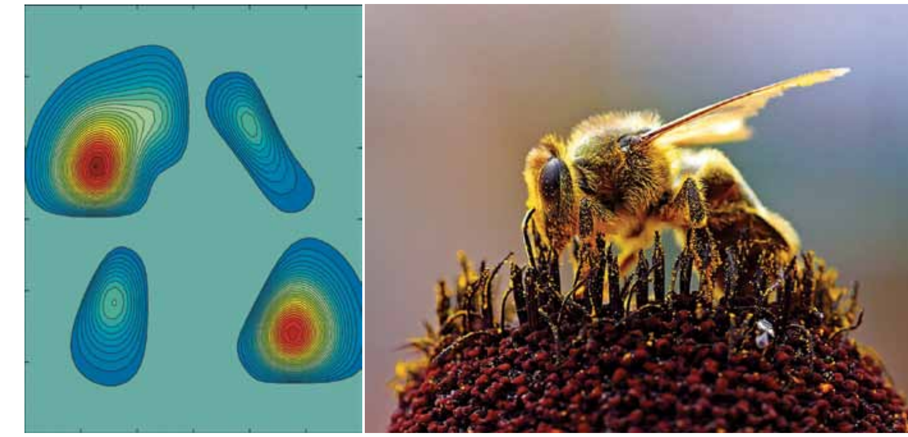
### A look to the past

If the cyborg beetles make it to the battleground, this would certainly not be the first time insects have been used for military purposes. "Bees have been used in warfare very explicitly, but in very different ways," says Kosek, who is working on a book that discusses the recent militarization of bees. As early as medieval times, armies were catapulting raging beehives at oncoming enemy troops or over the ramparts of enemy fortresses.

In the last few decades, military uses for bees have become much more sophisticated. According to Kosek, researchers at the University of Montana began to develop ways to use bees for environmental monitoring and landmine detection. Owing to the electrostatic charge on their branched hairs, bees are essentially aerial feather dusters, collecting all kinds of particles and environmental contaminants as they go. By analyzing the bees' bodies and contents of the hive, researchers could construct coarse-grained geographical maps of trace chemical contaminants including biological warfare agents, explosives, and landmine vapors. Bees can travel within a three- to five-kilometer radius of the hive, setting the spatial resolution for these passive detection techniques.

This range, however, is too large to be of much use for landmine detection, so the researchers refined their technology with the help of a DARPA contract. Bees can be trained using Pavlovian techniques to become sensitive to particular chemicals, much like dogs are trained to sniff out narcotics. By feeding them trace chemicals mixed with sugar water, researchers can sensitize bees to chemicals such as those present near landmines. Once the bees are thoroughly conditioned, their free-flight patterns can be imaged dynamically across a field using light detection and ranging (LiDAR), a technology that is similar to radar but uses laser light in place of radio waves and can locate the insects hundreds of meters away. In trials, bees were able to successfully locate 10 of 12 planted mines.

With this success, Los Alamos National Labs picked up the work from the Montana researchers and splintered it off into its own independent department, the Stealthy Insect Sensor Program. Rather than using bees to spatially map their environment, this program aimed to use them as lab sensors, using the unfurling of their tongues (proboscii) to quantify the concentration of deadly or toxic chemicals in a given sample. In general, much of this bee research has shifted underground to off-access arenas, even within the national labs. "People I used to interview at Los Alamos, I can't interview anymore," Kosek says. "Given this political moment, with the rise of militarism, much of this biotechnology research is going towards creating a new ecology of empire," Kosek says, contending that the military's financial involvement strongly dictates the direction of the developing technologies.



The Defense Advanced Research Project Agency has also funded research on bees. Bees can be conditioned to become sensitive to chemicals present in landmines. By tracking their flight patterns with lasers, researchers can pinpoint landmine locations.

PEG SKORPINSKI

FROM LEFT: SISI CHEN; JON SULLIVAN

### Up in the air

Kosek intimates that the grossly disproportionate funding of military applications for insects is disquieting. He says that the military has been investing vast sums into bee research, far outstripping governmental investments into their agricultural applications. In the hands of the military, promising technologies can often become classified, making the flow of information asymmetric. In that sense, DARPA-funded university research, such as the work done by Maharbiz and his team, may help to restore some balance to the tipped scale by ensuring that at least some of the work is made available in the public domain. Tiny insect spies may be a worrisome thought, but at least we now know this technology may soon exist.

Even Sato himself believes that many interesting applications of his work will bear fruit in other orchards. "Maybe in the future we can apply this kind of bio-interface to humans." Eyes widening, he suddenly realizes the implications of this statement. "No, no, not to control humans. I mean, maybe insight gained from this technology could eventually be used to design neural-interfaced prosthetics for people." Like other researchers developing micro air vehicles, Sato also believes that these cyborg insects may also be useful for locating trapped victims in natural disasters.

Maharbiz refrains from much speculation about future applications altogether. "I want to build these things because they're just plain cool," he says, eyes alight with enthusiasm. "I really can't tell you what it will be used for in the future."

"The fact of the matter is," he says, "people have very little predictive power over what a technology might be used for in the future. The Internet is a brilliant example of this." Developed originally by DARPA in the 1960s and 70s, no one ever predicted that it would be the technological *tour de force* it's now perceived to be. There is no question that military-funded research has brought about technologies that have profoundly impacted modern society, including the Internet, the computer mouse, and global positioning systems. These technologies, though invented with military intent, underwent a paradigm shift and were redefined as consumer products. Likewise, cyborg insects may find other uses as search-and-rescue tools for natural disasters or as distributed sensor networks for environmental monitoring of global warming. It's still up in the air.

Sisi Chen *is a graduate student in bioengineering.*

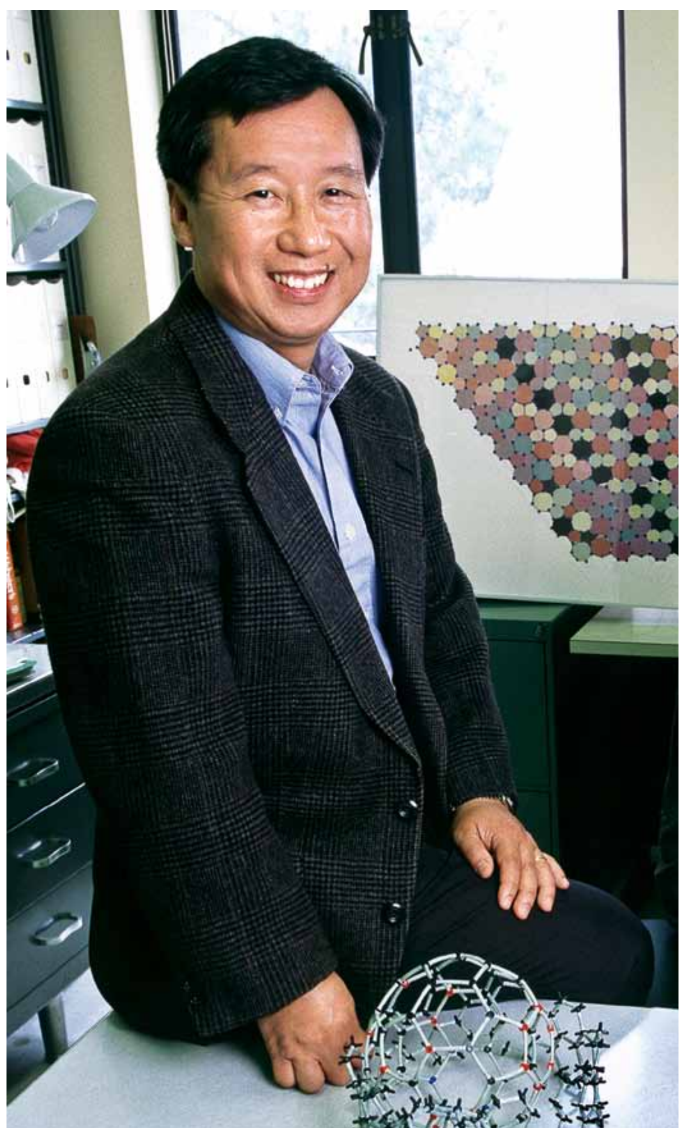
# faculty profile

## Steven Louie

Professor Steven Louie has spent a lot of time on the UC Berkeley campus. He graduated in 1972 with an undergraduate degree in physics and mathematics and then earned his PhD in physics here in 1976. Following postdoctoral appointments at IBM and Bell labs, he taught briefly at the University of Pennsylvania before returning to UC Berkeley as a faculty member in 1980. Today, he is a professor in the physics department and a Senior Faculty Scientist at Lawrence Berkeley National Laboratory. He also directs the Theory of Nanostructured Materials Facility at the Molecular Foundry. I spoke with him recently about his research and his impressions of UC Berkeley over the years.

**Your research focuses on nanomaterials and their physical properties. Why should people outside of physics be interested in nanomaterials?**

As you go from macroscale to microscale to nanoscale, the behavior of matter changes. For example, objects give out light of a certain color, but if you give the material a smaller and smaller diameter, you change the frequency, or color, of the light that comes out. This means that you can tune the properties of the material by just changing its size. In terms of fundamental science, many interesting phenomena occur in nanostructures that help us understand nature. At the same time, because properties change at the nanoscale, there are many applications for nanostructure research. Look at the electronics industry, where you try to make things smaller and smaller in order to pack more transistors and other devices into a given chip. If making the device smaller causes its properties to change dramatically, then you have to understand how the device behaves in these new dimensions.



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**What do you see in the future of nanoscience?**

The future of nanoscience is very exciting. There's a lot of promise in terms of new discovery and new applications. In the field of energy research, for example, a lot of studies are trying to develop new nanostructure-based photovoltaic devices that might function better than standard solar cells. They might also be cheaper to make, because making nanostructures might be cheaper than growing pure silicon crystals for solar cells.

**Is it the application that motivates you, or just a general interest in the subject?**

Well, both. The reason I chose condensed matter theory as opposed to some other branch of physics is because it's very much related to real-world phenomena—there are lots of practical applications. Another attraction is that the scale, both in terms of expense of doing experiments and how long it takes to do experiments, is much smaller compared to particle physics or other large scale investigations. That allows theorists like me to interact very closely with experimentalists. I could propose something or construct a theory that could be either proven or disproven by an experiment. There's a very strong interaction between theory and experiment in my field.

**Do you notice any changes in the campus community since you were first here as a student?**

When I was a student, there was much more student activism. Students were more involved with social issues. There was plenty of social activism at other universities too of course, but Berkeley led those activities in the late sixties and early seventies. Students now are much more mature and serious. They take their studies more seriously and plan out their futures at a much earlier stage. Also, students tend to be more aware of other issues like energy conservation, environmental issues, and so on.



**So the recent protests over the budget cuts reminded you of old times?**

Yes, though this is actually much milder than student activities in those days.

**Speaking of budget cuts: have you felt any impact on your research activities?**

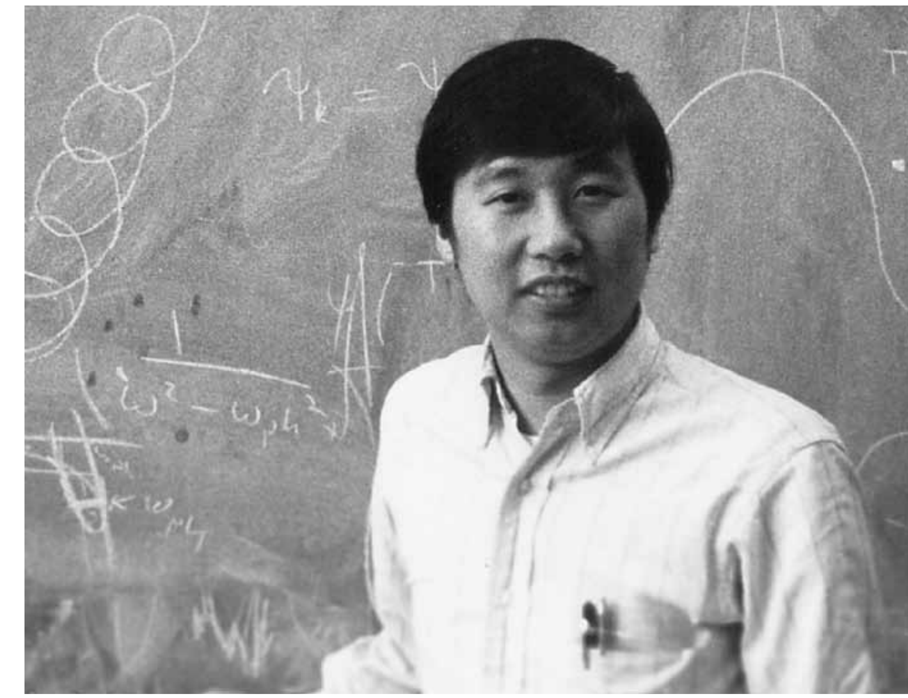
There has not been too much impact on research funding, because of the stimulus package money going into the sciences—funding for research in the physical sciences has in fact been quite good over the past two years. In terms of teaching, the budget cuts have had some impact. The number of courses being offered by the physics department has been reduced, and we cut the number of teaching assistantships and readerships. This means that students are not able to take required courses at the time they want them.

**I've noticed a gender imbalance in the physical sciences. Why aren't there more women in physics?**

We should really do something about that. I have two daughters and a son. I remember when they were in high school, I went to their AP physics class. In fact, there were many girls in the class and they were doing very well. I think in junior high and high school, females tend to be very competitive in terms of their performance and interest in sciences. But somehow, when they get to college and then go on to graduate school, the number of female students in the physical sciences declines significantly.

**What should we do about that?**

This is an issue that many bright people have thought about. I think that maybe mentoring and having good role models is important because young people in their first years of college are deciding what to do with their life, and seeing a lot of successful female professors and scientists might really influence their decisions.



JAMES R. CHELIKOWSKY

*Before he was a professor, Steven Louie was a UC Berkeley graduate student in Marvin Cohen's research group from 1972 to 1976.*

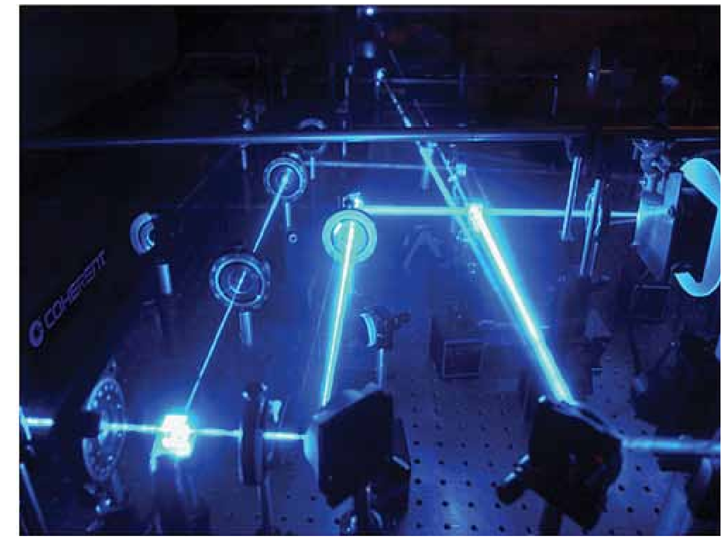
**I heard your colleagues held a symposium last year in honor of your 60th birthday. What was it like seeing all your former students?**

It was very exciting. It's always great to see how successful your students and postdocs are. Training students or postdocs is almost like raising children. You take somebody who's bright, eager and excited to do science. It's very satisfying to watch this person go from a stage where they're very bright, doing problem sets and learning knowledge from textbooks, all the way through independent researcher at the end. Sending them out into the world and watching them become successful is also very satisfying.

**What do you feel is your greatest accomplishment in life so far?**

That's a hard question. Being part of this great university is something I feel great about. To have my work recognized and be invited back to Berkeley, to contribute to making Berkeley an exciting place to do science is one of the most satisfying parts of my life. When I was in industry at IBM, I was a postdoc, and after two years you either continue on to be a permanent staff member or you move to a new place. And I decided that although it's great to do just science—basic research, practical research—I would rather have a life that involved more facets. Being a university professor is much more satisfying because you get to nurture people, you get to do science, and you have opportunities to do public service, too.

Anna Goldstein *is a graduate student in chemistry.*




In 1959, Robert Heinlein wrote a story about futuristic soldiers battling across the galaxy in unstoppable power armor. Despite all of their advanced technology, they were still fighting with old-fashioned rifles instead of lightsabers. That would change a year later, however, when Charles Townes, who would go on to become a UC Berkeley professor, and his brother-in-law Arthur Schawlow invented the laser at Bell Labs, profoundly changing science fiction weapons and the world.

During the 1950s Townes was focused on creating a MASER, or Microwave Amplification by Stimulated Emission of Radiation. "I was doing spectroscopy with radio frequency oscillators to measure the shapes of atomic nuclei and it was a very rich field, but I wanted to use shorter wavelengths, namely microwaves, to achieve higher resolution," Townes says. "The government appointed me chair of a national committee to investigate the possibility of a MASER, but we couldn't think of a useful approach at the time." During his fretting over the committee, Townes conceived of a design. He wasn't sure if it would work, however, so he remained silent and began to work out the details of his "crazy idea."

"I was at Columbia and the head of the department told me I should stop wasting the department's money, but thankfully I was an associate professor, which you can't fire for being stupid, so I kept working," Townes says. After several months, Jim Gordon, a graduate student, made a breakthrough and barged into Townes' class to announce his success. "Suddenly, it was a hot field," Townes recalls. After developing the first MASER, it became a race for researchers to generalize the invention to the next shorter wavelength, visible light. Townes knew he didn't have the resources to build the first laser, as it would be called, so he and Schawlow did the next best thing: they published a theoretical paper on the possibility, which eventually won them the Nobel Prize.

These days, lasers play and record DVDs, point at presentations, and can even trim trees. Despite these broad consumer applications, laser technology is still pivotal for cutting-edge research. "With lasers, we can isolate a single ion and cool it to the coldest temperature nature will allow," says Hartmut Häffner, a professor in the physics department who specializes in quantum computing. Lasers are so precise that such single-molecule manipulations are now routine in many physics labs.

Their uses are not restricted to physics, either. Biologists also make wide use of this technology in the modern era; two-photon microscopy is perhaps one of the most fascinating examples. "Most lasers are continuous, more or less, but with a two-photon microscope, we use a pulse laser where you save up a bunch of photons and then blast them at your sample all at once," explains Paul Herzmark, a two-photon microscopy expert in Ellen Robey's lab in the Department of Molecular and Cell Biology. Standard microscopes can only view the surface of tissues, but the immense power of two photon microscopes allow them to view the interior of living organs.

There remains room for growth beyond these already cutting-edge technologies. "Currently, we're engaged in trying to build an X-ray laser, which will be one of the most powerful lasers in the world," says Roger Falcone, the director of the Advanced Light Source synchrotron at the Lawrence Berkeley National Lab. X-ray laser beams are so powerful and fast that they could be used to investigate the motion of electrons during a single chemical reaction. Fifty years ago, Townes studied the shape of atomic nuclei, and now, the same concepts could soon be used to study individual electrons.

Lasers may also soon play a role in creating nuclear fusion. Just like lasers can cool molecules to their coldest possible state, they can also heat them to the temperature at the center of the Sun. The Lawrence Livermore National Laboratory has the most powerful laser currently available on the planet in their National Ignition Laboratory, a facility designed specifically to investigate fusion. Falcone explains that this device could be used to compress hydrogen to the density found at the Sun's core. Though the process will use petawatts of electricity (1,000 times more power than the entire US electric grid), fusion still has the ability to generate more energy than it consumes. It's currently theoretical, but many experts agree that soon man-made fusion may be a reality that could revolutionize the energy grid.

For the past 50 years, lasers have been turning fiction into fact, and they show no signs of disappearing. "I think laser technology has fulfilled all the applications we could imagine for it except maybe war," says Falcone. "It's kind of ironic that despite all the science fiction, the only thing we don't use lasers for is death rays."

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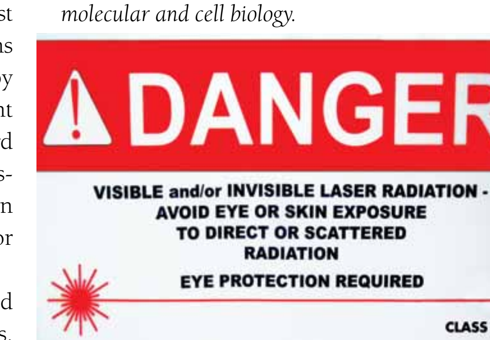
Zach Bochanan *is a graduate student in molecular and cell biology.*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