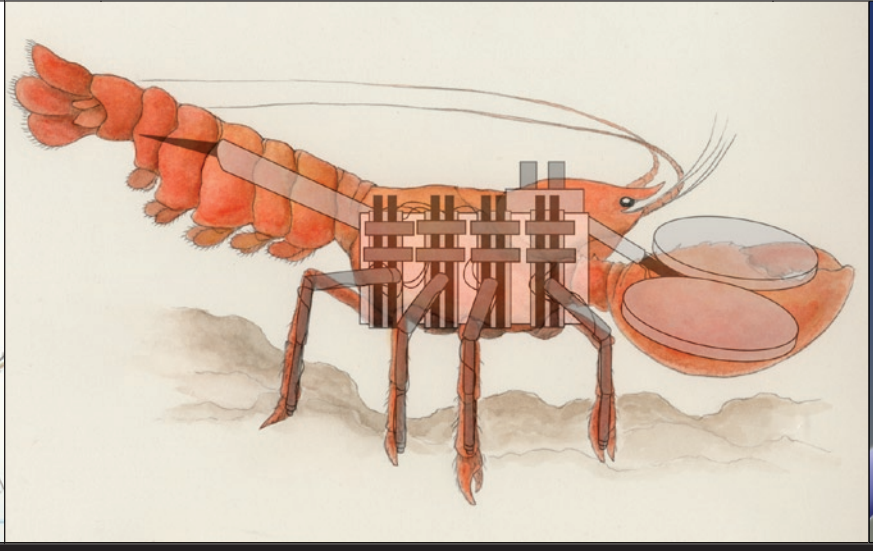

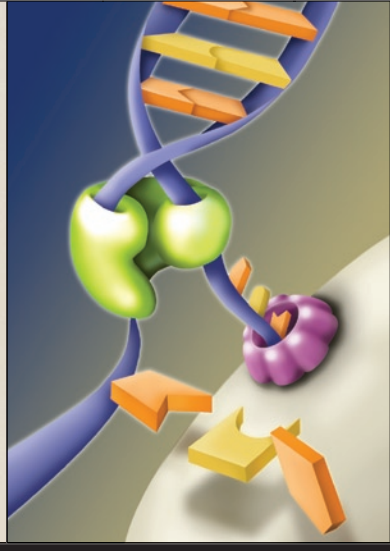

science notes 2002

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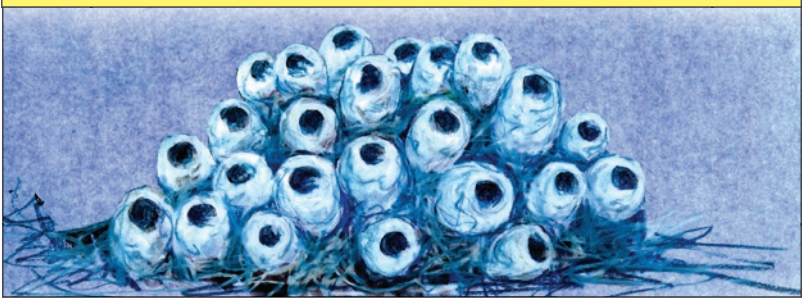

features

essays

about the writers

Daniel Bachtold has a Ph.D. in neuroscience from the University of Zurich, Switzerland. During his studies he characterized single neurons in the medical leech and looked at spatial behavior of humans. He now works as a freelance science writer based in Zurich. When not sitting behind his computer he can be found sailing on Swiss alpine lakes.

Genevieve Bookwalter graduated from the University of Illinois at Urbana-Champaign in 1999 with a B.S. in biology and a B.A. in rhetoric. She moved to California after graduation to pursue marine biology, which she studied for a year in Australia as a junior in college. Like most students in the program, however, she was less than enthusiastic about spending her future in a lab analyzing water samples, so in 2001 she entered the Science Writing program to combine her passions for biology and writing.

Kristin Cobb graduated from Dartmouth College in 1995 with degrees in biology and philosphy. She finished her Ph.D. in epidemiology at Stanford University after starting the UCSC science writing program. She spent spring quarter as the official science writer on a NSF-sponsored research vessel in the Southern Ocean. Her summer internship is at *Science News*.

Sean Griffing is a graduate of Oberlin College. He's most interested in the biosciences. But that's not much of a limitation since biology has exploded into almost every other scientific endeavor. He has interned at NPR's *Science Friday*, the *Santa Cruz Sentinel*, and the Stanford Medical Center News Office. This summer, Sean will be the web writer for the Cornell Laboratory of Ornithology.

Linley Erin Hall received her B.S. in chemistry with an empha-

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about the illustrators

Cornelia Blik B.A. (English literature) Bristol University, UK
Yesterday I was sitting in the Capitola surf, basking in the late summer sun, when I turned around and saw a harbor seal staring right at me. That's not bad for someone who grew up in the middle of London. America is an amazing place "an abundance of wild, vibrant beauty" and I can hardly believe I ended up here, on this course, with a year to look, learn and draw, marvelous!
Internships: Museum of Natural History, London, UK; *Scientific American* magazine, New York.

Alicia Calle B.A. (graphic design) Universidad Pontificia Bolivariana, Colombia; B.S. (biology) Universidad de Antioquia
Imagine yourself growing up in a place where new species are discovered every day; a small place that houses more bird, orchid or reptile species than Europe and North America together; a place with ecosystems unique in the world, full of endemic species; a place so rich that the word "biodiverse" just won't do, and has to be called "megadiverse." Then imagine such a place being destroyed before your eyes, and you cannot help it. I come from such a place, and my being here is no coincidence. It is my simple way of contributing – by leaving behind some significant testimony for those who won't be as lucky as I have been, and will learn about the wonders of the tropics only through our stories and illustrations.
Internship: *Scientific American* magazine

Tara Dalton B.A. (biology/art) UC Santa Cruz
The day I realized Science Illustration was my calling was during a tropical biology field study in Costa Rica. Surrounded by a breathtaking abundance of biology, amazing processes to study and organisms to discover, my classmates were consumed by their research projects and the latest journal article on treefall gaps and cloud forest succession. The nature there inspired me immensely, but unlike my classmates my inspiration was not to study but to draw. Through drawing I am allowed to explore my subject in such depth that it becomes a part of me. Every segment of a silver beetle's antennae, every feather on the back of a scarlet macaw, these are the things that I love. Through my art I hope to inspire in others the same reverence for the natural world.
Job with photographer Franz Lanting followed by an internship at *National Geographic* magazine.

Karina Ingrid Helm B.A. (biology/art) Pacific Lutheran University, Tacoma, WA
Throughout high school and college I was always the odd one out, trailing behind my friends, distracted by the way an ivy could so efficiently and delicately attach itself to a concrete wall or watching a limpet slowly graze in a tide pool. I remember thinking at age 15 that illustrating biological textbooks would be the ideal job, but I got distracted along the way and thought of becoming a medical doctor (along with every other freshman bio major) or even a creative writer (what was I thinking?). Three and a half years later, with graduation looming in the horizon, a random internet search brought UCSC's Science Illustration program to my attention. At that moment the realization hit that I really could meld my love of biology and art into a career, and there was even a program to teach this amalgamation. So here I am, ready to stare, draw, and stare some more – perfection!

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The Science Communication Program consists of two separate graduate certificate programs: science writing and science illustration. Each accepts 10 students a year for a one-year long program. More information is available at http://scicom.ucsc.edu/

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ESSAY

Scientific Corners

By LINLEY ERIN HALL

THE TECHNICAL CORE at my undergraduate college included courses in mathematics, physics, biology and chemistry. I learned about the laws of thermodynamics, integration and differentiation, natural selection, mechanics from Newton to Einstein, the pathway from DNA to RNA to protein, and the wonders of the periodic table. As a chemistry major I studied organic chem, physical chem, analytical chem, inorganic chem, biochem, instrumental chem, bioorganic chem, organometallic chem and nucleic acid chem. Thousands of pages of textbooks introduced me to the fundamentals of science.

During this time I spent three summers working in an organic chemistry laboratory. Among the drawers of glassware and amber bottles of nasty-smelling chemicals, I immersed myself in synthesizing two short amino acid sequences. Articles relating to my research stuffed a three-inch-thick navy blue binder. The cation-pi interaction, bovine pancreatic trypsin inhibitor, unnatural amino acids, native chemical ligation, high performance liquid chromatography: I understood it all. But none of my research, even if it had been successful, would have ever appeared on one of those thousands of textbook pages. It was too specialized.

Today's scientific research examines how the basic principles apply to specific cases, searches for more examples of a phenomenon, or fills in the details of a process. These details are far from inconsequential. A discovery about one tiny gene among the tens of thousands that make up the human genome can save lives. Yet because scientists now paint with tiny, delicate strokes instead of broad splashes of color, they often find themselves backed into corners.

Educational institutions encourage and even demand specialization beginning at the undergraduate level. At some universities biochemistry departments have broken away from chemistry, astronomy from physics, molecular biology from ecology and evolution. As an undergraduate the future scientist selects a major, which may be bioinformatics, chemical physics, or statistics as easily as biology, chemistry, physics or math. Then he focuses even more sharply while completing master's and/or Ph.D. degrees. According to unwritten rules, a postdoctoral fellowship should be in a different area. This means, however, that someone who earned a Ph.D. in a DNA lab studies RNA in a postdoc. He does not tag whales.

The system prepares scientists to be specialists, not generalists, because being a generalist would drive a scientist mad. B. L. Siegel said in 1984 that scientists produce enough information every day to fill seven complete sets of the Encyclopedia Britannica. I'd guess they're finishing a dozen sets a day by now. The American Chemical Society (ACS) introduced seven new journals in the past five years alone. The ACS Style Guide lists abbreviations for the 1000+ journals most frequently cited by its members. They range from the widely known Science and Nature to the extremely specific Cereal Chemistry and Xenobiotica. And that's just chemistry. No one reads all these journals. A typical scientist might flip through Science or Nature each week, noting titles and reading two or three articles closely. He might subscribe to a journal or two specific to his field, and read it more closely. If the media hypes a scientific discovery such as a new cancer treatment or water on Mars, he will see it in his local newspaper or on CNN. But most scientists remain wrapped up in the specifics of their own fields and, specifically, their own laboratories. To try to keep up with everything is insanity.

The commercialization of science has also driven specialization. Molecular biologists want to patent genes, and organic chemists race to make potential drugs. Scientists performing basic research scrounge for funding as their applied counterparts form industry partnerships. Commercialization depends on a scientific creation's uniqueness. Thus, young scientists examine others' work carefully, then carve out a unique niche with their research projects. Everyone wants to break new ground, and most want to sell it afterward. A scientist may break ground in snail antennae or protactinium compounds, but he owns the turf.

Acquiring funding is a huge hassle for scientists, and specialization helps keep costs down. Newton merely needed an apple, but today's experiments require Hubble Space Telescopes and particle accelerators, which do not come cheap. The amount of equipment needed for a project has also skyrocketed. Gregor Mendel performed the experiments that established the basic rules of heredity using pea plants, pen, paper, a magnifying glass, tweezers, sunshine and water. A friend of mine used in a plant genetics experiment more than 50 chemicals, several computer software programs, a cold room, incubators, a polymerase chain reaction machine, a DNA sequencer, a centrifuge and cooperative bacteria, not to mention the plants-all this to investigate a mutation in one gene that causes abnormal root development. After a scientist purchases a DNA sequencer, economically he can't allow it to collect dust while he works on something completely different. The expensive equipment keeps scientists in the niches they carve.

Sometimes a scientist attempts to venture out of his specialization. But, fierce competition for grants means that a biology proposal from a physics professor has little chance of receiving funding. Scientists depend on grant money to perform research which leads to publications which leads to grant money-and tenure. Some established researchers do slip into a related field through collaborations with other scientists, but a physicist will never become a biologist unless he halts his career to obtain another degree.

Over the course of his career in the 1500s and 1600s, Galileo researched magnetism, heat, microscopes, mechanics, and astronomy. No one could do the same today. Too much background material to read, too much equipment to buy, too much time spent trying to convince people with money to fund the projects. That's all right. A scientist can still discover much of interest and even value in his little corner of the universe. ■

alone in the deep

Exploring on their own, robotic submarines unlock secrets beneath the waves and ice of our oceans.

By KENDALL POWELL
ILLUSTRATIONS by MARY SIEVERT

In October 2001, the Dorado robotic submarine made a 15-minute test run under Arctic ice.

A YELLOW, TORPEDO-SHAPED VESSEL the size of a dolphin journeys toward the sea floor. It cruises along, taking nearly 100 measurements per second in the deep waters of Monterey Bay canyon. Then a low-power warning beeps and the crewless vessel, named Dorado, heads for home: a rendezvous point on the surface, scanned by nervous researchers who wait to see whether their prized possession will return in one piece.

They're anxious because their invention is out there entirely on its own. "Dorado is making the decisions it needs to make, because when it is underwater, it's completely out of communication with us," explains James Bellingham, director of engineering at the Monterey Bay Aquarium Research Institute, or MBARI, in California.

Dorado represents a unique new class of free-ranging, untethered robot submarines called Autonomous Underwater Vehicles, or AUVs. The MBARI invention roams the cracks and crevices of the bay's canyon much like a traffic helicopter, dipping and diving to take stock of forces shaping life in the marine sanctuary. Just as a surfer can feel a cold current passing by her toes, the small ship senses what flows beneath the ocean surface: glowing marine microbes, poisonous blooms of algae, and rolling underwater waves.

By gliding through the seas, AUVs are giving scientists an extraordinary new view of the ocean. The robot submarines can track oceanic events unfolding over a range of depths. They can survey a whole square kilometer of the ocean in just a few hours—a richness of detail impossible to obtain from traditional surface research vessels or by towing underwater vehicles behind ships. AUVs easily explore below polar ice or operate in high seas, opening a window on truly uncharted territory. Researchers are now using the unique traveling abilities of these vessels to answer questions on everything from global climate change to sea floor tectonics. In the quest to build these versatile underwater explorers, MBARI and the Woods Hole Oceanographic Institution, in Massachusetts, are leading the way.

"The ocean is terribly understudied. You can look in one spot in the ocean and things might be very different if you just move over one kilometer," says Bellingham. "In that way, the ocean is so much more difficult to track than the atmosphere, unless you dip something into it."

Dorado is MBARI's dipper. It can continuously monitor and record the temperature, saltiness, pressure, and light levels of the water it swims through. It also sends out sonar to identify the ocean floor below, a looming cliff of rock, or even ice overhead. Researchers reconstruct thousands of bits of collected data into a three-dimensional picture of the ocean.

That picture might reveal sediments wafting up from the bottom, warm and cool waters mixing to melt Arctic ice, or vast clouds of microscopic marine organisms, called plankton. No video camera can capture the information in these pictures, Bellingham says. Video footage might uncover fantastical unknown deep-sea creatures, but it doesn't record the temperature of their environs, nor can it count how many animals live in a given area of the ocean.

MBARI engineers named their robot submarine after the Dorado dolphinfish, hoping it would be "free-ranging, slick, and speedy" like its biological counterpart, says Drew Gashler, one of the AUV engineers. Suntanned and pony-tailed, Gashler works in the AUV lab, which was recently added to MBARI's beachfront complex at the midpoint of Monterey Bay. The lab is a workshop filled with scattered wrenches and pliers, plastic vehicle casings, spools of colored electrical wire, and several laptop computers. Next to the lab, a saltwater test tank 11 meters deep waits to try out the oversized bathtub toys. Through two large bay doors, the lab opens to the dock where Dorado's support ship, the Zephyr, a retired 26-foot pilot vessel, is moored.

MBARI engineers named their robot submarine after the Dorado dolphinfish, hoping it would be 'free-ranging, slick, and speedy' like its biological counterpart.

"Dorado comes in chunks, just like Legos," says Gashler. Modular by design, the sturdy plastic vehicle has a pointed nose cone and a tapered tail cone that ends with a blue plastic propeller. These two pieces directly snap together, or can also take on one or two middle sections in between that hold multiple scientific tool packages. "You can operate it on Monday for Billy Biologist and on Tuesday, you can operate it for Jimmy Geologist," Gashler says. With all pieces assembled, the vehicle stretches 5.5 meters long and half a meter wide—about the size of two dolphins, end to end.

Gashler opens the tail section to reveal the vehicle's guts: its computer brain, a hard drive for storing data, motion sensors that detect pitching and rolling, and the propeller motors. The sensitive electronics are housed under a glass bell that keeps water out and resists pressure up to 6,000 meters deep. Once Dorado submerges, other sensors record the properties of the seawater that floods its compartments.

Designing Dorado to navigate by itself proved tough. Navigating by global positioning satellites or dead reckoning only works at the ocean's surface. Dorado instead calculates its underwater position by listening for pings from sonar transponders scattered in known locations, and uses gravity sensors to tell which way is up. Its propeller acts

as a three-in-one tool: It propels by spinning, acts a rudder by moving left and right, and controls depth by moving up and down. Dorado might follow a programmed path at a certain depth or skim along at a certain height above the bottom, tracing the terrain with its sonar.

As the robot submarine sails along, its brain receives feedback from navigation and motion sensors so that the vehicle can dodge hazards or stay on course. If something goes wrong, computer programming gives Dorado enough smarts to finish its mission, or at least reach the surface safely. Coastal environments are full of hazards such as steeply rising shelf bottoms, piers, and ship traffic. Ensuring that an AUV comes back with its data is critical. Otherwise, says Bellingham, "your entire career is sitting on the bottom of the ocean and all you have left is an embarrassing story to tell your buddies around beer drinking."

It takes only two people on a small boat to launch Dorado on its way to record a slew of data. On a typical route, it travels along in one direction, but oscillates up and down from the surface to 60 meters below. When finished, it pops to the surface and signals, "I'm done," via a radio modem. Once it's back on board, scientists simply plug into the AUV and download enough data to keep them busy for the next several months.

JOHN RYAN, a physical oceanographer at MBARI, has chomped through AUV data for the last year and a half. He studies how physical structures and properties of the ocean change where marine lifeforms appear. "We get a 3-D view as the AUV zigzags back and forth and yo-yos up and down to sample the whole region," says Ryan, pointing to a series of rainbow-colored cross-sections of the ocean on his computer screen.

Each slice is a snapshot of the sea that he created using data collected by Dorado. The colors represent gradients of the water's properties, just like colors on a weather map show the gradient of temperatures across the country. By overlaying the slices in a composite, Ryan can see all of the dynamics in that segment of the ocean.

Using this technique, Ryan is studying how blooms, or growth spurts, of tiny single-celled algae are born. The blooms are important because they can dictate the feeding patterns of fish, which in turn become food for larger fish and sea creatures. Thus, the algae can influence the ocean's whole food chain. Sometimes, for instance, growths of toxic algae introduce a poison that works it way up to the top of the food chain, potentially harming marine mammals, birds, and even humans.

In August 2000, Ryan used Dorado to map an algal bloom in Monterey Bay. To monitor the growth, he attached a special light-reflecting sensor to Dorado. The sensor detects a specific shade of green light reflected by chlorophyll pigments found in the marine organisms. From these measurements, he mapped the bloom to a subsurface layer 5 to10 meters thick. Another sensor, meanwhile, sends out red light and then records how much is reflected back by particles suspended in the water.

When Ryan overlaid the cross-sections recorded by the two sensors, he clearly saw the cause of the bloom. The slice from the red-light detector revealed the same subsurface layer of algae, but also showed sediments coming up from the ocean bottom. Ryan speculates that these sediments contain nutrients that feed the algae—a process scientists had assumed was happening, but had never witnessed before now. The sediments might also trigger blooms by bringing dormant algae spores to the warm, sunlit surface, he says.

What's more, says Ryan, the water carrying the sediments is very cold. That means it came from deep within Monterey canyon in a coastal process called upwelling, in which water from the bottom of the ocean rises up to replace water blown out to sea by winds. This year, Ryan hopes to use Dorado to determine whether upwelling is a constant influence on algae growth in the bay.

"We caught a glimpse of a process that may be there all the time and have a persistent effect on the ecology of the bay. Now we can go back out there and look at it again with the same technology," he says. "Ultimately, we want to be able to predict what conditions are likely to result in a bloom."

> 'The ocean is big and we don't have a string attached. So it's a nerve-wracking thing because the AUV is expensive and one of a kind.'
>
> — DREW GASHLER
> MBARI

While Ryan used the AUV during summer days, another MBARI oceanographer, Steve Haddock, took it "night swimming." Haddock studies the distribution of glowing, bioluminescent plankton in the ocean. Besides the wondrous phosphorescent beauty that these organisms bring to the sea, they also give scientists a way of measuring the living particles at the base of the marine food chain. Just as photosynthesizing plants support the terrestrial food chain, one kind of photosynthesizing algae, called phytoplankton, keep the ocean ecosystem healthy. Haddock hopes to predict the abundance of the plankton from the blue-green light that many of them give off.

To measure bioluminescence, Dorado uses a device called a bathyphotometer, a cylinder the size of a paper towel roll that sucks up a water sample and stirs it around to stimulate any plankton inside to shine. The device amplifies and records the tiny sparkles of light.

"Inside the bay, we are trying to predict from circulation patterns where these lumps of ocean that have high bioluminescence came from," Haddock says. His slice of ocean from Dorado's data showed glowing plankton in the upper 30 meters of water. The organisms drop off sharply and disappear at about 12 kilometers offshore. This tells Haddock that the plankton feeding all life in the bay stays relatively close to shore, sometimes concentrated in pockets that move very little.

"We didn't have to do anything to get this, just drop the AUV in and pick it up," Haddock says with a smile. Most oceanographers work with a view of the sea that's like putting on a scuba mask and looking straight down below a ship, he says. If they want a different view, they have to move the ship. "But the AUV gives us a way to get an entire swath," he says.

SCIENTISTS NEED A BETTER perspective of the ocean under the polar ice as well. Last October, MBARI researchers and engineers put on their parkas and climbed aboard a U.S. Coast Guard icebreaker to take their brainchild under the Arctic ice north of Norway. Their experiment was a test run for the Atlantic Layer Tracking Experiment (ALTEX), an international project to determine the fate of warm Atlantic water that enters the Arctic Ocean. Many climate researchers believe that the first effects of global warming will appear in the polar regions, as warmer waters melt away the thick ice covering the polar oceans.

Before the invention of AUVs, scientists measured temperature and ice thickness of polar waters once a year from a Navy nuclear submarine traveling under the ice. But the Navy is gradually retiring its polar class of submarines. And, researchers would like to track ice thickness throughout the year. So, in collaboration with others, MBARI designed a full-length, modified version of Dorado that can swim just beneath the ice for more than 1,000 kilometers. The plastic vehicle cruises along at a much closer distance to the ice layer than a nuclear submarine can safely navigate, and returns more precise data.

One particular challenge was crafting the AUV so that it could surface periodically through the ice to check in with researchers via satellite. To pull the trick off, engineers dreamed up an ingenious solution: an "ice buoy" that ejects from the ALTEX vehicle through a swinging door and rises to the underside of the ice. The device releases a lithium pellet that reacts with seawater and creates enough intense heat to burn through the ice layer. Once it pops to the surface, the buoy deploys a satellite antenna to send its data by e-mail to the scientist, reporting on ocean conditions and ice thickness.

The Autonomous Benthic Explorer can navigate over the rugged terrain of the deep ocean, exploring the cooling lava of newly formed seafloor.

The crew of engineers began testing the AUV in the open water created by the icebreaker, keeping an eye out for polar bears. After a few short trips out and back went according to plan, they took a deep breath, gave the AUV a helping push to dive down, and sent it under the ice. After what one crew member called "the longest 15 minutes" aboard the monthlong cruise, cheers and high fives went around when they spotted the yellow vehicle in the rendezvous area.

Gashler designed the test programs, which he calls the "baby steps" of ALTEX. He stresses the importance of working out bugs while still in open water. "If it doesn't work, hold the phone, we're going to test it again until it does," he says. Once the $500,000 vehicle goes under the ice, there's no way to retrieve it if it breaks down. "The ocean is big and we don't have a string attached," Gashler says. "So it's a nerve-wracking thing because the AUV is expensive and one of a kind."

For most oceanographers, however, half a million dollars looks like a steal. "From the perspective of buying a car, that looks expensive, but you have to look at the fact that an average research ship costs $20,000 to operate for one day," says Chris von Alt, an engineer at the Woods Hole Oceanographic Institution in Massachusetts. Alt and his colleagues have built robot submarines similar to Dorado, but with different talents. Their vehicles launch easily from rubber Zodiak boats, work over whole seasons for many years, and only cost a month worth of ship research days. One model is available commercially for scientists to purchase and adapt to their own research purposes.

Alt wryly points out another advantage to robot subs. Recently, he and his colleagues took one of his AUVs on test runs off the New Jersey coast, with graduate students following the course of the vehicle from a ship. "The students were getting seasick, feeling miserable and cold, while we were in a warm room onshore having a good time," he says.

To delve deeper into areas left unmonitored by oceanographers, WHOI engineers developed the Autonomous Benthic Explorer, or ABE. Shaped like the Star Trek Enterprise, this vehicle can glide down to 6,000 meters to levitate above the ocean bottom. Al Bradley, an ABE engineer and caretaker, explains how the 1,600-pound vehicle differs from the lightweight Dorado.

"If you are flying in a light plane, you don't dare fly into low valleys because the mountains may climb faster than you can, so you stay well above the mountains. MBARI's vehicles are optimized for mid-water or flat areas," he says. Conversely, ABE is designed to take on the rugged terrain of geologically active seafloors, including vertical cliffs, valleys, and mountains. Instead of one main steering propeller, ABE has seven thrusters oriented to allow for movement in any direction, including reversing to travel up overhanging cliffs.

WHOI oceanographers have sent the benthic explorer out to explore cooling underwater lava flows, investigate how new seafloor forms, and study how mineral deposits form in cracks near super-hot water surrounding volcanic vents. Many scientists don't believe the data from ABE at first because they've never seen such a detailed view of the bottom of the sea, Bradley says. "The greatest reward to us as engineers is seeing the scientists tearing their hair out trying to figure out what to do with this data that is both exasperating and exhilarating," he says.

AUVs are revolutionizing the way oceanographers observe the ocean, Bradley says. "Trying to study the bottom of the ocean from a ship is like aliens trying to discover what a football field looks like from orbit. All they see is a tiny green blob. If they use deep-sea submersibles with a video camera, it would be like seeing the species of grass and insects on the field through a galactic microscope. What you need is the helicopter that hovers and scans back and forth and gives you a survey that tells you it is a rectangle of grass with white lines on it."

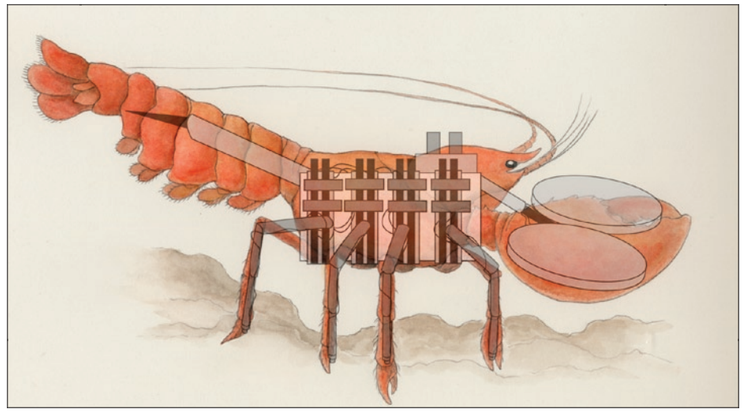
In other words, robot submarines give scientists a powerful way to spy on the ocean. Eventually, scientists hope to dock AUVs out at sea, where they could alert computers on shore when events such as toxic algal blooms occur. Then, with the push of a button, scientists could deploy the AUV to monitor the event, without ever getting their own feet wet. The knowledge gleaned from these free-roving ocean sentinels will reshape our understanding of marine chemistry, geology, and biology—forces that give the planet weather, continents, and life.

"The ocean is fundamentally opaque," says MBARI's Bellingham. "The only way to visualize it is to introduce sensors on a platform like an AUV." The AUV takes researchers to places they otherwise couldn't explore, such as the Arctic basin. "The Arctic is the canary in the coal mine for global climate change. The ice there is in fact warming and melting. But is it global warming or the Arctic oscillation, a normal climate cycle?" asks Bellingham. "You really need an AUV to get at these problems." ■

Sniff, Sniff. How Does a Lobster's Nose Know?

Scientists are deciphering the lobster's amazing sense of smell. What they've learned is helping them to build bomb-sniffing underwater robots.

By CHRISTIAN HEUSS
ILLUSTRATIONS by CORNELIA BLIK



LOBSTERS ARE NOT only the favorites of gourmets. A growing number of bioengineers now regularly scout the lobster market—and not because they're interested in how juicy the big-clawed crustaceans will taste in a stew. Rather, these scientists want to inspect the hairy noses that distinguish lobsters as the most sensitive sniffers on the ocean floor.

Lobsters are shy, sneaky creatures. During the day, they hide in safe dens and crevices in coral reefs, preferring only the company of their fellow buddies and mates. But at night, the spine-covered critters leave their shelters to roam and hunt. A pair of hairy antennae guides them through a rich world of scents—of yummy clams, delicious fish, or delectable black mussels—even in absolute darkness. The lobster rhythmically swings its "noses" up and down through the water, catching the faintest smells from predator or prey.

More than 20 years ago, neurobiologists showed that the lobster's brain detects scent only while it flicks its antennae. New studies now reveal exactly how these flicks are responsible for the lobster's marvelous sense of smell. The research, based at the University of California at Berkeley, and Stanford University, is part of a joint effort at several institutions funded, surprisingly, by the U.S. Navy. The military is involved for one reason: It wants better robots for detecting underwater mines or monitoring toxic waste. And the crustaceans can show the Navy the way.

"If you want to build unmanned vehicles or robots that go into toxic sites, and you want those robots to locate something by smell, you need to design noses for them," says UC Berkeley researcher Mimi Koehl. It just so happens there is no better nose to imitate than the lobster's schnoz, which has had plenty of time to improve over millions of years of evolution. Engineers and biologists are teaming up to learn and steal from designs that nature worked out long ago, a field called biomimetics. Lobsters are not only master sniffers, but they've also adapted nicely to the rough conditions of surf break zones without getting washed away. Both features are crucial for underwater robots to succeed in hazardous coastal areas.

Koehl, a biomechanical engineer, wants to understand how the lobster's nose masters the challenge of smelling underwater. On a recent afternoon in her lab, she explained her work. "Most biomechanics researchers are the guys who develop running shoes or artificial knee joints. But some of us straddle biology and ask questions about non-human organisms."

Like an aerodynamics engineer studying the flow of air over the wings of an airplane, Koehl looks at the flow of water and odor molecules over the pair of antennae attached to the lobster's head. This flow brings odor molecules into contact with sensory receptors in each "nose." Unlike in mammals, where smelly molecules stream into the nostrils with every breath of air, lobsters must move their antennae to "sniff" smells dispersed in turbulent water.

Each antenna is about two inches long and splits into a Y-shaped structure with two pointy tips—"hairy little legs," is how Koehl tenderly describes them. Peering closely through a magnifying glass at one of these antenna tips, she glimpses a dense zone of hair tufts staggered in a zigzag arrangement. It looks like a miniature toothbrush. Each hair is covered with multiple nerve cells that can detect odors. Along the edges of the toothbrush, larger hairs line up like a long alley of tree trunks. Up to five times thicker and taller than the smallest hairs, these hairs control the flow of odor molecules and water to the shorter, inner sensory hairs. For that reason, researchers call them "guard hairs."

"To understand the physics of smelling," Koehl says, "you need to understand the fluid dynamics of water interacting with hairs." She holds up a scaled-up plastic model of the toothbrush-like array of sensory and guard hairs. "If you look at the array of hairs, it is full of holes," she says, poking her fingers into the spaces between the taller guard hairs. Nonetheless, water can't normally flow through these gaps; instead, it takes the path of least resistance and flows around the hairs. It is only when the entire, hairy array is moving fast enough—when the antenna is flicked—that water can flow through the guard hairs. Then, sensory hairs can encounter odor molecules and transmit the scent information to the lobster's brain.

To observe the flow of odors, Koehl uses another plastic model that's about 300 times bigger than the lobster's microscopic guard hairs. She places the model, mounted on a small motorized cart inside a large glass tank. To approximate the drag that occurs when seawater flows through such teeny hairs, Koehl's tank is filled with gluey Karo corn syrup. She adds tiny little red beads that float in the sticky sweetener, like odor molecules in water. Moving the plastic model at various speeds through the syrup creates a flow of the red beads across the guard hairs. Koehl records it all with a video camera.

At slow speeds, the beads merely drift around the guard hairs. But as the speed picks up, the hairs get leaky and let the beads pass through. "Models are powerful tools. You can systematically dissect and understand what role each part has," Koehl says with satisfaction. "With organisms, nature never does that for you."

Koehl's work has established the role of guard hairs as selective gates. Based on her experiments, she predicted a double role for the lobster's antennae: When flicked downward, they act as sieves that trap odor molecules. But when slowly moved back up, the antennae behave more like paddles, pushing water and odors away.

Under a microscope, the tip of a lobster antenna looks like a miniature toothbrush, a dense zone of hair tufts staggered in a zigzag arrangement. Each hair is covered with multiple nerve cells that can detect odors.

Much like cigarette smoke in the air, traces of scent released by fresh fish form a constantly changing cloud, or plume, in the water. A lobster trawling for dinner is never aware of this full cloud. It senses only tiny slices of the plume from flicking its hairy antennae repeatedly. These series of flicks through odor plumes fascinate Jeff Koseff, an environmental fluid mechanics engineer at Stanford.

Using laser technology, Koseff has developed a method to dissect the plume's structure. In lab experiments, he mixes odor molecules with a special invisible dye into water in a tank. Then he aims a thin sheet of laser light (rather than just a single beam) into the tank, illuminating one slice of the odor cloud. Dye molecules within this laser-lit slice give off fluorescent light, allowing Koseff to record the cross-section with a videocamera. In the resulting image, the dye molecules look like fine, threadlike filaments swirling about, reminiscent of the pattern of an oil slick on the surface of a pond. The picture gives Koseff an idea of what the lobster smells while flicking its antenna.

To find out more, working with Koehl, Koseff built a simple robot out of a molted lobster shell filled with plastic. They added this mechanical creature to his experiment, positioning one antenna to move within the sheet of laser light. With the camera, they recorded which parts of the thin filaments of dye penetrated the hairy brushes on the tips of the antenna. "It's a bit like placing toothpaste on a toothbrush," Koehl says.

For the first time, the scientists could measure what the lobster encounters with each flick. Their results showed that during the upstroke, when guard hairs push seawater away, the odor filaments retain the original shape with which they first entered the sensory brush. The next flick, downward, breaks up the filaments as the antenna captures scent molecules from the water. It stores the odor sample for about a tenth of a second—just long enough for sensory neurons to detect the smell, even as the antenna is already swinging upward again. On the next downstroke, the stored odor is replaced by a new scent sample. Each flick is like a deep sniff supplying new smells.

Together with a neurobiologist in Florida, Koehl and Koseff are now working on combining electrical recordings of the lobster's brain with real-time imaging of the plume structure. If successful, they'll see what smells the antenna is picking up and what the lobster's brain is sensing, simultaneously.

SCIENTISTS ELSEWHERE are working on other parts that lobster-inspired robots will need. Underwater devices programmed to autonomously sniff out explosive underwater mines or toxic waste sites require some intelligence. And they need to navigate sand, stones, and rubble on the bottom of the sea. Two other research efforts are focusing on these goals.

At the Marine Biological Institute in Woods Hole, Massachusetts, neurobiologist Frank Grasso and his team has designed a robot to study lobsters' behavior in response to clouds of scent. RoboLobster, as it's called, doesn't actually look much like a crustacean. It's a two-wheeled vehicle about 30 centimeters long, featuring two smell sensors in the front and instruments to gauge its position. But its body size and shape are copied from the real animal, as are its speed, pattern of locomotion, and the way its sensors are arranged.

Grasso can program the way RoboLobster reacts to the fishy odor plumes it senses. In a typical experiment, he exposes a live lobster

Each antenna, about two inches long, splits into a Y-shaped structure with two pointy tips. On each tip is a dense zone of hair tufts staggered in a zigzag arrangement, like a miniature toothbrush. When the lobster flicks the antenna, the nerve cells on the tufts pick up scents in the water.

"Ultimately, our robotic lobster should be able to do all these things a real lobster does—except have sex."

JOE AYERS, NORTHEASTERN UNIVERSITY

and the robot to the same conditions. Based on the differences in how they respond, he finetunes RoboLobster's programming to better mimic natural lobster behavior.

Grasso and RoboLobster recently returned from a field trip to the bottom of the Red Sea off Israel, where he exposed his baby to its first real-world test. A team of frogmen swum out and covered a portion of the sea floor with long sheets of linoleum so that RoboLobster wouldn't get stuck on pieces of coral or other obstacles. The frogmen then escorted the robot three meters underwater, generated a colored odor plume—and let it roll. It was the first time the mechanical crustacean was exposed to the turbulence of naturally occurring waves, but it behaved just as it did in the lab: As soon as odor molecules reached RoboLobster's nose, the vehicle started moving towards the source of the scent.

For Grasso, it was a terribly exciting moment, to see his invention working in the environment that originally inspired its design. "I felt like a real Indiana Jones-kind-of-scientist," he says with a grin.

While RoboLobster is good at sniffing out plumes, another of its brethren is proving to be a versatile roamer. In just five years, neuroscientist and engineer Joe Ayers and his team at Northeastern University in Boston have constructed a fully biomimetic lobster robot. Even without seeing the robot in action, a viewer of the eight-legged metallic critter has no doubt of its heritage. With its thin legs, two front claws, and a long tail, this vehicle has all the key anatomical features of a lobster. Ayers built in these features not for their natural appeal, but for their function. The claws and the tail, for instance, stabilize the robot while it crawls along the bumpy sea floor.

Within the mechanical lobster sits an electronic "brain" inspired by Ayers' early graduate work at the University of California at Santa Cruz. As a trained neurophysiologist, he's deciphered all the nerve cells in the center of the lobster brain that produce the crustacean's pattern of locomotion. To build the controller that steers his robot, Ayers created a computer model based on these neurophysiological measurements. This artificial nervous system can command the robot to move in all directions exactly like using feedback from the lobster's own walking patterns. "What is really unique," Ayers says, "is that the robotic lobster can change its walking behavior on a step by step basis."

Ayers and his team recently finished building the second generation of the robot. This version can walk entirely on its own, and without the cable support that its predecessor needed. Compact battery packs provide enough energy to keep it going for several hours. Some sensors help stabilize the metallic critter's balance, while others that detect touching and bumping guide it around obstacles. From a base station, Ayers can send directional commands to the robot via sonar communication. He even designed the vehicle so that additional instruments such as cameras can be mounted on the back of its tail.

Though Ayers' efforts were fully focused on creating a robot capable of running on the sea floor to hunt for underwater mines, his invention currently lacks a nose for TNT or any other explosives. Yet he says with confidence, "If the Navy combines Grasso's RoboLobster with our robotic lobster, they will completely solve their problem."

What the Navy wants is a robot that can track explosives in the 30-meter zone off a shoreline. "We think that a legged walker that can search would be the ideal device on the rocky bottom of a surf zone," says Joel Davis, the research coordinator from the Office of Naval Research. Loaded with a camera and explosives, a robotic lobster would search for mines along an area enclosed by sonar buoys. Upon finding a suspicious object, it would transmit an image to a human operator, who could identify whether it had found a real mine—and trigger the robot to explode to get rid of the threat. At $300 a pop, the Navy's self-destructing robotic lobsters would be a cheap way to make seashore operations safer.

Meanwhile, Ayers is turning his attention to biological challenges in robot design. Just like Grasso, he hopes to do real-world experiments exposing his creature to the lobster's original habitats. One day, these robotic lobsters may even start to invade the dens of their natural compadres. "Ultimately," Ayers muses, "our robotic lobster should be able to do all these things a real lobster does—except have sex." ■

A HOT BET on ICE

Is the Arctic melting? An 85-year-old Alaskan betting contest offers some clues to the future.

By SEAN GRIFFING
ILLUSTRATIONS BY JACK (JOHN) MUIR LAWS

ONE SUMMER a few years ago, Raphael Sagarin was lying on a beach in Alaska when he chanced upon the perfect global warming experiment. He didn't have to do a lick of fieldwork because the research was set in motion by gambling railroad engineers—in 1917.

Sagarin, a marine biologist at Stanford University who studies climate change, was in Alaska to investigate tide pools. Taking a break on the beach, he learned of a contest called the Nenana Ice Classic from reading a Lonely Planet traveler's guidebook. Each spring, hordes of Alaskans place bets on the date and time a giant nine-legged contraption will fall through the frozen ice of the Tanana River. Last year, eight lucky winners split $308,000.

Sagarin realized that contest officials might have kept spring ice breakup records for the past 85 years, down to the exact minute.

In the Nenana Ice Classic, Alaskans bet when a 30-foot-high, nine-legged "tripod" will break through the ice of the Tanana River during the spring thaw. The records, precise to the minute, indicate that ice breakup now comes five and a half days earlier than it did in 1917 when the betting contest started, a possible indicator of global warming.

Their records, he recognized with excitement, could help reveal whether global warming has affected the Arctic by showing if spring has been coming earlier. As soon as Sagarin returned home, he called the Nenana Ice Classic contest headquarters. Officials there gladly mailed him copies of their records—and the documents were everything he had hoped for.

Sagarin's use of obscure historical records to answer a current research question is a prime example of a little-known science called phenology. Long a neglected backwater, phenology is the study of recurring natural events such as flowering, breeding, and migration—or, in Sagarin's case, spring ice breakup.

Relying upon old diaries or logs that tracked seasonally repeating phenomena has its own peculiar strengths and weaknesses. But today, such records are taking center stage as a surprisingly powerful tool in the study of climate change. For all their high-tech satellite studies of the planet, scientists still need the recollections of the long dead to understand global warming. Such insights are critical because global warming could disrupt weather patterns and ecosystems across the planet.

The Arctic especially fascinates global warming phenology researchers, because that's where the world's largest temperature increases have occurred in recent decades. Studies indicate that the Arctic has just gone through its warmest century in 400 years, with plant activity in the far north jumping 11 percent during the final decades of the twentieth century. One climatology researcher predicts that global temperature increases in this current century will be double that of the last, and the Arctic will be hardest hit.

IN THE WORLD of phenology, discovering historical data to study requires more than a modicum of serendipity. After all, how do you know where to look to find records in the first place? Recently for instance, John Magnuson, a lake ecology researcher at the University of Wisconsin in Madison, learned of a document listing 100 years of freeze and thaw dates for a lake in Maine. The record was hanging in a restaurant foyer, next to a board filled with business cards. "It's like treasure hunting," Magnuson explains. "Sometimes you find the records by accident."

That was certainly the case with Sagarin and the Nenana Ice Classic. The beauty of the annual contest is that it relies on the gambling compulsions of more than 100,000 Alaskans. To keep the contest fair and accurate, the rules haven't changed in 83 years. The yearly tradition is so popular that it was written into state law in 1959.

The Ice Classic traces its beginnings to a group of engineers who overwintered in 1917 in the town of Nenana, 55 miles southwest of Fairbanks. They were waiting to build a railroad bridge across the Tanana River. Until the river melted, they couldn't finish. Pooling their money, $800 in all, they placed bets on when the river's three-foot layer of ice would break under the pressure of upstream waters. Being engineers with too much spare time on their hands, they built a wood contraption that was cabled to an onshore clock to mark exactly when the ice broke up. Though they called a "tripod," the 30-foot device actually has nine legs rooted in the river's ice.

The spring thaw officially arrives when the black-and-white-striped tripod collapses through the ice or drifts far enough to move its cable a hundred feet, yanking the onshore clock to a stop. Sometimes, the tripod slowly sinks in rotting ice; other times upstream debris knocks it down. Either way, the lucky winner is the one who guesses the day, hour, and minute when the clock halts. Then Nenana waits another year to cut another tripod from the woods. "Nobody has no idea when the breakup is gonna come," says Perci Dike, a Nenana local. "If I did, if I had some idea, I would have win the dang thing there years ago."

As a safeguard against cheating, a 24-hour watch is stationed at the river during prime ice break days, usually April 25 to May 10. Along with that precaution, the tripod design and contest rules all make for a precise scientific experiment, says Sagarin. In fact, the Ice Classic has provided some of the most trustworthy data available yet in the field of phenology.

Every phenological experiment starts with a scientist trusting the stories of people who may not be the most accurate observers of nature, and that raises some potential problems. How does the researcher know that an observer's records are true? Take the example of an Arctic island explorer named Joseph Dewey Soper, who recorded when he sighted caribou throughout the year for the Canadian government. According to Soper's journal, he didn't see any caribou for seven months in 1931. But his documents neglected to mention that he couldn't travel during that time because of a knee injury from slipping on sea ice, Canadian researchers learned.

Another difficulty is how recordkeepers define when a noteworthy event has occurred. For example, a tree could be said to have new leaves when there are visible buds, or when the first leaf is fully grown. New observers who take over a recordkeeping tradition may do things differently if the rules aren't clearly defined when the old observers die.

By contrast, the records from the Ice Classic sounded too good to miss out on. Within two hours of receiving the documents, Sagarin plotted a graph with the ice breakup data—and found he had hit the jackpot. The results showed that spring melts in Nenana today come on average five and a half days earlier than in 1917.

Sagarin wondered whether other data existed that could back up his results. He attempted to find snowfall, rainfall, or air temperature records from weather stations in Fairbanks and Nenana, but ran into the sorts of problems that kill many phenological experiments. Nenana had not taken any measurements during many of the last 85 years. Records from Fairbanks, on the other hand, were not very helpful, in part because the station had moved once. For Sagarin's desired level of precision, snow or rainfall records taken in more than one location were useless.

And since Fairbanks had grown considerably over the years, the records were doubly damned. City growth creates a "heat island," where buildings, pavement, and cars raise local temperatures. Temperatures in town didn't reflect nature. At any rate, good temperature records—taken with the same thermometer, at exactly the same time of day, every single day—are rare to find.

Another type of seasonal data that researchers can sometimes track is the sudden greenery of spring, a global phenomenon they call the "green wave." (A classic example is the "cherry blossom front" that moves from south to north in Japan.) Investigators use satellite images to register spring's march across the globe—two swaths of green burning their way toward the Arctic and Antarctica. But since accurate images date back only 20 to 30 years, they're of limited help in following longterm changes. That's why scientists have fallen back on phenology records of all kinds.

On the ground, old journals recording the first buds of spring can't offer clearcut of climate warming either, though. The timing of plant buddings depends on more than just ambient temperature. Buds "count" warm days and then burst open, but a mild winter can confuse them and delay their opening.

All in all, says Sagarin, compared to the other methods, a more accurate way of measuring longterm temperature change is to study the freezes and melts of lakes and rivers. It's much easier to trust someone to write down when the ice melted than to track temperatures, he says. Magnuson, the lake ecologist, agrees. "In many places in the world, we have lake and river records going back 100 to 150 years," he says. "But a single record from a single point does not convince one that the world is getting warmer. It is critical to have long-term records from around the globe." Magnuson has compiled 39 different records that list ice breakups and melts in the northern hemisphere, from Asia to Wisconsin. His studies, like Sagarin's, show that spring ice melts are occurring sooner and winter freezes are coming later.

Ironically, the researchers note, global warming may destroy some phenological sources of data, as lakes and rivers at lower latitudes fail to freeze in warmer years. For instance, one of the longest running sets of historical records has tracked the freeze dates of Lake Constance, in Europe, for 1200 years. The logs belong to two churches separated by the lake; one sits in Germany and the other lies just across the border in Switzerland. Their chapels share a single Madonna statue. When the lake freezes, whichever chapel has the Madonna carries it across to the other. Unfortunately, the lake doesn't freeze every year. In some centuries, the lake didn't freeze at all. During warm periods—which experts expect to see more of—the record can't give enough information to measure climate change.

Scientists focusing on long-range bird migration patterns will face a similar problem as global warming speeds the arrival of spring. In the Netherlands, researchers have been tracking climate change by applying phenology to 20 years of records on the egg-laying habits of the pied flycatcher. Normally, at a set time before the start of spring, the birds fly north from dry tropical forests in Africa to Europe. They lay their eggs to coincide with the blooming of spring foliage that serves up a peak of insect abundance.

But with spring arriving sooner and sooner over the last 20 years, the timing of this bug feast has been moved up as well. As a result, the flycatchers have been laying their eggs on earlier and earlier dates. However, they're can't adapt forever. Many already are migrating to Europe too late to take advantage of the insect feast. Eventually, the birds may reach a point beyond which they can't lay eggs any earlier in the year, or possibly even die out; researchers have already begun to detect a decrease in the numbers of nestlings. Like a lake refusing to freeze, the spring breeding of flycatchers could become an imprecise record of climate change.

Over the past 20 years, the pied flycatchers have been laying their eggs earlier and earlier.

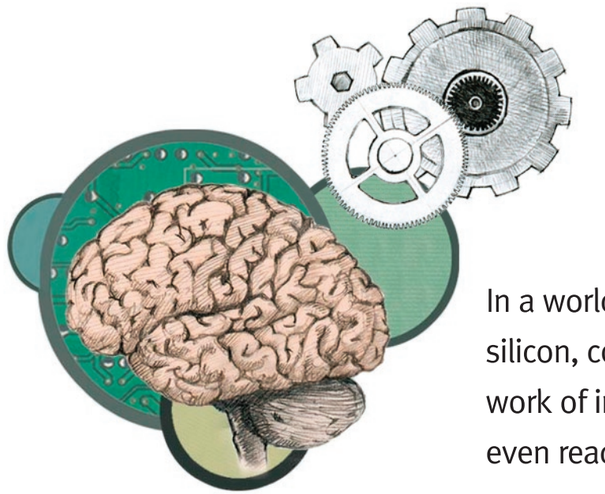
PIED FLYCATCHERS aren't the only ones having trouble with timing. Just about when Sagarin was going to publish his findings, he realized a major problem with his calendar was skewing the results. Wall calendars pretend that years are 365 days long, but the true solar year (the time it takes for the earth to go around the sun) is actually about a quarter of a day longer. Every fourth year, we add an extra leap day in February in sloppy compensation. Even so, by the end of a century, the calendar can still be off by almost a whole day.

By Sagarin's reckoning, he is the first researcher in phenology to notice this problem with records using years that start on New Year's Day. He proposes a solution: To reduce the discrepancy, researchers could start their year at the vernal equinox, the first day of spring when day and night are the same length.

The bias, however small, is real. Other researchers in the phenology world are taking Sagarin's criticism seriously. But not everyone agrees that the vernal equinox method is the best solution. Magnuson, for one, is considering whether to reorganize his own research using the winter solstice, the moment when the sun is farthest from the equator. Beyond accounting for leap years and historical calendar shifts, he hasn't applied any calendar corrections to his results. But in the worst case, his results are probably only a day off from Sagarin's.

At any rate, Magnuson likens the impact of Sagarin's suggestion to a group of people timing a race. Even if everyone's stopwatches aren't set to the right time, they can still tell who crossed the finish line first. Regardless of the exact timing of dates, the results from phenology studies still point to a strong global warming trend.

In the end, the experts say, phenology might well be one of the best ways to truly nail down the case that global warming is real. Handscrawled journals and logs from the past have provided a wealth of evidence to choose from, whether they come from priests, naturalists, or gamblers. So far, ice breakup records like the one Sagarin stumbled upon are providing some of the clearest proof yet of worldwide climate change. And as the years go on, the Nenana Ice Classic could show the fallout of global warming even more dramatically. That is, if the river is still freezing a century from now. Just don't bet on it. ■



In a world where brain meets silicon, computers do the work of injured neurons—even reading thoughts.

MIND MELD

By KRISTIN COBB
ILLUSTRATIONS by GIOVANNI MAKI

KRISHNA SHENOY HAS MADE A CAREER OUT OF EAVESDROPPING. But he listens to thoughts, not voices.

Shenoy, who heads a new lab at Stanford University, is one of several researchers across the country who are linking brains to computers as part of the growing field of neural prosthetics. He is devising ways to tap into a monkey's brain and read where the animal plans to reach its arm. He can route these signals to a computer icon that moves for the monkey.

By bypassing the need for the brain and arm to "talk" through the usual neural connections, this technology could eventually help people with spinal cord injuries to type, pick up a fork, or turn a page just by thinking about it. Electrodes set in the brain will talk to robots or stimulate distant muscles.

Shenoy is well aware that overblown research claims have raised the hopes of paraplegics in the past, only to fizzle. But he believes his monkey experiments are leading to practical results. "We have a view toward human patient tests. We've initiated those conversations with neurosurgeons here at Stanford," he says. "We have to have a bigger picture, an ambitious goal, or we're frittering away our time."

Researchers in neural prosthetics build devices that make up for lost neural activity. In the healthy body, the brain communicates with the limbs via the spinal cord. Messages zip along as electric pulses through end-to-end nerve cells, moving from the brain to the spinal cord and from the spinal cord to the limbs. Any break in this line of communication stops the message cold, usually permanently. Using sophisticated new electronic devices, researchers hope to bypass such breaks.

One approach to treating spinal cord injury, for example, is to build a neural prosthetic that mimics the work of the spinal cord. Three steps are involved in building such a device: plucking neural signals from the brain, making sense of them, and carrying out the intention encoded in the signals.

"The biggest bottleneck has been getting neural signals out of brain correctly," says Daniella Meeker, a graduate student who collaborated with Shenoy when he was a post-doc at the California Institute of Technology, before he moved to Stanford. Each electrode listens to a single nerve, and there's no wiggle room. If the electrode moves even 50 microns (the size of a pinhead) away from the neuron it's recording, it will lose communication.

Unfortunately for a scientist trying to place an electrode, the brain is a bit wiggly. The pliable brain moves slightly relative to the skull, threatening to move the target neuron out of earshot of the electrode, which is fixed in the bone of the skull. This loose connection between brain and electrode may be the limiting factor for using neural prosthetics in humans, Shenoy says.

Moreover, electrodes get gummed up with sticky fluids after a while, insulating them from local signals. The electrodes that Shenoy and colleagues plant in a monkey's brain have limited lifetimes. Improving the robustness and longevity of the electrodes also will be critical to transferring this technology into humans.

Nevertheless, these challenges haven't prevented researchers from achieving some startling successes in laboratory monkeys. Shenoy's research team at Caltech, led by Richard Andersen, trained a rhesus monkey to touch the right or left side of a computer screen in response to an on-screen flash of light. All the while, the scientists snooped into the monkey's brain, recording neural pulses. Using this code, a computer read "right" or "left" from the monkey's brain activity and flashed an arm icon on the corresponding side of the screen. The crafty monkey soon realized it didn't have to lift a finger to get its reward, a sip of juice; it just had to think about moving. The thought alone was enough to get the virtual arm to do the work and earn the reward.

"They preferred using the icon to play these video games we provided them instead of using their real arm," says Meeker. She and others were surprised that it was so natural for the monkeys to quit moving their arms.

The researchers bring the monkeys to a dark, isolated room where there is no background interference. It's so quiet in these chambers that you can almost hear yourself think. And that's exactly what Shenoy is trying to do—hear the monkey's thoughts.

What exactly does a thought sound like? "If you're listening to it, it is sort of like a buzzing, and the buzzing increases or decreases its frequency," describes neuroscience expert Andrew Schwartz, who does related work at the Neurosciences Institute, a private foundation in San Diego. The raw language of neural pulses is better suited to a computer's ear than a human's.

But even for a computer, reading these buzzing thoughts is tricky. "We don't know the language of the brain. We're tourists with only a visitor's guide book," Shenoy says. "The brain is magic. How do wet squishy neural cells compute? It's just fascinating."

Information is contained in the speed and intervals at which neuron cells fire their electric pulses. By monitoring that process for a while, researchers can correlate the nerve-firing rate of a nerve cell with a monkey's actual movement. "We listen in during the normal behavior, and we make our little map. For example, 100 spikes per second means right, 10 spikes per second means left," says Shenoy. Thereafter, they can predict movements from the rate of cell firings in the recorded neuron.

Once the monkey's intention has been read, that intention must be acted out. In Shenoy's experiment, the researchers simply flashed an arm icon to the correct side of the screen. Eventually, researchers aim to move a real arm through muscle stimulation or to move a robotic arm.

If you ask Shenoy when this technology will be available in humans, one answer he gives is "two years ago." Though there are no systems that move arms, researchers Philip Kennedy of Georgia Tech and Roy Bakay of Emory University have implanted electrodes in humans with amyotrophic lateral sclerosis ("Lou Gehrig's disease") or strokes in their brain stems. These patients can't move a muscle but are cognitively alert. The implants allow them to move an icon over a virtual keyboard and slowly tap out messages, simply by thinking. This is the first example of a human brain communicating directly with a computer.

Kennedy and Bakay implanted two glass cones, each about the size of a tip of a ballpoint pen, into the brain of Johnny Ray, a 53-year old brain-stem stroke victim who is completely paralyzed. His brain functions perfectly but the signals don't get anywhere. With special chemicals, Kennedy and Bakay induced neurons in the motor cortex—which controls movement—to grow into the glass cones, ensuring that the electrodes would stay in place. Ray was told to think about moving his finger. A circuit routed this signal to an icon on the screen instead of into his arm. After practicing, Ray eventually learned to will the cursor to move right or left and up or down. The brain signals act as a computer mouse. They move the cursor across the screen and select prescripted phrases, such as "See you later. Nice talking with you," or "I'm thirsty."

Beyond these initial human tests, the field of neural prosthetics is embroiled in many controversies. One major quandary is where to place electrodes within the still-mysterious brain.

Shenoy's group placed electrodes deep in the brain, in an area called the "parietal reach region." This area of the brain first specifies where to you want to go, and precedes any formal plan for how to get there. It's the place where thoughts are born.

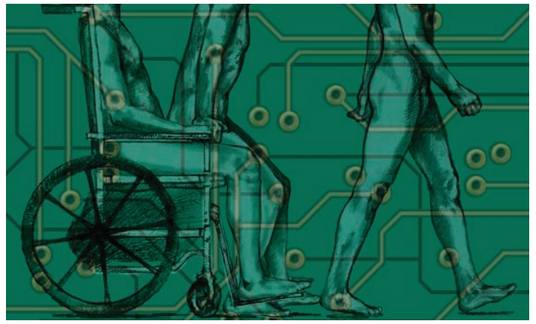
"This is the highest level, the most abstract plan of how you want to move your arm," Shenoy says.

Most other researchers place electrodes in the motor cortex of the brain, which is the last place thoughts visit before they exit the brain for the spinal cord. But tapping into the planning region of the brain has advantages, Shenoy believes. Whereas motor neurons coordinate movement along a pathway, planning neurons simply tell where and

when the arm should go next— an easier set of instructions to read and transfer. If the neuron just specifies a target, then scientists should be able to engineer a robotic solution of how to get there, without having to read tons of neurons. Recording electrical impulses from a few neurons is technologically simpler and surgically less invasive, and thus may be more feasible to do in humans in the near future, Shenoy says.

Planning neurons may also be less susceptible to the changes that may take place in motor neurons after paralysis, when the muscles they control become inactive. "We're going to a deeper, more isolated, more central part of the brain, farther from the sites of potential injury," Shenoy says. "It may well be that, since the motor cortex is closer to the periphery, if you have a spinal cord injury the motor cortex reorganizes and the parietal reach region remains intact."

But not everyone agrees with this theory. "I think most of the data are against them," Schwartz says. "My point of view is even if it [the motor cortex] does reorganize you can train the individual to reorganize it again to the way you want it to work. In my mind it's not such an issue."



Shenoy's experiment involved only one neuron, but he says this was just a proof of concept. He plans to expand to reading from several neurons, using electrode arrays. "It could be that if we then go listen to a second neuron or a third or a fourth or even 100 neurons all at the same time, then we can do a very good job of predicting where the monkey wants to reach—not just left versus right, but up versus down, and near versus far," Shenoy says.

Indeed, there are distinct advantages to reading more than one neuron. John Donoghue, a top neuroscientist at Brown University, says that it is crucial to read from populations of neurons. "How we're coming to understand the brain is like trying to understand one instrument at a time in a symphony," Donoghue says. "Certain things arise from interactions, such as harmony, that can't be heard one at a time."

Donoghue and his collaborators at Brown look at groups of 6 to 25 cells in the motor cortex using multi-electrode arrays. They read out specific motor plans, three-dimensional pathways with direction and speed, not just binary movements. "Our lab is interested in turning thoughts into behaviors," he says.

In Donoghue's experiment, a monkey plays a video game, rather like ping-pong, where it has to capture an on-screen target by moving a mouse with its hands. It doesn't take the monkey long to master the game. After the monkey has played for a few minutes, the scientists disconnect the mouse from the computer and switch from mouse control to brain control, unbeknownst to the monkey. Instantaneously, the monkey controls the video game from its brain.

"What's coming out of the brain is some kind of code that mathematical filters can decipher in minutes," Donoghue says.

Donoghue was surprised the monkeys could do it so well. Eventually, one monkey even realized he didn't need to move the mouse, and he quit moving his hand altogether.

Based on these findings, Donoghue says he could reconstruct how a person was scribbling on a paper just from recording his brain activities. "Once you have that signal, you can control any kind of device that you can imagine," he says.

The system performs better when the team reads more nerve cells, he says. However, it's a trade-off. Breaking into the brain is one of the biggest obstacles to this type of technology. The more electrodes in the brain, the greater the chance of infection—a particular danger once the procedure is moved outside the controlled environment of a lab.

Says Donoghue, "If you had simply paralyzed one leg, would you do this [in order to walk normally again]? I'd say we're not sufficiently comfortable with this technology to recommend it in this case."

"The holy grail in these communities would be to have a totally non-invasive way of reading out the brain and what you want to do," Shenoy says. "We're not there, but we're at least getting much closer to the invasive way of doing what we've been discussing."

There are procedures that involve cutting into a part of the body other than the brain, and these might be better for people who are only partially paralyzed. For example, scientists have sent signals from a working shoulder to a non-working hand through external electrodes, letting the shoulder take on some duties of the injured spinal cord.

He cites functional Magnetic Resonance Imaging (fMRI), which remotely images brain activity by measuring blood flow changes. However, like normal MRI, the machine takes a huge room. Even if you could miniaturize the technology to a pinhead, the resolution is not good—you're not able to say, "That neuron just fired one spike," Shenoy says.

The history of practical successes in the field of neural prosthetics is rather short. The two biggest success stories involve reading signals into the brain instead of reading them out.

The cochlear implant, a commercially available device, restores hearing to some deaf people, was the first real interface between the brain and an external, man-made device. The implant takes over for damaged cochlea organs, which normally turn sound waves into electric pulses that stimulate nerve cells in the brain. A receiver under the ear receives digitized sound from a microphone and converts these signals to electric pulses. The pulses trigger microelectrodes in the cochlea, which then spark the brain neurons

Another electronic device, made by Medtronic, Inc., prevents tremors in Parkinson's patients by writing signals into the brain and disrupting neural circuits.

In fact, for neural prosthetics to be truly useful, they must be able to both read signals out of the brain and read them in. "The typewriter is helpful for a paraplegic, but from a longer-range scientific view, we want to be able to do much more than this," Shenoy says.

For example, just picking up a glass is a complicated coordinated process between the brain and the fingers. Grip too hard and you might break the glass. Grip too lightly and you'll drop it. The prosthetic either has to be intelligent enough to gauge how to react, or it has to be able to talk back and forth with the brain.

Ultimately, the neural prosthetic should be able to learn to work with the brain. "The brain is going to change. Therefore, our algorithms and our electronics have to keep up with, if not encourage, the brain's behavior. That way, the whole system improves itself, just like a child learning to catch a ball," Shenoy says.

"Eventually, you want to have the computer system intelligent enough that it fine tunes itself, sort of like modern cars giving themselves tune-ups."

Listening to the brain is going to satisfy Shenoy for only so long. Eventually, he wants to have a conversation. ■

Listening to the Bones

Fur seals mysteriously vanished from California's shores 800 years ago. Prehistoric trash implicates human hunters as the chief culprits.

By KENDALL K. MORGAN
ILLUSTRATIONS by ELIZABETH MURDOCH

PAUL KOCH AND DIANE GIFFORD-GONZALEZ are gravediggers of sorts. They're bone collectors with a fascination for skeletal scraps—from ancient northern fur seals, to be precise. Like crime-scene detectives in search of a culprit, the two scientists from the University of California in Santa Cruz are investigating the suspicious disappearance of northern fur seals from the shores of the Golden State.

The black, densely furred creatures today breed exclusively on offshore islands, primarily in cold northern waters. Nearly a million of the marine mammals make Alaska their home base, but migrate as far south as California in the winter to feed. Only one established colony of 10,000 seals breeds off California, near Santa Barbara, and the seals never touch the mainland unless sick or injured.

But the California seals aren't the oddballs they seem to be, according to Koch, an earth scientist, and Gifford-Gonzalez, an archaeologist. By studying old seal bone collections in new ways, the two have recently reached surprising new conclusions. The bones tell them that until 800 years ago, countless northern fur seals actually crowded the shores of northern California. For thousands of years, the research suggests, the animals lived in California year-round and established large breeding grounds, called rookeries, on the mainland.

"Now we know something about the seals that we didn't know before," says Koch. "The habits of surviving northern fur seals are misleading. The seals have the capacity to survive on California's mainland—they don't need to go someplace cold."

So why did the animals vanish from California beaches? Some scientists think they retreated due to natural causes, such as changes in climate. Other researchers believe that predators on the mainland, such as bears, forced the seal population to seek a safer home. But Koch and Gifford-Gonzalez aren't so sure. They suspect that early human hunters, driven to hunt the creatures heavily during lean times, are responsible for California's current dearth of northern fur seals. Indeed, the fur seals may be just one example of a more general shift of pinniped species—a group including seals and sea lions—from the Pacific Coast mainland to offshore island refuges.

The UCSC scientists' theory not only challenges the current dogma, but also raises fundamental questions about the seals' future. If humans forced the animals offshore, Koch says, then perhaps humans should help the seals back onto the mainland.

Definitive answers about why the seals vanished won't come easily, says Gifford-Gonzalez. Just as in some criminal investigations, the scientists need to rely upon many indirect clues. "If you want to know who the perpetrator was, you must look at how many lines of evidence point to a common cause," she says. Thanks to the UCSC team, that proof is mounting.

ONE OF THE "crime scenes" under investigation is Año Nuevo State Reserve, 55 miles south of San Francisco. Here, rolling sand dunes stretch for miles before ending in a low, rocky point that juts into the Pacific Ocean. Año Nuevo is home to the world's biggest mainland colony of northern elephant seals, the more hulking relatives of the fur seals. Thousands of people flock to this shore each winter to gawk at the two-and-a-half-ton elephant seals that come to

breed. They put on quite a show. Males hurl their massive bodies and stretch their necks toward the sky, battling with one another for mates. On the brink of extinction only decades ago, elephant seals have made a remarkable comeback. They are a conservation success story at a time when many other animal species are dying out at unprecedented rates.

Closer inspection of the Año Nuevo dunes, though, reveals ancient mounds of shell and bone that hint at a distinctly different history. Evidence recently collected by graduate student Seth Newsome and archaeologist Mark Hylkema point toward a vision of Año Nuevo's past in which northern fur seals were the dominant marine mammal on the beach. "In the past there was a really healthy population, and 800 years ago, it crashed," says Newsome.

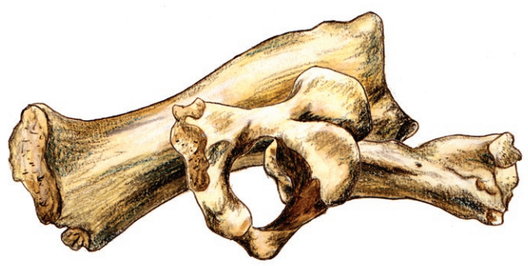
The shell and bone are the remnants of the original human inhabitants of the coast, the Ohlone people. The Ohlones lived in the San Francisco Bay Area for thousands of years before Europeans arrived in North America. They dwelled in houses of reed and willow, and subsisted on the fruits of the land and sea: acorns and berries, as well as deer, mussels, fish, and seals.

The mounds at Año Nuevo are ancient heaps of Ohlone kitchen scraps dating back three thousand years. But their trash is gold to the scientists. Careful excavation at Año Nuevo and other sites in central California has uncovered many bones of northern fur seal adults, juveniles, and sometimes even pups too young to swim—a striking find, given the absence of the animals in those coastal areas today.

Unlike other tribes in the Pacific Northwest and southern California, the Ohlone never became blue-water sailors; they hunted and fished close to shore. That suggests fur seals must have bred on the California coast. What's more, when Koch's team looked at trash piles older than one thousand years, they found that northern fur seals were the most common seal among the remains—accounting for up to 80 percent of seal bones in any given mound. So far, within this time period, elephant seals haven't made an appearance.

Thanks to a knack for geochemical wizardry, Koch and Newsome are able to use the discarded bones to pry further into the past lives of California's northern fur seals. Their brand of magic relies on a simple and familiar idea: You are what you eat. The main clues are the basic chemical elements, principally carbon and nitrogen. Each of these elements come in different versions called isotopes, which have slightly differing atomic weights. The isotopes end up preserved within an animal's bones in varying proportions depending upon its diet.

For instance, according to data gathered from living seal populations by UCSC graduate student Rob Burton, the bones of seals feeding close to shore are laced with more "heavy" carbon and nitrogen than the bones of those foraging in deeper waters. Similarly, marine mammals that spend their days at middle latitudes carry more heavy elements in their bones than animals hunting in colder northern waters. Thus, analyses comparing carbon and nitrogen levels in ancient and modern seal bones can pinpoint shifts in where the seals lived and dined.



The bones of seals feeding close to shore are laced with more 'heavy' carbon and nitrogen than the bones of those foraging in deeper waters.

In Koch's lab, small zipped plastic bags hold the yellowed skeletal remains of long-dead California northern fur seals: ear bones, bits of rib, maybe even a toe. The researchers crush and dissolve the bone samples into amorphous clumps of collagen fiber. Then they convert the collagen globs into even more basic parts inside an incinerator, which, in a flash of fiery orange, vaporizes the bone fibers into carbon dioxide and nitrogen gas. The incinerator sends the gases directly to an instrument, called a mass spectrometer, that sorts the isotopes of each chemical in turn. For example, carbon dioxide is sorted into molecules of three separate atomic weights, in quantities reflecting the proportion of different carbon isotopes in the bones. The researchers simply sit back and watch the results appear on a computer screen as a series of red and blue peaks—each representing a separate isotope.

Using what they knew about the influence of nutrition on the bone makeup of living seals, Koch's research team has decoded the bone chemistry of the ancient seals into information about their prehistoric dietary habits. The isotope studies reveal, not unexpectedly, that the creatures fed in deeper offshore waters. But the bones show no evidence that seals strayed to higher latitudes—confirming the idea that some colonies of ancient northern fur seals stuck around California all year, rather than seasonally trekking down from the icy waters of Alaska.

To learn the cause of this drastic shift, the scientists looked at the leading suspect—ocean climate change—again with the aid of geochemical tools. The Ohlones snacked on mussels and tossed their shells in the trash heaps along with the fur seal bones. Luckily for Koch and his associates, mussels, which live two to ten years, serve as natural recorders of ocean conditions. As they grow, their shells thicken and form annual growth rings like those found in trees, so that the chemical makeup of each shell layer reflects the climate conditions in a given year. By measuring the amount of oxygen and carbon isotopes in each layer, the researchers are reconstructing the temperature and nutrient composition of ocean waters off California over time, and identifying periods of major climate change.

So far, after poring over 3,000 years' worth of Ohlone mussel scraps the researchers have yet to find any sign of unusual changes in ocean climate. The usual suspect seems to be off the hook. Prehistoric Ohlone hunters became the prime suspects instead.

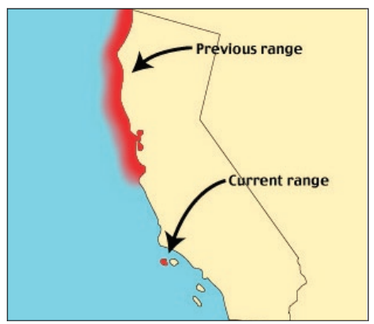
According to Gifford-Gonzalez, drought conditions on land may have led to overhunting of fur seals. Evidence from tree rings suggests that California got warmer and drier 1,000 years ago. A shortage of their standard fare—acorns and grains—may have left the Ohlone little choice but to target more of the rich, fatty seals, she says.

Indeed, says archaeology grad student Newsome, contents of the Ohlone trash heaps show an increase in marine scraps around the time the seals disappeared, possibly indicating that other food resources were drying up. And seal bones from the mounds suggest selective hunting of females, which are smaller and less threatening than males.

The practice of targeting females would have put the fur seals at greater risk of extinction. Successful male seals are quite the playboys, forming harems of up to 40 females, while the other males just hang out on the sidelines and may not mate at all. So most males fail to contribute pups to the next generation, and are irrelevant to population growth. On the other hand, the loss of females directly spells fewer young seals the following year.

ALL IN ALL, the bone studies by Koch and Gifford-Gonzales' crew provide irrefutable evidence that northern fur seals once thrived on California's mainland. "It challenges longstanding ideas about pinnipeds' limitation to offshore islands," says Dan Costa, a seal ecologist at UCSC who isn't involved in the bone research. The findings highlight the value of a deep time perspective. Ecologists tend to think in terms of decades, while an animal's true history extends over centuries and even millennia. "The way the seals are now may be an artifact of human habitation and disturbance—not to mention lots of environmental change," Costa says.

However, Costa has doubts about the importance of Koch's mainland fur seals to the species as a whole. The number of seals that made their home on California's mainland centuries ago can't be guessed from the Ohlone bone fragments. Maybe, mainland fur seals were just small populations on the outskirts of their ideal habitat range, says Costa. One line of evidence fuels his skepticism: Today's California seals wean their pups in just four months, a feat uniting them with Antarctic seals. This leads Costa to conclude that northern fur seals belong in the icy waters where they mainly live today.



Koch sees his point, but maintains that fur seals weren't a rarity in California. Studies over the last decade have found that they were the most common seal species at many archeological sites, from Santa Barbara to the Oregon border. But until the number of ancient seals that lived onshore is well established, the importance of California's mainland fur seals will remain a matter of debate.

The mounds at Año Nuevo are ancient heaps of Ohlone kitchen scraps dating back three thousand years.

In the meantime, should the seals' ancient history alter how ecologists work to protect them today? A precedent for applying archaeological proof to questions of conservation has already been set, in Yellowstone National Park. Opponents of the reintroduction of wolves to the park argued that the wolves weren't a crucial part of the community, says National Park Service archaeologist Ken Cannon. But fossil evidence contradicted their story. "Tens of thousands of wolves once roamed Yellowstone," he says. So wolves were let back in.

Similarly, Cannon says, northern fur seals could be brought back to the mainland at sites specially designated for them, much like the dedication of Año Nuevo to the northern elephant seal. At the very least, any conservation plan should consider all the information available so that wildlife managers and the public can make an informed decision. "Whether or not we reintroduce a species becomes a larger societal issue about what people want," he says.

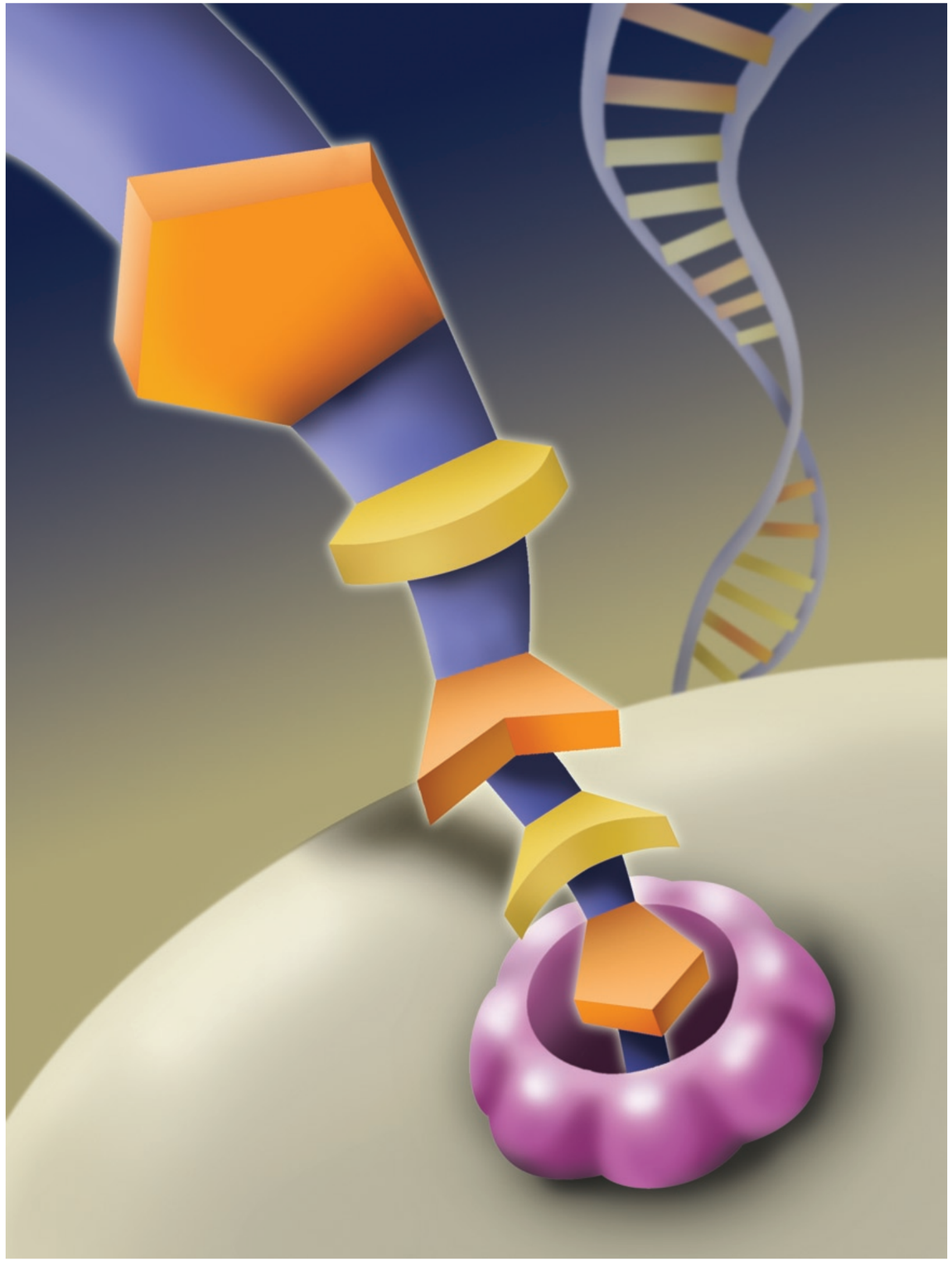
However, according to Costa, the odds run against a successful re-colonization of fur seals. The animals are stubborn, typically giving birth within a few meters of where they themselves were born. Young females sometimes strike out for new ground, but the world's population is shrinking. "Seals generally move to new areas when the core population increases," Costa says. "In a declining population, you don't expect to see new areas developing."

Even so, it isn't impossible. Northern fur seals have proven they can make it in the waters of coastal California. In 1968, a crew of them found its way south to establish the breeding colony off the coast of Santa Barbara, on San Miguel Island. And 1986 marked the first year in recent times that a new pup was born on the South Farallon Island, near San Francisco. According to Peter Pyle, a Point Reyes Bird Observatory researcher, that island's population of 20 seals is showing signs of growth. But the creatures are sensitive to human activity, Pyle cautions. "If they were to re-colonize the mainland, it would have to be somewhere remote—where there were no people. These days, it's hard to find that."

Other seals, as well as sea lions, may face a similar predicament, Koch says. "In Oregon, the abundant pinniped is the Steller sea lion; in southern California, the Guadalupe fur seal," he says. "Today, all of them breed offshore. There may have been other seal rookeries on the mainland." Did these pinnipeds get evicted from Pacific beaches like the northern fur seals did? Koch hopes scientists will start studying that question.

Koch sees a broader lesson here. Humans have made their mark on nature since prehistoric times, though the rate of environmental change has risen rapidly in the modern era. Since the goal of conservation is to preserve species well into the future, management efforts stand to benefit from consideration of the distant past.

"We often think the present is the key to the past," Koch says. "But in this case, the past is the key to the present. To understand how species have changed, you need the fossil record. And there are lots of fossils. If you really want to uncover the ecology of the past, all you have to do is look." ■



How to Speed Read a Gene

The world's fastest gene sequencing could work by slipping DNA through a tiny hole.

By CAMERON WALKER
ILLUSTRATIONS by ALICIA CALLE

IT TOOK 11 YEARS and a lot of sweat. Last year, scientists in the widely-touted Human Genome Project finally deciphered a rough draft of the three billion pairs of genetic building blocks that make up the recipe for human life. But imagine if there was a way to shrink the time it took to read a person's entire genetic makeup from a decade to a day. Imagine if your family doctor could anticipate and prevent health problems lurking far ahead in your future, by simply testing a tiny scrape of cells from the inside of your cheek-right there in his office, with answers back the same day. A new genetic analysis technique under development at the University of California at Santa Cruz just might make these scenarios possible someday.

The experimental new technology makes use of a tiny hole in an artificial cell membrane. Called a nanopore, the hole is about 40,000 times narrower than a human hair. By passing a strand of DNA through the pore—sort of like threading a noodle through a Cheerio—scientists can actually scan its genetic code, or sequence. They think nanopores will be able to read DNA far more quickly than the current sequencing methods used in the genome project. Although recent developments in conventional sequencing have sped up the process, nanopore sequencing holds the promise of working at mind-boggling new speeds. A group of 100 nanopore sequencers, working together, could read the human genome in just three hours, speculates Daniel Branton, a Harvard biologist.

Scientists across the country have been poking and prodding at nanopores, and high-tech companies are starting to clue in to the technology's potentially revolutionary value. Still, the diminutive pore is a work in progress that has yet to prove itself. And if this high-speed sequencer does make its way into the wider community, a new stream of questions will need to be answered. For Americans leery of national identification cards, the advent of individual DNA sequencing might open the door to unwanted peeking into the most private details of a person's identity.

The nanopore sequencing idea first surfaced more than a decade ago on a scientist's road trip from Oregon to California. Reminiscing in his Santa Cruz office, that scientist—biochemist David Deamer—pulls out a notebook from a triple-tiered file cabinet. He flips open the cardboard cover and peruses the first two pages, covered with cursive notes and sketches in red ink. His main drawing shows a series of shapes parading in a single file through what looks like a narrow tunnel. Each shape is a pentagon with squiggles sprouting from its corners like wildly-waving arms and legs. The pentagons come in four types. Each one is a building block—called a base—that makes up the DNA of genes. Genes, in turn, are the blueprint for the body's appearance, attributes, and often, its predisposition to disease.

Deamer's scribblings serendipitously came out of his past research into the origins of life. In order for life to begin, certain chemical compounds had to get together and start interacting from scratch. In one project, Deamer looked specifically at enzymes, which he collected in a hollow ball of a cell membrane called a vesicle. During his experiments, he noticed that a tiny hole in the vesicle could let in molecules like ATP—the cell's energy source—while also keeping in the enzymes needed to jump-start life. "I said, well, if I can get ATP in, why can't I get a molecule of DNA in?" Deamer recalls. "And that's really what bubbled up in my mind."

Then, during Deamer's road trip, his musings led him to a brilliant idea: What if he ran an electric current through the pore while a DNA molecule went in? As each base of the DNA passed through, it would momentarily block the current. And because each base is slightly different, it would interfere with the current in a unique way that would single it out, just like a name tag. Deamer could then pick out bases in their order of appearance—and at a rate hardly imaginable even with today's high-speed computers. "If we could have this working right now in our laboratory, one instrument would equal the entire world's ability to sequence DNA," he says. "That's how fast it really is."

In 1991, Deamer teamed up with Branton, who was his post-doctoral adviser when the two worked at the University of California at Berkeley, to test his road-trip daydream in the lab. Searching for a suitable pore, the pair looked at a well-studied protein called alpha-hemolysin, which comes from a toxic bacterium. The bacterium, which causes staph infections, uses the protein to punch holes in a cell's membranes in order to sink the cell like a ship bombarded with cannonballs. The cell-killing protein forms a passageway just large enough for only one chain of the double-stranded DNA molecule-which resembles a twisted ladder-to pass through.

By this time, Deamer had contacted biophysicist John Kasianowicz at the National Institute of Science and Technology in Washington,

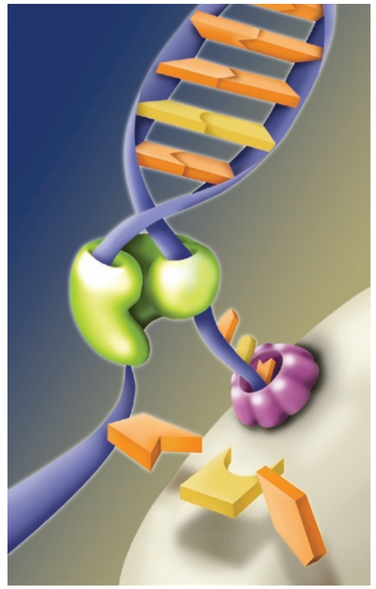
D.C., who was studying the same alpha-hemolysin pore in his own research. In 1993, the two scientists conducted a test in Kasianowicz's lab. They placed the protein in an artificial membrane in a solution of potassium chloride. Then they set up an electrical current through the fluid from one side of the membrane to the other through the nanopore. With the current up and running, they threw genetic molecules into the mix.

The first molecule to squeeze through the tiny tunnel was RNA, a single-stranded relative of DNA that helps cells make proteins. At its smallest point, the pore is less than two nanometers wide—two billionths of a meter. Just as they'd hoped, the RNA molecules made the current plummet as they slid through.

"When Kasianowicz and I saw that, we realized that we really did have a detector," Deamer recalls. He points to a picture of the current-a straight horizontal line, with long, thin spikes poking down from it. Each downward spike shows the current was blocked for a fraction of a second by a passing RNA molecule.

Deamer's group had shown that the pore could tell when genetic material was traveling through. But what they really wanted was for it to detect the sequence of RNA or DNA bases as they zoomed single file through the hole. The researcher who began tackling that challenge in 1995 was biochemist Mark Akeson, who joined Deamer's lab from the National Institutes of Health. Akeson began studying how to use the nanopore to distinguish between different bases on long strands of molecules. He made his own strands, consisting of a group of the same building blocks all in a row. For example, one molecule was a long series of adenines—one kind of base—while another was all cytosines. Then he pushed each chain through the pore. As each one went through, it blocked the current in a different way.

Akeson was the first to demonstrate that the method could actually detect sequences, albeit not on a base by base level, says Deamer, leaning back in his office chair and interlacing his fingers. "We realized then—Mark realized—that we might be able to fulfill our dream of sequencing in a very rough way," he says.



HAVING SET THE STAGE with a prologue explaining his team's work, Deamer displays the star of the show. The prototype nanopore lives in a cramped corner of his lab, within the walls of a cubicle. From the outside, a small, thin aluminum box sitting on the cubicle's desk looks like it might hold dominoes or a small video game. Actually, the box is the stage where all the action happens.

Graduate student Veronica DeGuzman squints through a microscope, focusing on a glass slide positioned atop the box where she's trying to place the pore. Manufacturing the pore itself for an experiment is no easy trick. The slide must be coated with the thinnest layer of fatty molecules called lipids, creating a cell membrane structure. DeGuzman dips a small paintbrush into a finger-sized test tube containing the oily lipids. She scrapes out a tiny, sticky droplet with the brush. Then, she picks up another brush, this one topped with a single sable hair. She holds up the two brushes to the light, trying to tease away one slippery lipid from the droplet to transfer to the slide.

After assembling the basic lipid membrane, DeGuzman adds the alpha-hemolysin protein to create the pore. Then it's a waiting game. "It's just like fishing," says Akeson. "You have to wait and see if you've caught something." Sometimes this process takes an hour, sometimes a day, but eventually the protein punches a hole through the lipid layer. Because the pore narrows as it goes through the membrane, it prevents double-stranded DNA from squeezing by. But single-stranded DNA and RNA can speed right through. "It would look like somebody slurping up a spaghetti noodle," says Akeson, pursing his lips into an O-shaped circle.

But so far, the pore slurps too quickly to read DNA base by base. A single base zips through the pore in microseconds. This doesn't give the computer program that reads the electric current enough time to differentiate between the normal and blocked current. To slow things down, Deamer's lab tried working with a convoluted form of DNA. By using single-stranded hairpin DNA—a string of bases that folds up into a U-shaped structure—the two found that the pore could savor a single base at a time. As it tries to fit through the narrowing pore, the hairpin DNA gets stuck. Then it begins to unfold, stretching one end into the pore. By measuring how the current is obstructed, the researchers can distinguish between the last sets of bases on different hairpins. This has given the researchers a hint of single-strand sequencing, though only for the bases sitting at the very end of the hairpin.

So far, no one has yet reached the goal of reading a full strand of DNA base by base. Even the researchers confess they aren't completely sure it can be done. "It still remains, from the point of view of sequencing, a high-risk project with a high-risk payoff. There's no guarantee it's going to work," says Harvard's Branton.

Even so, nanotechnology companies are taking the gamble. In May 2001, Agilent Technologies in Mountain View, California, began working with Branton, hoping to develop the first commercially available nanopore. But Agilent's pore is different: it's carved out of a synthetic material called silicon nitride. Branton and Harvard physicist Jene Golovchenko blasted a stream of ions at a sheet of the synthetic material to drill a hole for DNA to pass through.

The silicon nitride nanopore is much tougher than its biological counterpart. It should be able to handle endless streams of DNA for widespread sequencing use. "Unlike alpha-hemolysin, these pores could be made and stored in a can, so to speak," Branton says. The researchers have shown that strands of 30,000 DNA bases can pass through their synthetic pore-chains thirty times longer than those sequenced by conventional machines. But so far, their pore has only been able to identify bases in groups of ten.

Despite the potential advantages of a synthetic pore, naturally-occurring pores may be able to read DNA more precisely, Akeson says. "Nature has made this protein to fit exactly with DNA," he says. The successful pore of the future, the one which can read DNA one base at a time, could have both biological and synthetic components, he adds.

Both biological and synthetic nanopores could beat out conventional sequencing when it comes to efficiency. All current sequencing is based on the Sanger method, developed in the 1970s. With this technique, enzymes chop strands of DNA into segments. The researchers separate the fragments by length, then piece them together to determine the sequence of their bases. Many fragments are needed to solve the puzzle, so the scientists must start out with many, many copies of the DNA.

Today, although many improvements to the Sanger method have been made over the decades, sequencing machines still require large volumes of DNA. But with the nanopore method, just one copy of the DNA is all it would take: A single strand could be decoded base by base without any amplifying, chopping, or reorganizing. "The next sea change [in sequencing] is going to have to be with a single molecule," Akeson says.

Akeson is hoping that grad student DeGuzman's current project is the work that will really establish single-strand nanopore sequencing as a viable technique. DeGuzman is investigating a different way of slowing down DNA's transit through the tunnel, so that the pore can read it. She's trying to use a DNA-chewing enzyme to control DNA's entrance into the nanopore. This enzyme grabs onto the double-stranded molecule and chops one of its chains into individual bases. The other strand escapes unscathed and feeds into the hole at the same slow rate at which the enzyme munches along.

DEGUZMAN AND OTHERS in Deamer's lab are working with collaborators across the country who are studying the nanopore from many angles. Many of the people working on the project predict that a commercially available pore could be running within ten years. But not everyone is so confident. For large-scale challenges such as the exploration of the human genome, a working nanopore sequencer would certainly be a godsend. "It's conceivable that everything you could do with a nanopore would be better," says Jeffrey Schloss, a cell biologist who heads the Technology Development Coordination program at the National Human Genome Research Institute. "The big question is, will it ever work?"

But even if the technology doesn't turn out to be the single-base sequencer of Deamer's brainstorm, Schloss says, it may have other useful applications. For instance, Andre Marziali, a physicist at the University of British Columbia in Vancouver, wants to use the nanopore to count pieces of DNA after they're already been separated according to length by conventional sequencing. Right now, scientists use a laser the size of a boxy computer to count the chopped-up DNA. Many sequencers also use expensive dyes to detect the DNA fragments. Nanopores could replace both the lasers and these dyes-bringing the whole process down to a smaller, cheaper scale-by directly tallying individual DNA molecules as they whiz through the pore. Marziali believes this application of the nanopore can be put into practice sooner than the elusive nanopore sequencer.

If a faster sequencing method succeeds, however, it is certain to raise new worries about the privacy of genetic information. A person's DNA sequence could become like a social security number, following a person from place to place—but with far more intimate personal details. But chemist Rashid Bashir, who is developing a synthetic nanopore at Purdue University, thinks the potential gains in health care outweigh these concerns. "Science and technology are really like tools," Bashir says. "Technology can be used for good reasons and bad reasons, like anything else."

Indeed, this technology may go places Deamer never imagined on that long car ride years ago. He's confident that scientists will come up with new ways of improving the basic nanopore-sequencing idea that no one's even dreamed of yet. "Someone's going to make it work," Deamer says. "We just hope that it's us." ■

If DNA Be the Music of Life, Play On

David Deamer's creative interest in DNA has found another outlet: music. For two decades, the biochemist at the University of California at Santa Cruz has been making a hobby of translating the genetic sequence of life into a series of musical notes.

It all started when Deamer encountered students who were puzzled over the idea that a piece of DNA contains information. "Music is a sequence of notes, just like DNA is a sequence of bases — and musical notes make sense to people," he says. "If you could somehow play DNA as music, you get across the idea that DNA contains sequence information. You play it from one end to the other, just like DNA."

So Deamer started gathering segments of DNA to turn into melodies. "It was kind of a wild idea, but it started to sound sort of musical." He started a company, Science in the Arts, which puts out recordings of this "music of life." Many of these DNA song snippets sound like a lilting waltz, moving along in three-quarter time.

Teachers across the country have been using Deamer's tunes to show students how those little building blocks can link up to make something beautiful. (One unexpected result of Deamer's musical work with DNA has been its appeal to people he calls "mystics." High on their list of "new age" concerns is the fear that music may somehow rearrange a person's DNA.)

One of Deamer's favorite tunes comes from the "alu consensus," a sequence that makes up ten percent of our DNA. "We and our colleagues on the earth, the chimpanzees, have this musical sequence in our genes," he says. The scientist's investigation into the music of DNA, along with his nanopore research, is providing a fresh perspective on the genetic symphony of life.

Cameron Walker

The Seafood Dilemma

Is the fish you're eating about to go extinct? Neither you nor your waiter nor your supermarket may know for sure.

By GENEVIEVE BOOKWALTER
ILLUSTRATION by TARA DALTON

THE YOUNG WAITRESS shifts her weight as she stands next to a table of four businessmen, waiting to take their order in the small, San Francisco seafood bar. "What's in the Cioppino again," one of them asks.

"Clams, cod, salmon, seabass—," she recites. The gentleman who asked the question cuts her off. Is that Chilean seabass, he asks. If it is, he's not ordering any, he can't believe restaurants would even think of still carrying it, doesn't everyone know it's almost extinct.

"Um, I don't think it's Chilean," she replies. He ends up choosing the dish, as does one of his associates. While walking back to ring their order into the computer, she wonders to herself where the fish is really from. She doesn't know, but if it was endangered, her restaurant wouldn't be allowed to serve it, right? Our seabass still sells at the same price as the salmon, she reasons. It's probably not Chilean. If it were it would be more expensive.

More and more seafood lovers are questioning the origins of the fish they eat. The campaign "Take a Pass on Chilean Seabass" received nationwide media coverage earlier this year, as chefs from coast to coast pledged not to serve the delicate white fish. The National Environmental Trust, a Washington D.C.-based environmental group who initiated the campaign, warns that if fishing continues at current levels, the Chilean seabass, also known as a Patagonian toothfish, could be commercially extinct in five years. In other words, the few fish left in their native Antarctic waters wouldn't be worth the time, effort and money to haul them in. This campaign follows similar efforts in past years to invoke voluntary consumer boycotts of tuna that isn't caught with "dolphin safe" nets and overfished Atlantic swordfish.

Unfortunately for those dedicated to preserving threatened ocean species, it is a David-versus-Goliath battle.

The Monterey Bay Aquarium's Seafood Watch Program is one such David. Founded in 1999 in Monterey, California, the program aims to provide chefs, market owners and consumers with information about how the fish they are serving, selling and eating is caught. The program supports "sustainable fisheries – those managed so that there will be plenty of fish left for the future," says program coordinator Jennifer Dianto. "This isn't a ban on seafood. We love seafood, we want to keep it around." Seafood Watch simply wants to teach people about the environmental consequences that may result from having a certain fish for dinner.

Researchers at Seafood Watch are slowly building a library of reports on the biology, markets, fisheries, and farm fishing practices for each creature commonly found in the seafood trade. They prepare these assessments by painstakingly poring over data from scientific papers and international sources, including the United Nations Food and Agricultural Program and National Marine Fisheries Service. Once a report is compiled on a fish, crustacean, or shellfish, Seafood Watch submits it to marine biologists for peer review. Only after receiving the specialists' final approval is the data considered accurate.

After a report's completion, the evaluated critter is placed on one of three lists: "Best Choices", "Proceed with Caution", or "Avoid." The team asks three questions while making its decision: do fishing levels threaten the animal with extinction? Is it fished or farmed in a way that hurts the surrounding habitat? How many other sea animals die in the fishermen's nets or lines?

SO FAR, THE PROGRAM HAS EVALUATED 44 seafood species, focusing on varieties common to California menus. Seafood Watch prints its three lists of recommendations on a wallet-sized card that concerned diners can consult in restaurants or at the grocery store. The public can request the guide for free by mail from the aquarium, or download a copy from **www.montereybayaquarium.org**. The Seafood Watch website also includes a detailed chart explaining its listings fish by fish.

For example, mahi-mahi rank as a "Best Choice" because they reproduce quickly, thus maintaining their population and allowing them to withstand a lot of fishing. Chilean seabass sit on the "Avoid" list because they grow slowly and don't replenish as quickly as they are caught. Imitation crab (or Pollock fish) is labeled as "Proceed With Caution" because some scientists believe that fishing for it takes food away from sea lions. Following Seafood Watch's advice, the Monterey Bay Aquarium restaurant only serves fish from the "Best Choices" or "Proceed with Caution" lists.

Seafood Watch also contributes its three lists to the Seafood Choices Alliance, a clearinghouse organization where chefs, wholesalers, grocers, and fishermen can seek answers, free of charge, to questions on which fish to serve or catch at sea. The alliance can link concerned purveyors with environmentally conscious fishermen who will stock the nightly dinner specials while ensuring the restaurant or market meets its economic bottom line. "We see the Seafood Choices Alliance as the place to exchange this information and as a way to create new relationships, so that together we can restore the natural luster and abundance to our oceans," says Vikki Spruill, executive director of SeaWeb, the nonprofit group that created the alliance. It currently boasts over 200 subscribers.

While Seafood Watch followers aim to do the right thing, it's still easy for card-carrying consumers to get confused about what to order. For example, wild Alaskan salmon are a "Best Choice," because the industry that hauls them in is well-regulated, and because the fish reproduce quickly. But farm-raised salmon are a choice to avoid because their ocean pens pollute the water with disease-carrying feces. Shrimp and prawns get the "Proceed with Caution" yellow light if they were netted in U.S. waters, because American fisherman use devices on their nets that allow endangered sea turtles to escape, but not enough research has been done to determine how many other animals still die. Farmed shrimp or those caught internationally are red-flagged, because shrimp farming destroys mangrove trees where wild fish eat and breed and fishermen from other countries don't all promise that sea turtles can escape from their shrimp nets. Wild Caspian sturgeon, the traditional source of caviar, stays in the "Avoid" category because it is overfished. Yet caviar from U.S. farm-raised sturgeon is a "Best Choice."

For most consumers, such distinctions are bewildering to decipher. If a waiter can't help or the grocery package doesn't say, it's tough for the average seafood lover to tell the difference between wild and farm-raised salmon, and nearly impossible to find out if a shrimp was caught in U.S. or international waters. And if a wealthy friend at the table orders caviar to go with the champagne, is it rude to question the gift?

Despite the confusion, Seafood Watch's advice is still making an impact. Card-carrying diners called attention to Chilean seabass served in Yosemite National Park restaurants last fall, and as a result the fish was removed from menus at all Yosemite properties. Amfac Parks and Resorts, the concessionaire that provides food services for Yellowstone, Grand Canyon and the Everglades national parks, pulled not only Chilean seabass but also Atlantic swordfish, shark and bluefin tuna from its tables because Seafood Watch recommended doing so.

However, the popular practice of changing or even making up a fish's common name threatens Seafood Watch's success. There are no government or industry regulations as to what a market name must be for any species. "Most people don't know what escolar is, so we call it Mexican seabass," says Mario Uribe of LusAmerica Foods, Inc., a seafood distribution company in San Jose, California. LusAmerica supplies fish to grocery stores such as Safeway, Nob Hill, and Pack and Save. But the escolar Uribe refers to is not from Mexico—it's from Alaska.

AT CASA BLANCA RESTAURANT in Santa Cruz, California, a waiter informed his table that the "butterfish" entrée on the menu was a reef fish caught off the coast of Hawaii.

According to Seafood Watch, butterfish is a California species to avoid, but Casa Blanca orders it from the Hawaiian Fish Company. So does the entrée get a red light or not? To investigate further, this reporter visited a website at **www.fish-**

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Choices for Healthy Oceans

BEST CHOICES

Abalone *(farmed)*
Catfish *(U.S. farmed)*
Caviar *(farmed)*
Clams *(farmed)*
Crab, Dungeness
Halibut *(Pacific)*
Hoki
Lobster, Rock *(CA, Australia)*
Mussels *(farmed)*
Oysters *(farmed)*
Sablefish/Black Cod *(AK, BC)*
Salmon *(CA, AK; wild-caught)*
Salmon, canned
Sand Dabs
Sardines
Shrimp/Prawns *(trap-caught)*
Squid/Calamari *(CA market squid)*
Striped Bass *(farmed)*
Sturgeon *(farmed)*
Tilapia *(farmed)*
Tuna, Albacore
Tuna, canned white *(albacore)*
Tuna, Yellowfin/Ahi *(troll/pole-caught)*

PROCEED WITH CAUTION

Clams *(wild-caught)*
Cod, Pacific
Crab, Imitation/Surimi
Crab, King
Crab, Snow
Lobster, American
Mahi-Mahi
Mussels *(wild-caught)*
Oysters *(wild-caught)*
Pollock
Sablefish/Black Cod *(CA,WA,OR)*
Salmon *(OR, WA; wild-caught)*
Scallops, Bay
Shark, Thresher *(U.S. West Coast)*
Shrimp *(U.S. wild-caught)*
Shrimp, Bay
Sole, English/Petrale/Dover
Swordfish *(U.S. West Coast)*
Trout, Rainbow *(farmed)*
Tuna, Yellowfin/Ahi
Tuna, canned chunk light

AVOID

Caviar, Beluga/Osetra/Sevruga
Chilean Sea Bass
Cod, Atlantic/Icelandic
Lingcod
Monkfish
Orange Roughy
Rockfish/Rock Cod/Pacific Snapper
Salmon *(farmed/Atlantic)*
Scallops, Sea
Sharks *(except U.S. West Coast Thresher)*
Shrimp *(wild-caught or farmed)*
Sturgeon *(wild-caught)*
Swordfish *(Atlantic)*
Tuna, Bluefin

AK = Alaska
BC = British Columbia
CA = California
OR = Oregon
U.S. = United States
WA = Washington

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GREEN MEANS GO AHEAD

Your best choice is seafood from the green list. These fish and shellfish are caught or farmed in environmentally friendly ways.

YELLOW MEANS PROCEED WITH CAUTION

If your favorite fish is on the yellow list, there are some problems with the fishery or fish farms. These items are better choices than seafood on the red list. Check the source carefully before you buy.

RED MEANS AVOID

We recommend that you avoid seafood on the red list until the population recovers from overfishing, or until the fishing or fish farms cease to harm the environment.

base.org, a global information system that claims to track "practically all fish species known to science." FishBase is a non-profit research organization working with the United Nations Food and Agriculture Organization. A search of its online database for "butterfish" spits out a list of 30 different species from 26 countries—all referred to as butterfish. If FishBase's numbers are accurate, both Seafood Watch and the Casa Blanca waiter could be telling the truth—which may cause some to doubt Seafood Watch's credibility as a reliable source.

With so many exotic-sounding species hitting the market, it's easy to understand why fishermen and purveyors often classify them under a common label. If it's a white, flaky fillet, shoppers will recognize it as seabass. They won't identify with Lates calcarifer or Centrarchops chapini, the Latin names for two of the 21 FishBase-listed seabass species.

The debate over names is one reason why Matt Derrick, manager of Asia SF restaurant in San Francisco, keeps serving Chilean seabass. "If you've got a warehouse full of fish, you'll call it whatever you can to sell it," he says, questioning whether the Chilean seabass on his dinner menu is really Chilean at all. He also wonders if other restaurants serve the threatened fish unknowingly, as suppliers get rid of stock they accumulated before the voluntary boycott began. "Overfishing is a myth, like global warming," Derrick adds. "The guys at the fish house say, Look, the Chilean seabass is fine." He believes that since fishermen make their living off the ocean, they know it more intimately than researchers in a lab do. So he continues to serve Chilean seabass—assuming that's what it really is.

Derrick's view embodies the current controversy between scientists and fishermen over what's going on at sea. In the Monterey Bay area, Frank Ealy, commercial fisherman and owner of Santa Cruz Boat Rentals and Capitola Boat and Bait, is one seaman quarreling with the researchers. "I was born and raised here, I know the fish come and go all the time," he says. "We'll have no fish for a couple of years, and all of a sudden they're back."

Ealy and fellow commercial fisherman Todd Fraser, owner of Bayside Marine Commercial Fisherman's Supply, are especially irate because rockfish and lingcod, two locally-caught favorites, are now under strict fishing limits based on data which they believe is inaccurate. "The scientists go up into Bodega Bay"—140 miles north of Santa Cruz—"and take one study from one party boat, and use it as data for the whole coast," Fraser says. Seafood Watch lists both rockfish and lingcod as fish to avoid.

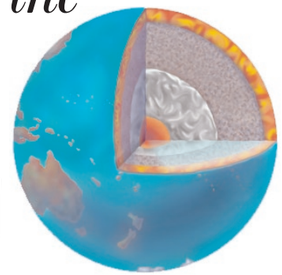
But Joan Roughgarden, a marine ecologist at Stanford University who studies fish populations along the California coast, stands by her colleagues' recommendations for the two species. "If this fishery collapses, I don't want them to come to me and say I gave them too low a number."

For many concerned consumers, a Seafood Watch card still doesn't provide the confidence to choose an environmentally friendly fish dish. But the Marine Stewardship Council—a partnership between the World Wildlife Federation and Unilever, the world's largest buyer of seafood—is stepping up to help. The council began issuing "Ecolabels" in 1999 to verify that a fish was caught by a sustainable fishery. Wild Alaskan salmon was one of the first to receive the label, which is easily located on certified fish products like stickers are on organic fruit. The council hopes to eventually classify every seafood product in a supermarket, but it will be years before all fisheries are analyzed.

Until Ecolabels are commonplace, researchers at Seafood Watch say that consulting their card or a similar guide, such as The Audubon Guide to Seafood (available at **http://magazine.audubon.org/seafood/guide/**), is the best way for seafood lovers to choose their meals responsibly. "I'll remember the Chilean seabass thing now," says Alexandra Dumas, 23, a Santa Cruz resident and occasional seafood eater. "If I see it I won't get it."

The program is now expanding its recommendations to include popular East Coast varieties, and will release an East Coast version of its card this summer. It is also collaborating with aquariums, museums, and zoos nationwide to create guides for six other regions. "We're trying to keep the message positive," says Seafood Watch coordinator Dianto. "Consumers have an awful lot of influence. What we buy drives what they catch." ■

ECHOES *from the* CORE



About 1,800 miles beneath our feet, liquid iron sloshes against solid rock. It's a boundary with far-reaching consequences—and some surprising properties.

By DANIEL BACHTOLD
ILLUSTRATION by KATURA REYNOLDS

IN JULES VERNE'S 1864 novel **Journey to the Center of the Earth**, Professor Hardwigg, an eccentric old scientist and his nephew Harry set out to explore our planet's core. They enter a dormant volcano in Iceland that leads them down to the center of the Earth. After weeks of arduous traveling, the explorers reach the shore of a vast ocean—the Central Sea, as they call it. Gigantic mushrooms and pine trees thrive at its shore while a cool breeze ripples the water. The water is fresh and inviting and Harry plunges into it.

In reality, though, Earth's innards are barren and hellish. It is a place where horrendous temperatures and pressures ensure that no human being will ever be able to set foot there. In one respect, however, Jules Verne got it quite right: Hundreds of miles beneath our feet close to the center of the Earth, there is a vast ocean—not of water, though, but of hot liquid iron.

The place is so inhospitable, in brief, that scientists must base their knowledge of the center of the Earth on indirect evidence. Like physicians who look at an embryo with ultrasound waves, earth scientists study the structure of the Earth by analyzing seismic waves that radiate from earthquakes. On their way through different layers of rock, seismic waves change in a way that gives clues about the structures they have passed through.

Basing their work on such observations, earth scientists have come up with a model of the planet that resembles the layering of an egg. The Earth's crust is as delicate and brittle as the shell. Underneath the crust is Earth's mantle, which corresponds to the egg's white. The upper part of the mantle is partially molten, whereas the lower part consists of solid rock. The iron core in Earth's center is the yolk. At the boundary between the mantle and the core, about 1,800 miles beneath the surface and roughly half-way to Earth's center, the physical properties change abruptly. The swirling iron of the outer core has the consistency of water, and its temperature exceeds that of the neighboring solid, rocky mantle by more than 3,000 degrees Fahrenheit. Finally, the inner core, Earth's center, consists of a solid iron ball about 1,500 miles in diameter.

Now, seismologists Sebastian Rost and Justin Revenaugh from UC Santa Cruz have found new evidence that the boundary between the solid mantle and the liquid outer core is not as sharply defined as scientists once believed. From the seismic fingerprints of seven earthquakes beneath the Pacific Ocean, Rost and Revenaugh resolved a very thin patch of the core-mantle boundary about the size of Santa Cruz that has both mantle-like and core-like properties. "It is a very flimsy sponge of solid material with a lot of liquid iron in it," Revenaugh says.

"People have assumed for a long time that the core and the mantle are completely separate reservoirs of material with no interchange across the boundary at all," he adds. "Now people are starting to think that there is some communication."

So far, Rost and Revenaugh can only speculate about what this odd patch does. And because they haven't yet found it in other places, they can only guess that such patches cover the entire core-mantle boundary. Its location at precisely that boundary suggests, however, that it is part of the process that regulates the heat flow between the hellish furnace of the core and the cooler rocks of the mantle above. Volcanoes, hot springs, and geysers are the most conspicuous signs of this escaping heat. Less evident is that this heat is the force behind the slow drift of continental plates.

The radical notion of drifting continents dates back to 1912, when Alfred Wegener, a German meteorologist, suggested that the

continents once clustered together to form one vast landmass. Wegener was struck by the fact that South America's east coast and Africa's west coast fit together like two puzzle pieces. Wegener's ideas, however, weren't seriously considered until the 1960s—mainly because earth scientists didn't see a plausible mechanism that could have broken up the super-continent.

The skepticism vanished when scientists found evidence that vast plumes of hot rock coming from the core-mantle boundary surge toward Earth's surface like air bubbles in a glass of water. Millions of years ago, such plumes first lifted and then eventually broke the monolithic continental landmass into huge pieces. These pieces now slowly drift about as today's continents. According to measurements of rock formations in the Atlantic Ocean, the gap between South America and Africa widens by as much as half an inch every year.

The separation of continents and the collision of other continents remodeled the appearance of Earth profoundly. Oceans formed and mountain ranges rose, lush jungles turned into deserts, and land once flooded fell dry. Animal and plant species colonized and adapted to these newly formed ecological niches. The diversity of life forms widened.

"In terms of the history of life on Earth, super-continent break-ups are very important. If that's related to plumes, then we have this tie to the base of the mantle," Revenaugh says. "It is kind of a neat thing, that the history of life might be tied to these little patches 1,800 miles below us."

Rost and Revenaugh discovered the patches about 900 miles north of New Zealand. They analyzed seismic waves of earthquakes originating beneath the islands of Tonga and Fiji. Like any other earthquake, they spawned two types of seismic waves. The pressure or "P" waves propagate in a sort of push-pull manner, like a crawling earthworm. The shear or "S" waves vibrate back and forth perpendicular to their travel path, like a fast-moving snake. Generally, P waves travel faster than S waves. And unlike S waves, P waves can travel through liquid. Both seismic waves either bend or reflect when they encounter a layer of rock with different density—much like a ray of light that passes from air into water or vice versa.

Both P and S waves reflect off the core-mantle boundary and zip all the way back to the surface. P waves might reflect as P waves, or they can convert into S waves. S waves behave likewise. From the changes the waves undergo during the rebound, scientists learn a great deal about the boundary's structure.

Rost and Revenaugh found odd looking ScP waves—S waves that are converted into P waves—that they didn't understand at first. But then Rost, a postdoctoral fellow in Revenaugh's lab, discovered that these ScP waves must stem from a structure predicted by Bruce Buffett from the University of British Columbia, Canada, and his colleagues on theoretical grounds more than one year ago. "The [patches] were postulated before, and I knew about the models, but I never thought about detecting them," Rost says.

Buffett came up with the idea of iron-rich patches at the core-mantle boundary when he and two colleagues, Edward Garnero from Arizona State University and Raymond Jeanloz from UC Berkeley, looked for a way to predict the wobble of Earth's rotation axis.

New evidence indicates the boundary between the solid mantle and the liquid outer core is not as sharply defined as scientists once believed.

This so-called nutation—a sort of nodding motion of the rotation axis—is caused by the gravitational pull of the sun and the moon. Astronomers are especially interested in Earth's motion in space. When they track a distant spacecraft with telescopes, they have to know when and by how much the Earth reorients itself in space, Buffett says. If they don't correct for Earth's nutation, they lose the spacecraft pretty quickly.

Buffett, Garnero, and Jeanloz knew that the way in which the Earth responds to this celestial pull is strongly affected by the fact that the liquid iron sloshes back and forth in its interior. The amount of sloshing scientists agreed upon at the time was quite vigorous. When Buffett and his colleagues put this variable into their calculation to predict Earth's nutation, they merely came up with a close approximation. When the scientists assumed a less vigorous liquid iron core, however, they succeeded. But what force would be strong enough to slow down thousands of cubic miles of sloshing iron? Buffett suspects Earth's magnetic field.

The moving iron in the core generates the magnetic field, the powerful natural force that drives both compass needles and the northern lights. Buffett's model suggests that conductive iron patches at the core-mantle boundary deflect the magnetic field that passes otherwise unhindered through the mantle. "The magnetic field threads out from the core through the mantle and we ultimately see it at the surface," Buffett says. "When it passes through this layer of conductive material [the iron-rich patches], it tends to connect the fluid a little bit more tightly with the mantle." Thus the patches slow down the whirling iron.

How do these patches emerge in the iron core? Nobody knows for sure. Buffett and his colleagues believe, however, that lighter elements such as oxygen, sulfur, silicates, or carbon are dissolved in the liquid iron to the point of saturation—like a glass of water that contains so much dissolved salt that any more salt simply sinks to the bottom. As Earth's core cools, some of the liquid iron solidifies and amalgamates with the solid inner core. Subsequently the concentration of these lighter elements increases until they precipitate out and float as sediments on top of the iron soup like foam on root beer. This froth accumulates in pockets at the core-mantle boundary. During that process, liquid iron is trapped and incorporated.

Other scientists find the research intriguing. "It is another important piece of information that tells us the earth isn't as simple as we so commonly portray it to be in our introductory textbooks," says Edward Garnero of Arizona State University. "It is important because it opens up our perspective that we might have a scum collecting in places where once we assumed it was all just homogenous liquid iron."

But Garnero cautions that this is only the beginning. "In any first study like this, it is rare that everybody says 'You showed us the truth!'" he says. Now that the scientists have an idea what these patches look like in their earthquake data, they should try to find them in other places too, Garnero suggests. A finding is generally accepted as the 'truth' when enough evidence accumulates and points in the same direction, he says.

The knowledge we have of the structures deep in our planet is still sketchy. And due to the elusive nature of inner Earth, scientists will never know for sure whether their models reflect the truth. All they can do is gather bits and pieces of information and then try to come up with a plausible explanation. "It is detective work," says Bruce Buffett of the University of British Columbia. "But if you like mysteries and detective stories, this is the business to be in." ■

ESSAY

The Thought Collector

By KENDALL POWELL

WHEN I WAS a graduate student, I would see him while walking to and from the Salk Institute parking lot, perched on the cliffs above La Jolla. Of course, his car, parked in the "reserved" spot closest to the Institute, was a little more distinctive than mine. The gleaming white Mercedes had California tags that read "AT GC," the bases that made up the double helix of DNA, which he and James Watson discovered more than a half century ago. Francis Crick's full head of white hair would always alert me to the fact that I was sharing the sidewalk with one of science's living legends. I never mustered the courage to speak up, but every time our paths crossed I would wonder, "Does he appreciate this beautiful afternoon the same way I do?" Surely, now that he is immersed in the problem of human consciousness, he must be thinking about how our brains process appreciation for hang gliders at sunset.

The encounters with Crick had me pondering what distinguishes a great scientist from the good ones. I thought of the question as grist for the mill of my graduate school self-education. If I could establish a pattern, then perhaps I could tap into the formula for success and at least bump myself up from "floundering" to "mediocre." As far as I could determine, the pattern was that these scientists had not just one or two good ideas, but a lifetime of them. So, on a more fundamental level, I wanted to know where those ideas came from.

Maybe, I thought, certain researchers had been graced by God-given genius. Others might simply work harder and spend more hours thinking about problems. And some individuals possessed the ability to contemplate problems in drastically different ways. Was there some magical combination of traits? The answer would require some deeper digging. Since Crick and his work made appearances throughout my studies, I decided his lifetime of ideas would make a good case study.

Like every other obedient biology undergraduate, I had read "The Race for the Double Helix," so I roughly knew the story of how Crick and Watson solved the structure of DNA. Later, I would recognize that Crick used all of his creative and critical thinking skills during this race. But what struck me at an impressionable young age was that he and Watson weren't just mere biologists who stumbled upon a chance discovery. Rather, they knew physics and chemistry in such detail as to synthesize the bits of data scattered across various fields. They had to translate the X-rays of DNA crystals into a 3-D structure. Their knowledge of the laws governing hydrogen bonds told them that A's paired only with T's and C's only with G's. They tried each piece in different configurations, until through trial and error, they found a model that fit the physical data and made sense biologically. In an interview 36 years after their discovery, Crick asserted, "We deserve credit for learning about a lot of different subjects so we could put it all together. And not many people were prepared to do that."

Today scientists are more narrowly specialized than in Crick's time, so even fewer aspire to be a jack-of-all-trades. But those who do make big discoveries. Biochemist Roger Tsien is one of them. I was a rotation student in a neighboring lab when Tsien was inducted into the National Academy of Sciences. The champagne flowed as the elder scientists congratulated him on his achievements. His lab had solved the structure of Green Fluorescent Protein (GFP) and then modified it to study the inner workings of the cell. GFP, a protein found in jellyfish, glows green owing to a unique physical structure. Tsien's enhanced version of the GFP protein is one of the most important research tools in cell biology today. Scientists attach GFP to any unknown protein and then simply look through a microscope to find out where that protein acts inside the cell.

At different times in his career, Tsien has belonged to departments of chemistry, physiology, pharmacology, and cell and molecular medicine. His lab continues to design new molecules that will light up under different cellular conditions, such as pH or calcium concentration. To do this design work, lab members must apply chemistry and physics at the submicroscopic level of the GFP molecule and within the dynamic confines of the cell. This is an example of how, by crossing multi-disciplinary techniques, Tsien develops unique methods for answering his next set of research questions.

I came across more of Crick's creative work the next year of graduate school in my critical reading class. His landmark 1961 paper established the genetic code as sets of three bases (A, T, G, or C) coding for each amino acid as it was added to a protein chain. We studied the paper as a classic example of using deductive reasoning to arrive at the best possible hypothesis.

One elegant experiment showed that triplets of bases were the most likely configuration. A pair would only have given 4 (A, T, G, or C) X 4 (A, T, G, or C) = 16 different amino acids and Crick knew that at least 20 amino acids existed. The researchers used a specific mutation-causing chemical that either adds or subtracts one base at a time from DNA. Then they could use combinations of mutations such as (+, +) or (–, –, –) to discover how the mutations affected the protein building. Mutations in sets of three resulted in a protein—presumably with one amino acid added or subtracted. But one or two mutations would result in nothing—presumably because the code had been shifted by one or two and was now unreadable.

Next, they criticized their hypothesis against every other piece of available data. In the paper, Crick marches through all of the reasons why overlapping codes, codes of two and three, and nonlinear codes do not fit the observed evidence. Because their hypothesis withstood this trial of ideas, it was accepted almost as fact—even before it could be proven beyond a doubt with experimental techniques.

Crick used critical thinking to advance his own ideas at a time when

the laboratory methods to solidify those ideas did not yet exist. A similar phenomenon occurs in lab meetings in which scientists play a brainstorming game. Thinking out loud about a piece of experimental evidence, they challenge each other to prove that their ideas are both feasible, given other data, and testable. They hone their critical thinking skills so that they carry out only rigorous experiments. Crick explained that the candor between himself and Watson allowed for this relentless back-and-forth critical reasoning. "If one of you gets an idea which is a cul-de-sac, or which gets you off on a false trail, the other one will pull you back and get you out of it," he said in a 1989 interview.

Crick made his last appearances in my graduate career during the Salk Institute's weekly seminars. He would frequently be sitting in the front row of the half-filled lecture hall. Typically, he would have a brilliant question for the speaker at the end of the lecture. His questions would always be broad, yet astute, and the speaker would smile and say, "Yes, well, that will be our next experiment."

Crick listened thoughtfully to whatever lectures came through the auditorium, from HIV vaccine design to the genetics controlling floral patterning. By keeping up with these widely disparate areas of research, he expanded his horizons and gained insights into areas far beyond his expertise. Crick does not run a lab at Salk anymore—he only keeps a study with a spectacular ocean view. Nevertheless, I suspect that he talks to more people about his ideas each day than do most investigators running 20-person labs. Crick thinks, reads, talks—and, lately, writes—his way through ideas.

Crick's creative genius comes from a mixing of the following three ingredients: knowing many fields of study, being critical of each idea, and keeping in close and frequent contact with other brilliant minds. Toward the end of my graduate school days, many of my friends had left or were leaving shortly to start their own labs. In a rookie version of Crick's broad-based yet highly focused networking, these young scientists spent their days on the phone or shooting email messages to each other. While a substantial portion of this communication revolved around last night's Simpsons episode, an important process was nevertheless at work. These young investigators were forging new alliances with people in other fields. They were trotting out new hypotheses for testing. And they were keeping one another honest by razzing a poorly formed game plan. Collectively, they were brewing the next generation of scientific discoveries. ■

ESSAY

Into the Woods

By CAMERON WALKER

THERE IS A TRAIL I FOLLOW, most mornings, that swings away from the road and curls uphill toward a snub-nosed peak. The view from the trail isn't one that will appear in National Geographic photo spreads. On one side, the ledges of the county dump form a grassy staircase; on the other, a gravel mine creates a grey bullet hole in the hillside. But at most points, these two scars are hidden from the trail by rollicking oak trees that drip moss from their branches. Redwoods, too, create a darkened theater in which the autumn leaves of poison oak appear as red flares, where the oranges of paintbrush and sticky monkey flower wink in the spring.

The walk I take usually fails in its main purpose, which is to sap the energy of a Labrador retriever without exhausting his human companion. The adolescent canine seems to be coaxed into dreamland by nothing less than an all-out sprint. But the walk lightens my mind anyway, giving it time and space to flicker through last night's dreams and today's shopping list.

I duck under spiderwebs that cross the trail and look for their makers. Salamanders with slick neon backs speckle the trail after a rain. I stoop over a pile of dried coyote scat, indulging the amateur naturalist within me with a guess at the howler's previous meal. The morning walk has become my mind's playtime, a chance for it to linger in the wild. But a stroll through the trees can be more than a quick vacation for mind and body. For serious scientists, with unanswered questions tugging at the edges of what they know, drifting away from the laboratory may generate uncommon solutions to complex problems.

By leaving the confines of the laboratories for the expanse of nature, scientists can let their new surroundings inspire a novel perspective. Far away from bubbling beakers and scribbled equations, the sights and sounds of nature—shimmering leaves, cascading bird song, the buzz of cicadas—may lull the mind into a drowsy state in which imagination begins to open. And this simplicity creates an alchemy of sorts, changing questions into ideas, a transformation even more useful than spinning lead into gold.

Poets and writers have often drawn inspiration from this natural creative chemistry. Thoreau, who walked daily, believed the frontier of the American wilderness changed the way people's minds worked. "In the very aspect of those primitive and rugged trees there was, methinks, a tanning principle which hardened and consolidated the fibres of men's thoughts."

In his essay "Walking," Thoreau recounted a story about the poet William Wordsworth: "When a traveler asked Wordsworth's servant to show him her master's study, she answered, 'Here is his library, but his study is out of doors.'"

Excursions into nature can develop a scientist's thoughts as well as inspire an artist's creativity. Although the world of science may produce its visible efforts in basement workstations and high-rise buildings, the source of its discoveries may not always be so concrete. The contrast between the natural world and the technological age may draw the searching mind to new visions. Nature's elegant design, in snowflakes and spider webs, has already found the answers. Although people may search for a synthetic solution, a new way of thinking may rest beneath a single leaf.

These types of discoveries do not usually come to my casual breed of observer. Heraclitus, a philosopher of ancient Greece, extolled the secrecy of nature that comes with its inventions. "Nature loves to hide," he said. "Unless you expect the unexpected you will never find it, for it is hard to discover and harder to obtain."

My search for that which is hidden sometimes comes at the end of the walk, when I run my fingers through the dog's fur to check for foxtails and other stowaways. If these stay in his fur too long, they can burrow into the skin and get infected. Many of the plants along the trail use these stubborn burrs to transport seeds to new ground.

Looking at these thorny hitchhikers in a new way led George de Mestral to a creation that symbolizes, for many, life in the 1980s: Velcro. On a hike through the woods, these burrs seemed to jump out at him, plastering his socks and pants with a prickly blanket. He stopped to pry them loose, wondering what made them so tough to shake. De Mestral realized the hooked arms of the burrs could lock into the weave of his clothes. By mimicking the burrs' design, he created his own hook-and-loop fastener that started to appear on tennis shoes, clothing, and even in the space shuttle.

Returning to nature for inspiration has resulted in discoveries that have blended in to my daily life. During my walks, I often mull over the words I want to set on paper, but I usually take for granted the basic writing tools needed to begin my work. Even the reams of paper that stack up beneath my desk have been shaped by thinkers whose ideas were inspired by nature.

One 18th century French scientist took a stroll in the woods that lead to such a discovery. Réne-Antoine Ferchault de Réaumur, a bug lover at heart, went out one day to observe his favorite small creatures. On the walk, he noticed an empty wasps' nest. Having no barbed occupants to fear, he couldn't resist peering into the abandoned home. The scientist's chance inspection inspired an idea that may well have contributed as much as Gutenberg's printing press to the spread of the printed word.

Réaumur, a renowned scholar in physics, mathematics, and chemical engineering, struggled with a perennial challenge in the scientific community: publishing his work. Scientists today share this concern, but Réaumur's problem was even more severe. There simply wasn't enough paper on which to print scientific discourse, journals, or anything else.

Centuries before Réaumur, Chinese, Egyptian, and Mayan people had all worked out methods to make paper from what they found around them. With the advent of the printing press in the fifteenth century, Europeans became seriously interested in papermaking. They started to make paper from rags, a carryover from the Chinese method.

As the years went on, the lowly rag became a hot commodity as more and more people began to see that paper could be used for tasks from sending letters to making buildings. There weren't enough old clothes and blankets for the shredding to keep up with the demand for paper. People started to rip up their books, writing letters to friends and family around the stories already printed on the page.

Réaumur and his contemporaries were frustrated. How could they show other scientists their work when there wasn't anything to print it on? In the midst of his more-technical research in steel production, he held on to his fascination with insects. As Réaumur looked closely at the nest on his walk, he may have been surprised by its light, thin walls. Without any noticeable bedsheets to build their home from, the wasps were making paper.

The woods surrounding the nest held the key. Réaumur realized wasps made their lantern-like nest out of the twigs and branches that littered the forest floor. The scientist, who had studied bird digestive systems for years, suspected that the wasps' stomachs held the paper factory. After several months of exploring the insects' wood-chewing habits, he reported his findings to the French Royal Academy in 1719. "The American wasps make a very fine paper," Réaumur wrote. "They extract the fiber of common wood and teach us that one can make paper from fibers of plants without the use of rags or linens, and seem to invite us to try whether we cannot make fine and good paper from the use of certain woods."

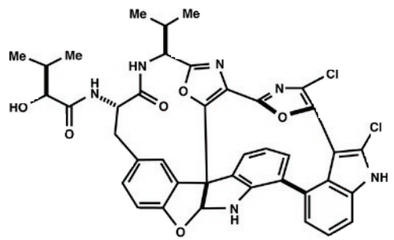
Although Réaumur had found a better way to make paper, none of his works appeared on the woody sheets in his lifetime. His ideas resurfaced one hundred years later in Germany, where several inventors created working versions of a wood-grinding paper machine after reading Réaumur's work. In 1868, the first wood-based newspaper hit the stands in New York. Now paper holds precious secrets and throwaway visions; it is saved, shredded, framed, and recycled.

The wasp's original work has found its way into my house. Sheets of paper filled with illustrations of red-tufted woodpeckers, photographs of the white foam of a crashing wave, a sketch of a fir tree topped with snow: these pictures fill my bookshelves and plaster the refrigerator door, the bare walls. The simple beauty of nature's design has come inside with me, in these small replicas of the life around me.

The beauty of nature may satisfy those who search for solutions. A French mathematician, Jules Henri Poincaré, suggested that nature serves its own purpose, apart from the successes and failures of science. "The scientist does not study nature because it is useful; he studies it because he delights in it, and he delights in it because it is beautiful. If nature were not beautiful, it would not be worth knowing, and if nature were not worth knowing, life would not be worth living."

And if the answers still flicker out of reach, a quiet walk in the woods may put the mind at ease. For what idea could not grow where seeds sprout, where pollen sails, where wasps chew slowly, building a nest. ■

Make This → and maybe you have a cure for cancer (Joe Konopelski is trying)



By LINLEY ERIN HALL
ILLUSTRATIONS by JENNIFER KANE

MOST DIVERS would have ignored it. The four-by-six-inch, cream-colored, jellylike mass clinging to an underwater cliff off the coast of the Philippines hardly even looked like an animal. Nevertheless, a team of American and Filipino scuba-diving researchers collected about half a pound of it, back in 1990. From this small store, they extracted less than a thimbleful of a chemical substance. Studies showed that it killed cancer cells in a test tube, but the scientists needed more of it to assess its potential as a drug in human patients. They returned to the Philippines several times, but it took eight years to find the animal again.

In 1991, the researchers published their findings in a chemistry journal. That's where Joe Konopelski, a scientist at the University of California, Santa Cruz, saw a drawing of the cancer killer's complex structure for the first time. It fascinated him. He was inspired to open up his chemist's bag of tricks. Konopelski's repertoire includes many more chemical reactions than David Copperfield has illusions, but what he hoped to accomplish was no simple abracadabra. What the sea animal does biologically, Konopelski is attempting to do, chemically, in his laboratory. He's trying to make the anticancer molecule from scratch.

He's not alone: A dozen labs around the world are working to synthesize the substance, called diazonamide A ("die-ah-ZONE-ah-mid"), which has "a structure like no one has seen before," Konopelski says. Even tiny quantities of it can kill cancer cells. "It will be a powerful biomedical agent," he predicts.

Researchers have been racing to make diazonamide A for more than 10 years now, and while several labs have come close, not one has succeeded yet. Whoever pulls it off first could help save lives—and become quite wealthy. The means are as important as the end, however. Chemists tackling a specific challenge often invent entirely new

About 85 percent of all anticancer and antibacterial medicines are natural products or modified versions of them. Sometimes, however, natural products are too toxic, or too difficult to synthesize.

chemistry. When Konopelski works on synthesizing a new molecule, he often finds that what he learns along the way can be useful for a broad range of problems, such as studying other pharmaceuticals or completely different compounds.

Seeking medical cures from the natural world is nothing new. Humans had already been treating diseases with medicinal herbs for centuries when scientists first began to extract active ingredients from plants in the mid-1800s. This spurred some chemists to look for synthetic routes to manufacturing natural products. Researchers produced salicylic acid, a component of willow bark, from coal tar in 1859. Acetylsalicylic acid, a man-made cousin better known as aspirin, hit the market forty years later. Since then, the pharmaceutical industry has taken off. Plants as well as animals plucked from far-flung places, ranging from the rainforest to coral reefs, have yielded potential drugs.

Isolating the compounds is often the easy part. Most natural products cannot simply be extracted, because plants and animals usually contain only tiny amounts of toxins that would make good drugs. For example, taxol, a drug used to treat breast and ovarian cancer, was extracted from the endangered Pacific yew tree's bark in the 1970s. One patient's treatment requires killing six trees, so using natural taxol would have quickly wiped out the species. Thus it was up to chemists to find a way to make the compound. In 1994, two research groups reported their successful chemical routes for synthesizing it.

About 85 percent of all anticancer and antibacterial medicines are natural products or modified versions of them. For example, drug companies purify penicillin directly from mold. "No chemist can beat a bug at its own game," says Konopelski. Pharmaceutical firms also extract a compound similar to taxol from European yew tree needles, then convert it to taxol in a few chemical reactions. Sometimes, however, natural products are too toxic for human use, or too difficult to synthesize. Then, medicinal chemists may adapt them into similar compounds that can get the job done.

In the hunt for natural remedies, chemists first looked for drug candidates from sources on land. A few decades ago, research groups met with indigenous peoples and learned how each group used local flora and fauna in healing. The scientists then extracted useful compounds from those plants and animals, and tried to make them in the lab. But now, many land sources are exhausted, so investigators are turning to the sea. "No marine natural product has ever been made into a drug," Konopelski says, "but the field is still in its infancy."

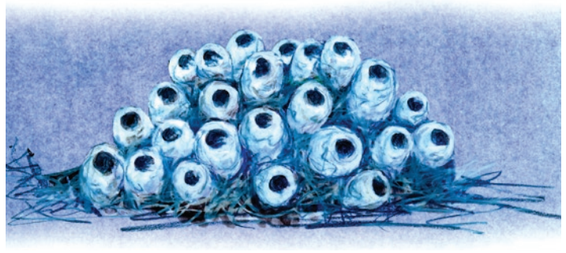
Chemists who study marine natural products focus on organisms that appear defenseless and yet manage to escape predators. "We collect animals that we're relatively confident will lead to something interesting. The hypothesis is that soft-bodied marine animals have developed chemicals for defense," says chemist Bill Fenical at the Scripps Institution of Oceanography in La Jolla, California.

It was Fenical, along with collaborators from Silliman University in the Philippines, who in 1990 discovered the jellylike animal—called Diazona angulata—containing diazonamide A. Fenical has also identified another potential cancer drug, elutherobin, in a soft coral. Even though he includes only the most promising animals in his creature collection, Fenical doesn't often find good drug candidates. "Over a ten-year period, diazonamide A and elutherobin are my two discoveries with true significance," he says.

Diazona angulata actually contains two diazonamides, A and B. In 1990, Fenical's group prepared a tiny crystal of a daughter molecule, called a derivative, of diazonamide B and sent it to Jon Clardy, a chemist at Cornell University in Ithaca, New York, for X-ray crystallography. In this technique, bombarding the crystal with X-rays reveals how the atoms are arranged within the molecule. For the technique to work, the crystal should be perfect or very nearly so. Neither diazonamide A nor B would form perfect crystals, so they couldn't be directly analyzed themselves. But by determining the derivative's structure, and then comparing it with data on the two diazonamides from other tests, Clardy and his colleagues were able to figure out their structures.

At the same time, Fenical's group started performing biological tests on the diazonamides. Of the more than 150 kinds of cancer cells available for study, Fenical chose to test the compounds against a certain type of colon cancer cell. "It's traditionally one of the more difficult cancer cells to kill," he says. "If a compound inhibits its growth, chances are it will inhibit other cancer cells' growth too." Diazonamide B showed mediocre cancer-fighting abilities, but miniscule amounts of diazonamide A killed the colon cancer cells. When divers returned to the Philippines to gather more of Diazona angulata, however, they found only its cousins. Lacking material, Fenical reluctantly turned to other projects.

Finally, three years ago a researcher from the National Cancer Institute found the creature again in Philippine waters. The chemists extracted enough diazonamide A for more biological tests. Experiments revealed that, like many other cancer drugs, the substance prevents cells from multiplying by binding to tubulin, a molecule important in cell division and many other cell processes. However, the compound attaches to tubulin in a different place than other drugs do. "We realized that the molecule has a unique way of interacting at the cellular level," Fenical says. "We asked, Couldn't this be part of a whole new set of anticancer drugs?"



UNFORTUNATELY, WORK GROUND TO A HALT again when the new supply of material was almost gone. Making a commercial drug out of diazonamide A therefore rested upon finding a chemical way to copy it. The race to synthesize the precious molecule had already picked up steam in labs nationwide, after biological tests on the

substance initially stopped in the early nineties. Joe Konopelski recalls his first encounter with the compound. "I was sitting there, at that desk, paging through a journal," he says, pointing across his office to a small table, "and I saw the structure. It was the coolest thing ever."

After seeing diazonamide A's structure, he tried to build the compound with a plastic molecular model kit that estimates how much space each atom takes up, and represents chemical bonds as overlaps connecting the atoms. Such "space-filling" models are more realistic than other types, but they aren't perfect. "I couldn't make the structure using these models. I couldn't close all the bonds," Konopelski says. He decided he had to try to make the molecule in the lab.

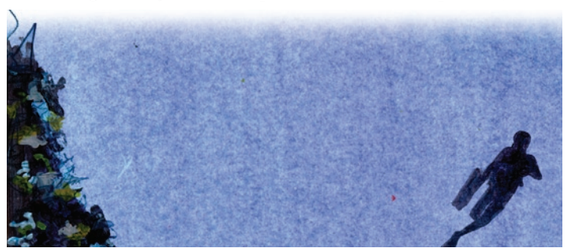
Diazonamide A contains several rings of carbon, nitrogen, and oxygen. It also includes two chlorine atoms—unusual in biological molecules—that lie near each other. In all, the compound contains 88 atoms. Konopelski's task was to find a series of chemical reactions that would build the molecule, putting it together piece by piece.

He began by working backwards. Looking over the structure of diazonamide A, he asked himself, "What is the last bond you want to make? Can you make it? Is it reasonable?" Once he made that choice, he next considered the second-to-last bond he would make. Then, the third-to-last bond. And so on, through the rest of the molecule, until he had synthesized the complete structure on paper.

Another way to think of Konopelski's task is to imagine that diazonamide A is the trunk of a tree. Above it, the tree has many branches that split many times into smaller ones. The tips of the smallest branches represent chemical "starting materials," pre-made compounds the chemist can buy. Each junction of two tree branches represents a possible reaction between compounds.

Again, first working backwards on paper, the chemist climbs up the tree as he maps out a reverse route from the trunk (the final product) to the tree tips (the starting materials). Later, in the lab, the chemist climbs down the tree by performing in glass flasks a chain of reactions—beginning with the starting materials—that build the molecule step by step, branch by ever-larger branch, until he reaches the trunk and the final product is complete. However, the paper route is not a magic spell; often, parts don't work. "Some pretty good people have walked up some blind alleys and had to step back," Konopelski says.

Running into a dead end bothers some chemists more than others. Some believe if you can't be first, be best, so they search for the most efficient route to the final product. Others think that the chemistry they learn along the way is more important than the final product, which they may never even make. They work at a slower pace, often taking detours to investigate interesting reactions that they discover.



Konopelski definitely belongs to the latter camp, as does his graduate student, Brian Gerstenberger. "Once we learn one thing, it spawns 20 questions. That's when you know you're doing good science," Gerstenberger says. He sees himself as an architect, engineer, and construction worker wrapped into one. "I use paper to find how to build a molecule, then go out and do it," he says. The difference is that he is trying to build something he can't see.

A molecule of diazonamide A may be invisible to the naked eye, but compared to other compounds, synthesizing it is as complex a job as building a skyscraper. A closer look, however, reveals that the compound is partly constructed from smaller, simpler molecules. Called amino acids, they usually act as the building blocks of proteins. Diazonamide A isn't a protein, but it contains fragments of several amino acids, which is extremely useful because these amino acids are commercially available.

Twenty different amino acids are naturally found in proteins. All but one come in two forms that are mirror images of each other, known as left-handed and right-handed versions. Many molecules have left- and right-handed forms, and the difference between the two types can be essential. The most notorious example of this is thalidomide, a drug widely prescribed for morning sickness in Europe in the 1950s. Many babies were born with birth defects after their mothers took the drug. Further research showed that the therapeutic form of thalidomide, which relieves nausea, spontaneously converts in the human body to the harmful form that causes birth defects.

At four points along the diazonamide A molecule, it has parts that can be either right- or left-handed. Three of these pieces can be purchased as amino acids. So Konopelski's synthetic strategy has focused on making the fourth point, not commercially available, which has bonds linking it to four other carbon atoms—a rare and difficult arrangement to make.

But difficult and complex chemistry is something that occurs all the time in Konopelski's laboratory, a cluttered room on the third floor of the UCSC campus chemistry building. The lab smells faintly of acetone, the main ingredient in nail-polish remover. Stains on the floor bear witness to the years of work this room has seen. To protect themselves from dangerous chemicals, chemists do most of their work at a fume hood, an enclosed counter with an air intake vent overhead to draw away vapors. Glassware fills this hood: glass tubes packed with silica beads for separating mixtures, a still to remove water and oxygen from solvents, and two racks of test tubes with yellow or colorless liquid in them. The counter beside the hood is a mess. Small vials with white caps hold liquids and solids of different colors, labeled with numbers or names. Several flasks nestle in cork holders, and white powder sits on weighing paper.

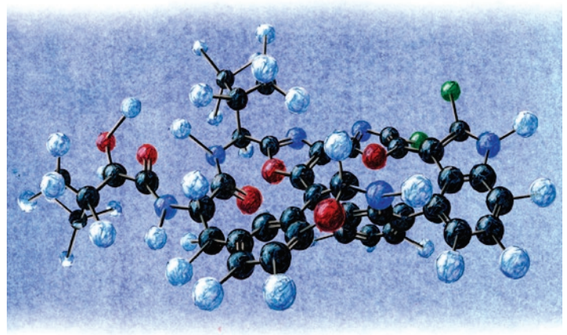
David Francois, a post-doctoral researcher in Konopelski's lab, holds up a thin glass tube, called a pipet. A yellowish crystal the size of a sesame seed perches precariously on one end outside the tube. Under a magnifying glass, the crystal has a smooth face. The crystal is the

Recently, labs working on diazonamide A suffered a major, shocking setback. They had been trying to make the wrong compound.

product of a year's work, but Francois isn't sure he has made what he intended. His goal was to build an intermediate, a molecule partway between the starting materials and the final product—just one small branch en route to the diazonamide A tree trunk.

Getting even this far was a challenge. Another researcher previously made almost the same intermediate compound, but it was an oil. Since X-ray crystallography requires a near-perfect crystal, Francois had hoped that he could produce a crystalline intermediate by beginning with a different starting material than his colleague—by using a left-handed, rather than right-handed, form of the material. However, the left-handed version wasn't commercially available, so he had to make it himself. Francois spent a lot of time in the library, evaluating the approaches others had used and trying to determine the best one for his problem.

"It's like a puzzle," Francois says. "You study a lot of reactions; you have a target. It's up to you to choose the best route to the target." Eventually he started testing different reactions, changing factors such as time and temperature to maximize the amount of product. After four months, Francois succeeded in building his left-handed starting material. And eight months later, he had his yellowish crystal of the diazonamide A intermediate. The next step is to prepare it for X-ray analysis, to see whether his creation is what he hopes it is.



The diazonamide A molecule: black = carbon, white = hydrogen, red = oxygen, blue = nitrogen and green = chlorine

REGARDLESS OF THE RESULTS, Francois knows his molecule has a problem. Recently, all labs working on diazonamide A suffered a major, shocking setback: Researchers learned they had been trying to make the wrong compound all along.

Last December, biochemist Patrick Harran's group at the University of Texas Southwestern Medical Center in Dallas announced it had successfully made the diazonamide A structure originally reported by Clardy in the early 1990s. Harran's compound did kill cancer cells in the lab. However, it also degraded rapidly and behaved differently in other tests than did the natural product. So Harran double-checked the data Clardy had used to decipher the molecule's structure. Harran's group reinterpreted the results, publishing a corrected structure for diazonamide A that included three changes. This new structure is the true configuration of the compound extracted from Diazona angulata. The version everyone had been working toward is an interesting cousin of diazonamide A, but not a natural product.

"I was surprised," says Francois. "But I was not disappointed. That's research. Sometimes you have good news and sometimes bad news. Now the competition between groups starts again. It's a whole new game."

Still, the old game isn't over yet. Harran's group began attempting to make diazonamide A's cousin four years ago. Of that time, the scientists spent a year and a half finding a way to create the last bond in their synthetic route. They eventually finished the job with a tricky reaction called photocyclization, in which a flash of light triggers a bond that completes a ring. "You very rarely see labs using photocyclization in the total synthesis of a large natural product because it's hard to control," says Anthony Burgett, a graduate student in Harran's lab. "We were winging it at the end."

The photocyclization reaction in Harran's method has about a relatively low yield, only about 35 percent of what they would ideally expect to produce. "For a photocyclization that's not bad, but you're throwing away two-thirds of a material that took you 20 to 30 steps to make," Burgett said. Those steps are expensive and an enormous time investment. Using Harran's techniques, it takes about two months for one person to produce diazonamide A's cousin. Jing Li, a post-doctoral fellow in Harran's lab, is now repeating the method using more chemicals.

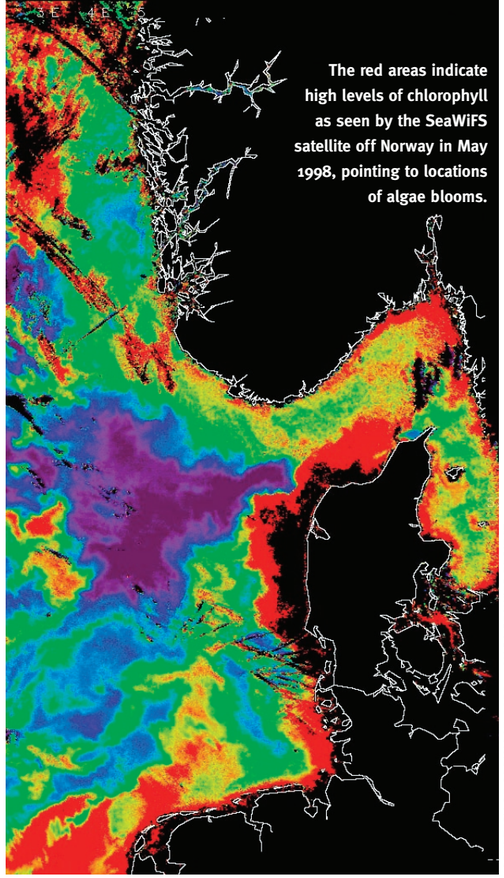
In the end, Li hopes to produce 200 to 300 milligrams of the compound. (By comparison, one dose of the over-the-counter pain reliever ibuprofen is 200 milligrams.) That's enough for additional studies of how the compound affects cells, but the researchers would need to develop a faster, more efficient way of synthesizing the cousin before it could become a serious drug candidate.

With a feasible route for this cancer-killing cousin so close, is it worth it for researchers to continue working on the true diazonamide A? In Konopelski's lab, for instance, the chemists are up a tree, so to speak. One of the original starting materials they used included an oxygen atom, but the revised diazonamide A structure contains a nitrogen in place of that oxygen instead. Therefore, to make the true compound, Konopelski and his colleagues must begin again from the branch tips. However, Harran's lab has shown that diazonamide A's cancer-fighting ability does not depend on that particular nitrogen atom. So, the Konopelski lab has decided to finish their work on the old structure while also beginning to tackle the new one.

Since Konopelski focuses on the chemistry he discovers en route, and not just on the end product, he says it doesn't bother him that he must start his magic act all over again. "Once you have the structure, someone like me will make it," he says. "[It's] simpler now. It was hard to see before how the animal synthesized it." With the true diazonamide A structure in one hand, Konopelski is using the other to dig deeper into his chemical bag of tricks. He's sure the answer lies in there somewhere. ■

THE BIG VIEW ON TINY ALGAE

Sometimes a camera hundreds of miles up in the sky offers the best perspective on microscopic sea plants.



The red areas indicate high levels of chlorophyll as seen by the SeaWiFS satellite off Norway in May 1998, pointing to locations of algae blooms.

COURTESY OF ORBIMAGE CORP. & NASA SEAWIFS PROJECT

By DESIREE SCORCIA
ILLUSTRATIONS BY KARINA HELM

LOOK WESTWARD from the cliffs of Davenport, California, just north of Santa Cruz, and you'll feel as though you're standing at the edge of the world. The blue Pacific Ocean stretches unbroken to the horizon, a liquid mirror throwing the yellow sun back up to the sky.

If you could see absolutely everything through that mirror, you'd observe a space teeming with all kinds of life, from the biggest whale to the most microscopic bits of plant-like aquatic organisms called algae. And if you could gaze infinitely skyward past the bright sun, you'd catch a glimpse of a satellite that biologists are using to study this vast web of life, starting with the algae.

It's funny to think that scientists are using high-tech space satellites, and not microscopes, to study such tiny lifeforms. But the approach makes perfect sense to marine biologists such as Raphael Kudela of the University of California at Santa Cruz, who is trying to understand the balance of life in the ocean. In the marine realm, as on land, small creatures get eaten by bigger animals, which get devoured by still larger predators, and so on. Thus energy in the form of food travels up the so-called food chain. But exactly what controls the growth of sea life? "Where does the energy go? These are biologists' big, driving questions," says Kudela.

Scientists know that one important kind of algae, called phytoplankton, forms the base of the food chain. The microscopic phytoplankton hold a key to many riddles about everything from global warming to overfishing. If scientists could measure exactly how much phytoplankton floats around in the ocean, for instance, they could make reasonable predictions about how many fish, whales, sea turtles, or sharks the ocean can feed. And knowing that answer would help answer the urgent question of how much humans can fish without upsetting the ocean's ecosystem or pushing different species towards extinction. Alternatively, monitoring how phytoplankton respond to changes in climate from natural or manmade causes might offer clues to the planet's state of health.

Now, studies by Kudela and a colleague are taking a closer look at these tiny fish-snacks. Kudela has been using satellite pictures of the Pacific Ocean off central California in a new formula for predicting the amount of phytoplankton, in pounds, that will become food for fish in the area on any given day, month, or year. This new phytoplankton growth model, which Kudela developed together with marine biologist Francisco Chavez of the Monterey Bay Aquarium Research Institute (MBARI), combines data collected from boat cruises, aquarium moorings, and most importantly, the satellite.

The best thing about using a satellite to do algae research, say the biologists, is that it gives them a view they can't get anywhere else. "Satellites are the only way to get that really big picture," says Kudela. "On a boat you can only go out so far and get so much data. You're always wondering if you're getting the big picture or not."

WHEN SCIENTISTS USE SATELLITES to study the land or the sea, they call it remote sensing. First used decades ago to observe dry land, the technology taught scientists about the complex seasonal and yearly changes of plants, animals, and geography. The tool was so helpful that marine researchers soon wanted to see whether it would unlock the secrets of the oceans, too.

Kudela studies pictures of Monterey Bay and beyond taken by a satellite called the Sea-Viewing Wide Field Sensor, or SeaWiFS, which is owned by NASA and Oribmage, a private company. The three-foot-long, torpedo-shaped satellite was lofted into space five years ago by a cruise missile launched from the back of a 747 jet. Every day, SeaWiFS beams images from all over the globe to more than 80 subscribers worldwide, including Kudela.

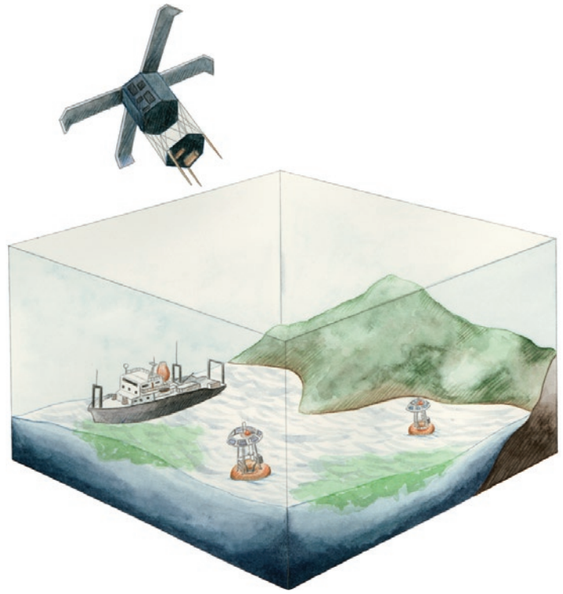
SeaWiFS takes pictures at eight different wavelengths of light. It takes one photograph each of violet, blue, yellow, green, and red light and infrared heat that radiates back to space from the ocean's surface. Images recorded at the other two wavelengths allow researchers to correct for the scattering of light that occurs in the earth's atmosphere. Each color reveals something different about the ocean. Green light, for example, tells scientists how much green chlorophyll—a pigment found in algae—is floating at the surface.

SeaWiFS data has proven a goldmine for a range of applications. Scientists use the satellite to track the movement of surface ocean currents that are otherwise invisible to the eye. Because water currents each have their own unique temperature, the satellite can detect them; it measures temperature by reading the infrared heat signal at the ocean's surface. The satellite is sensitive enough to distinguish between currents only one-twentieth of a degree apart. SeaWiFS can also follow currents of dissolved sediment and pollutants as they run from rivers and dissipate into the ocean.

Still other investigators use satellite photos to track phytoplankton to figure out what ocean conditions give rise to blooms of toxic algae. Called red tide, these dangerous blooms poison fish, seals, and shellfish. They can also make humans terribly sick.

Phytoplankton are generally underrated, Kudela says, but they're important to the planet. Fully half of the plants at the bottom of the global food chain live and grow in the ocean. Anchoring that chain, phytoplankton feed on inorganic nutrients such as carbon, nitrogen, and ammonia that enrich cold ocean water. Chlorophyll pigments in the algae absorb sunlight and allow them to turn those nutrients into more phytoplankton, via a process called photosynthesis. Because of this talent for making something out of nothing, ocean biologists call them "primary producers."

Most biologists working on the problem of primary production first calculate the weight of phytoplankton produced in a given time frame. Then they roughly estimate what percentage of the algae will be eaten by animals. Kudela and Chavez say they've created a better formula that skips the first step and instead directly calculates how many pounds of phytoplankton travel up the food chain into the bellies of crustaceans, fish, whales, and the like. The researchers call this measure "new primary production."



SeaWiFS supplements data from research ships and ocean buoys.

"Most biologists are still looking at primary production," Kudela says. "But the new primary production is really what you want to be measuring if you're interested in where most of those nutrients are going."

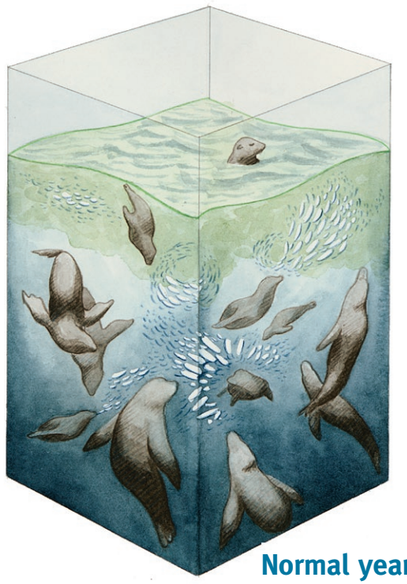
To arrive at their calculation, they plug five pieces of data into a computer equation. The first three come from SeaWiFS: the surface temperature of the ocean water, the amount of chlorophyll in the water, and information about which direction the chlorophyll is moving. The researchers also include water temperature at about six hundred feet below the surface, and wind speed and direction in their calculations.

"It's an integrated observing system," says Chavez. "We use data from ship point measurements, moorings, and satellites." Each data source provides essential information, but the satellite provides a valuable comprehensive view of Monterey Bay.

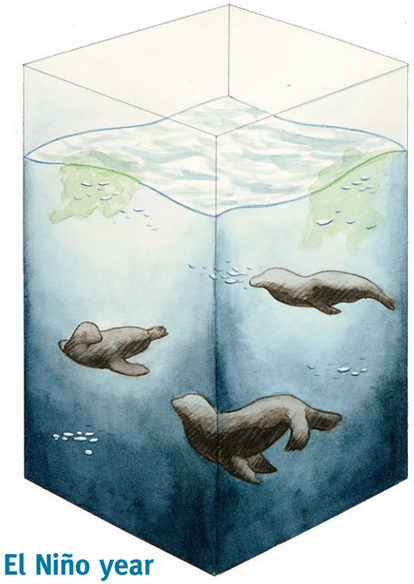
Case in point: An interesting pattern emerged when the researchers compared images of the open ocean with those taken near the coastline. Far offshore, the ocean reflects only a deep blue color back to SeaWiFS. That's because there's very little phytoplankton floating at the surface so far from land. Most of it grows in shallow waters off continental coasts, where cold, mineral-rich water from the ocean floor slides up the continental shelf to the surface. This water has likely been flowing along the ocean floor for thousands of years, absorbing nutrients released by decomposing plants and fish before reaching the surface. One plume of this water wells up right off the coast of Davenport. From there, one current travels north towards Alaska, while another moves south into Monterey Bay.

So far, Chavez and Kudela are pleased to report that their formula is accurate within a factor of two at predicting new primary production in Monterey Bay. That means that if the mathematical model predicts two pounds of phytoplankton per cubic yard of ocean water, the actual value would lie somewhere between one and four pounds.

With a reliable formula in hand, the scientists can estimate how much food is in the ocean to support fish. Laws of nature say that an animal population will grow if there's ample food, but shrink if subsistence becomes scarce. Instead of trying to count all the fish hiding



Normal year



El Niño year

In a normal year, fish eat phytoplankton, and then seals and sea lions eat the fish.

In an El Niño year, nutrient-rich cold water from the depths does not reach the surface, disrupting the food chain. Phytoplankton grow scarce, fish swim further out in search of food, and the seals and sea lions starve.

deep in the ocean-an impossible task-scientists can calculate population numbers by simply looking at how much food the fish have. Then, in turn, they can estimate how many fish could be harvested without harming the survival of different species.

With the oceans in increasing danger from overfishing, Kudela and Chavez's formula will add some certainty to a field dominated by guesswork. "Many people are worried that we're taking more out of the oceans than we can support," says Kudela. He hopes environmental agencies will someday use the new primary production estimates to set limits on fishing. The formula could even help provide independent scientific verification of whether fishermen are really restricting their catches to the numbers they report, he says.

RECENTLY, KUDELA AND CHAVEZ were able to test their model by retrospectively crunching data collected under the extreme conditions of the El Niño weather pattern during the winter of 1997 to 1998. Along the central California coast during that period, many seals and sea lions washed up on shore, dead or dying of starvation. Seventy-five percent of sea lion pups died that breeding season, and the average weight of a weaned elephant seal was the lowest ever recorded. To a lesser extent, the same thing had happened during the 1992 - 1993 El Niño.

Why? El Niño had tipped the ocean's balance and brought abnormally warm water to California. Scientists know that phytoplankton cannot thrive in warm water, which lacks the nutrient richness of the old, cold water from the ocean floor. The devastation at the base of the food chain rippled up to the top. Without phytoplankton, the fish had little to eat. And without fish, animals starved.

Oddly, however, readings from the moorings operated by the Monterey Bay Aquarium six and twelve miles offshore didn't record much of a difference in phytoplankton levels, and this puzzled researchers. Some theorized that the inner bay had sheltered a large amount of phytoplankton from the warm water, and that the real damage had occurred just beyond their instruments. But they couldn't prove it.

Fortunately, SeaWiFS, which was launched in the summer of 1997, had recorded the whole thing. When Kudela and Chavez finished looking at its pictures, they found proof that the theory was right. Warm water had reduced the phytoplankton population two hundred miles offshore to just one fifth of its usual size. Most fish had migrated out of the bay and beyond to colder waters, where they could find food. But many of the sea lions and seals that stayed behind starved, because so little was left for them to eat.

What's more, when Kudela and Chavez ran the SeaWiFs data through their formula, results showed that 98 percent of the phytoplankton that normally becomes food was killed or failed to grow in the warm El Niño waters. The extent of the mass starvation made even more sense.

Beyond the California coast, the new model can be customized to help other researchers studying other parts of the ocean. A complex environment like Monterey Bay, with wind and currents coming from all directions, requires different numbers than a more stable system, like the open ocean. Andrew Thomas, a marine biologist at the University of Maine at Orono, uses SeaWiFS data to study red tide in the Gulf of Maine, and to track how ocean color changes as a result of upwelling currents—one way of monitoring the health of the oceans. Thomas says a formula to predict new primary production would be highly useful to his studies. "It's one of the missing parts we have to have," he says.

Keeping track of the yearly cycle of new primary production is one more tool biologists can use to keep tabs on ocean conditions, says Kudela. "You can watch to see the impacts that humans have had over time," he says. With so much uncertainty about how global warming will affect the oceans, monitoring them closely has become especially important.

Scientists forecast another El Niño for the coming winter of 2002-2003. Californians everywhere are groaning with dread, but Kudela and Chavez are getting excited. It's another chance for them to further test and refine their formula under another set of extreme weather conditions. Next winter's SeaWiFS pictures will bring more answers, and they just can't wait. ■

about the illustrators

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Internships: California Academy of Sciences (Paleontology), San Francisco; Shannon Point Marine Center, Anacortes, WA

Jennifer Kane B.S. (biology/visual arts) Brown University

I believe I began to understand the logic behind the if science, then art / if art, then science statements that led many of us to scientific illustration, when asked by a friend of mine who attended art school why, exactly, was I still studying biology, and why, in that case, did I continue to take so many art classes. Caught off-guard and struggling to explain my seemingly irreconcilable interests, I heard myself say, "Biology. Art. They're both about observation, about learning to understand the world and to really see." This word observation resonated with me, and moreover, fascination, and beyond that even, wonder: each of these driving me to unravel DNA sequence and fill pages in my sketchbook; to find my way through forests, studios, and laboratories to the Science Illustration Program; and to seek new means of expressing the entwined beauty of scientific and creative processes, here and throughout my life.

Internship: Museum of Natural History, New York

Jack Laws B.S. (conservation and resource) UC Berkeley; M.S. (wildlife biology) University of Montana

I have been interested in natural history since childhood. In elementary school I began to make sketches of my observations. As the years progressed, my interest in natural science grew, and with it, my collection of illustrated journals. As a biologist, I am a generalist with interests from inter-tidal life to the high Sierra. I earned a Masters of Science in wildlife biology studying song birds. I have worked in education for many years, most recently for the California Academy of Sciences. I am interested in developing illustrated field guides that will be easy for amateurs to use, yet comprehensive enough for more experienced naturalists.

Internship: Writing and illustrating a field guide to the natural history of the Sierras under the sponsorship of the California Academy of Sciences

Giovanni Maki B.F.A. (art) UC Santa Cruz

I am a native of the San Francisco Bay Area and have been living in the Santa Cruz area for over three years. As an undergraduate I chose art as it seemed to be the right thing to do at the time, and there is no better excuse, if you ask me. I can say that because my instincts led me to UCSC to finish my undergraduate work. And it was here at UCSC that I found what I didn't know I was looking for, my calling. I realized that I would be a science illustrator. My talent is my drawing and sculpting, but my interests are broader then my own self-expression. This just feels right.

Internship: Filoli gardens, Woodside, CA

Elizabeth Murdoch B.S. (biology) University of Michigan B.F.A. (scientific illustration) University of Michigan

I have always loved science and art, but I could never decide what I wanted to do "when I grew up." When I thought about a career in biological research, I had difficulty focusing on one area. I soon realized that as a scientific illustrator I could delve into numerous topics of science, and learn as I illustrated. I am very interested in the forms and functions of the diverse structures and patterns found in nature. I have a specific interest in marine mammal anatomy, and I find their adaptations to the aquatic environment especially fascinating. I would eventually like to illustrate exhibits for natural history museums and marine science institutes.

Currently engaged in dolphin research at Harbor Branch, Florida

Katura Reynolds B.A. (art) UC Santa Cruz

When I first went to college, the only thing I knew for certain was that I was not going to major in art. Then I "snuck into" a graduate level science illustration class, and I was hooked – it was more challenging and more compelling than anything else I'd studied. Since graduation, I've been working in education: two years in a museum, two years with the local Girl Scout council, and even a four-month stint with Peace Corps Honduras. But a good illustration is worth as least as much as a lecture, if not more. I'm glad to be back.

Internships at the Arctic Studies Center and the Paleobiology department of the National Museum of Natural History, Smithsonian

Mary Sievert B.S. (graphic design) San Jose State University; M.A. (museum studies) San Francisco State University

As an exhibit designer, the crafts of interpretation and 3D communication have been rewarding, yet all the while becoming a professional illustrator has remained a persistent life-long dream. In 1997, serendipity and a late start for a project meeting played a huge role in my arrival here at UCSC. Back then I met sculptor and GNSI member Gloria Nusse who was contracted by our team to create a large-scale bronze fly head for a National Science Foundation traveling exhibit called Animal Eyes. Prior to the start of the meeting Gloria and I talked shop a bit – I literally picked her brain as she arranged her clay model, sketches and reference materials for the team review. She encouraged me to enroll in Science Illustration summer courses at UCSC. After two classes I realized that this was the kind of work that I would love to do for the rest of my life.

Internships: Monterey Bay Marine Sanctuary Foundation and the Palo Alto Open Spaces and Sciences Division

about the writers

continued from inside front cover

sis on biochemistry from Harvey Mudd College. Between classes and internships, she has written about lizards, oil drilling technology, yoga, the Olympic torch relay, space debris, and, yes, chemistry. Linley hopes to work for a magazine, then launch a wildly successful freelance career.

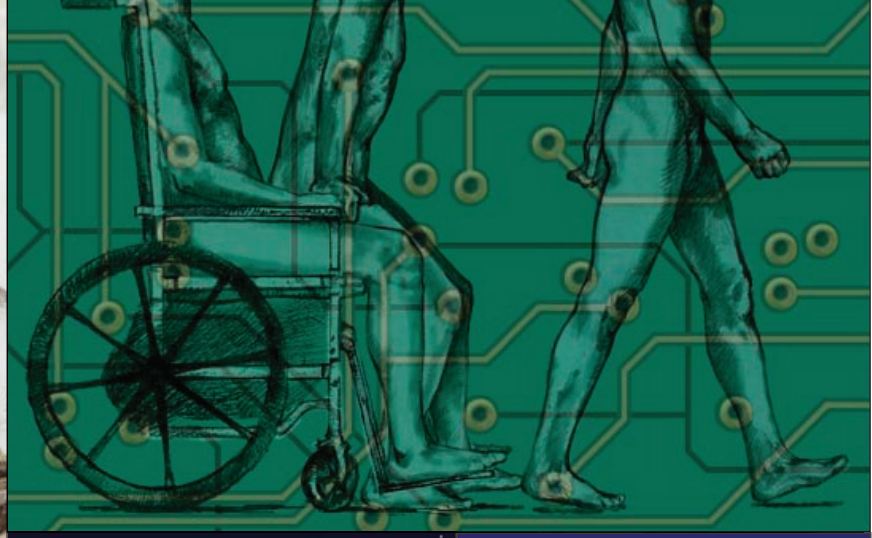
Christian Heuss graduated with a Ph.D. in neuroscience from the University of Zurich, Switzerland. His interest in the brain led him to the Brain Research Institute in Zurich, the Marine Biological Institute in Woods Hole, MA, and Cold Spring Harbor Laboratories, NY. As a science journalist, Christian is aiming to communicate science to a broad public through print, radio and multimedia. In his spare time, Christian passionately explores other lands and cultures around the world.

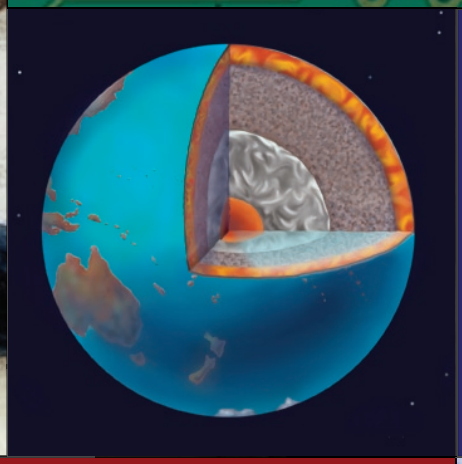
Kendall Morgan graduated from Earlham College with a degree in biology. She then went on to complete her doctorate in Ecology and Evolution at the University of Oregon. She has written for *Stanford Medicine* magazine and AAAS's Science of Aging Knowledge Environment (SAGE KE) and will intern at the Idaho National Engineering and Environmental Laboratory this summer.

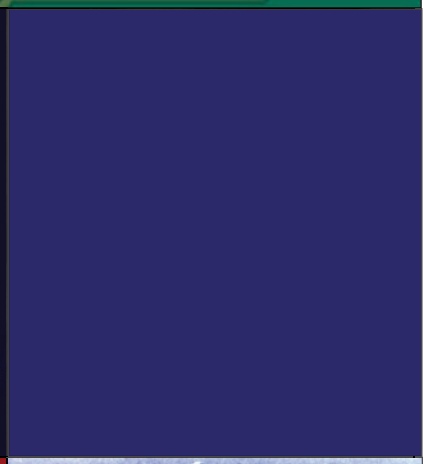
Kendall Powell has a B.S. in Biology from William and Mary and a M.S. in Biomedical Sciences from University of California, San Diego. Kendall's career goal is to become a science journalist or freelance science writer and she looks forward to her removal from student life.

Desiree Scorcia graduated from Boston College in 2000 with a bachelor's degree in physics. When she graduates from the UCSC science communication program, Desiree will pursue a career in physics writing and public information. In her spare time, Desiree likes to travel, sail, and knit. She hopes to one day retire to Maine.

Cameron Walker has finally been released by the notorious UC Regents from UC Berkeley after five years, with degrees in bioresource science and creative writing. Since then, she's created small avalanches in the Sierra, been bludgeoned by a wayward surfboard, and been the victim of early-morning attacks by a truly wild beast — an 83-pound puppy.







"There is no science without fancy and no art without facts."

VLADIMIR NABOKOV