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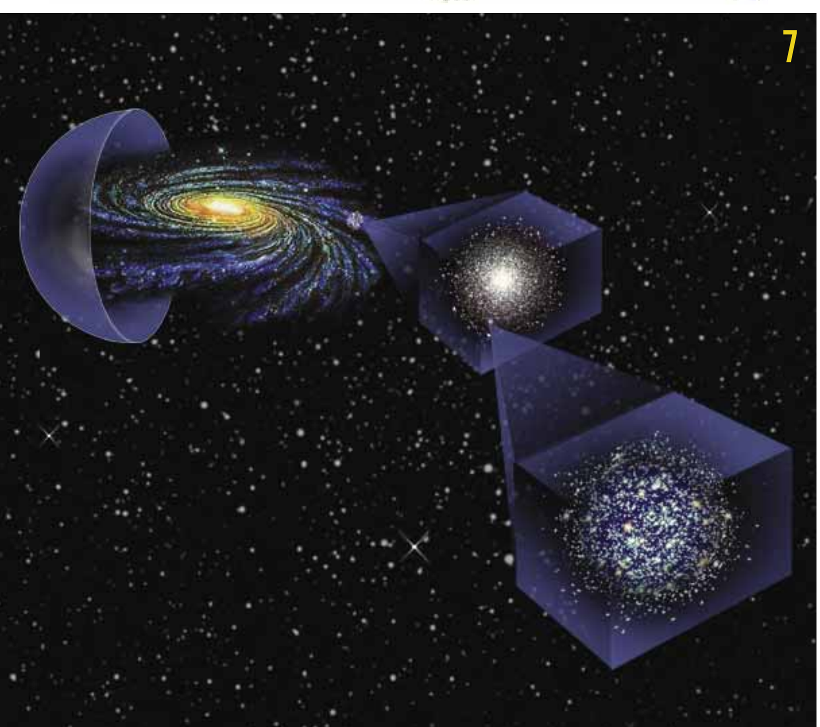


SCIENCE NOTES 2003

a publication of the Science Communication Program
at the University of California, Santa Cruz

about the artists

Evan Barbour ("Along Came a Spider") graduated from Reed College in 1999 with a B.A. in psychology. Since then he has worked as an environmental educator. Spending much of his time outdoors, Evan has developed interests in ornithology and entomology and hopes these interests will develop into areas of professional expertise. He drew birds at Cornell's Lab of Ornithology, after which he hoped to return to the West Coast to intern at the Oakland Museum of California and illustrate a book on California owls.

Christine Field ("The Creativity Conundrum") has a B.A. in music from U.C. Berkeley and a certificate in graphic design and visual communication from U.C. Santa Cruz extension. She has run a successful graphic design business in Los Gatos for the past eight years, and is now ready to embark on a wildly successful illustration career. This summer, Chris worked with an animator getting ever closer to her goal of making science animation her livelihood. In her spare time, Chris frolics with her husband and new daughter, hiking whenever possible.

Holly Gray ("Global Fever") graduated from U.C. Santa Cruz in 1999 with a bachelor's degree in biology/environmental studies. She has moved to Alaska to pursue unemployment in tree climbing and raindrop dodging, and she also hopes to refine her rock painting skills.

Megan O'Dea ("Staring at the Sun") earned her undergraduate degree from Iowa State University in biological/pre-medical illustration. She then worked for a year as a graphic artist in a small printing company in her home state of Nebraska before coming to University of California, Santa Cruz. She spent her summer interning at the Bermuda Natural History Museum, Aquarium and Zoo. So far her career path has taken her places she didn't fathom, and she hopes that continues as she pursues a freelance career in illustration. Megan's ultimate dream is to spend her mornings on the golf course and her days in the studio!

Nicolle Rager ("Recipe for Life") received a bachelor's in biochemistry from Lewis and Clark College in Portland. Working in a biochemistry laboratory for three years, she found the overall hypotheses and rationales inspiring, but the day-to-day bench work left her lost in details, without the time or energy to explore other aspects of science and beyond. She considered forgoing her science education for fine art, but feared that by commercializing her art she risked spoiling her reprieve from the stresses of the world. Scientific illustration seemed the perfect avenue to explore subjects in the broader biological and scientific spectrum, while allowing her to focus on shaping her artistic skills into a new set of tools. Her goal is to create visually engaging, accurate illustrations that help explain things that are difficult to visualize, whether they be microscopic or grand in scale. Her internship was at the Stanford Linear Accelerator Center.

Lucy Reading ("Teaching an Old Owl New Tricks") received her B.A. in American studies from the University of Kent at Canterbury, England. She specialized in American literature. In 2002, Lucy made a dramatic move from the U.K. to California, to study scientific illustration at Santa Cruz. It was not a surprise for family and friends, as Lucy had always shown that her prime passion was for drawing. This summer Lucy found herself lucky enough to intern at Scientific American magazine in Manhattan, where she soaked up some scientific American literature!

Art and illustration have been the focus of **Andrew Recher** ("Fish Tales") for many years. He started private art classes at the age of eleven, and his undergraduate work includes an A.A. in illustration, and a B.A. in scientific illustration. Andrew would enjoy a staff position at a museum, aquarium or zoo, but also looks forward to freelance illustration work.

Katherine Oliveri Rizzo ("Mind Over Stomach") graduated from St. Mary's College of Maryland with B.A. degrees in biology and studio art. Scientific illustration just seemed to be a natural field to go into. Her mediums of choice are color pencil and watercolor and she is mainly interested in illustrating zoological subjects. Outside of illustration, Katherine enjoys horseback riding and equestrian sports. She hopes to establish herself as a freelance illustrator and riding trainer in the Washington, D.C. area.

Rachel Rogge graduated from Humboldt State University in Northern California in 2002 with a B.A. in art history and a B.S. in science illustration. As an undergraduate, she worked as an illustrator/display artist at the H.S.U. Natural History Museum. As a science illustrator, Rachel hopes to continue to share information about the world with whoever is willing to look.

Nadia Strasser ("The Light of Dr. Jean Brodie") graduated from the University of California, San Diego in 1998 with an independent composite degree in biology (behavior, ecology, and evolution) and studio art, and a minor in psychology. Before attending the program at U.C. Santa Cruz, she worked in jobs ranging from research to architecture. She completed two internships this summer and fall: the Academy of Sciences in San Francisco and Scientific American magazine in New York.

about the writers

Rachel Ehrenberg ("Teaching Old Owls New Tricks") has new respect for the term "bird brain." She majored in botany at the University of Vermont and graduated with a master's degree in biology from the University of Michigan, Ann Arbor. Ehrenberg worked for the Dallas Morning News during her summer internship.

After graduating from Carleton College with a B.A. in biology, **Helen Fields** ("A Battered Mollusk") wandered the world for a few years, then studied the behavior of harvester ants for her master's thesis at Stanford University. She has interned at National Public Radio, U.S. News & World Report, the Monterey County Herald, Science magazine's ScienceNOW, and the Stanford University Medical Center. Much as she loves being an intern, she dreams of finding a real job someday.

Jyllian Kemsley ("Staring at the Sun") earned her B.A. and Ph.D. in chemistry from Amherst College and Stanford University, respectively. After interning at the Santa Cruz Sentinel and Chemical & Engineering News, she is now a freelance writer concentrating on the physical sciences.

Greta Lorge ("The Creativity Conundrum") has a B.A. in human biology from Stanford University and a M.S. in neuroscience from the University of Michigan. She has written for Stanford Report, Stanford Medicine, the Salinas Californian, and California Wild. She spent her summer working at the Atlanta Constitution-Journal as a 2003 Kaiser Family Foundation health reporting intern.

Romanian-born **Elisabeth Nadin** ("Global Fever") can tell you all about the power of extreme heat, having survived a summer writing internship at Earthscope in Tucson, Arizona. She studied geology as a college student at the University of Rhode Island, and earned a master's degree in the subject from the California Institute of Technology. Nadin can be reached at enadin@nasw.org.

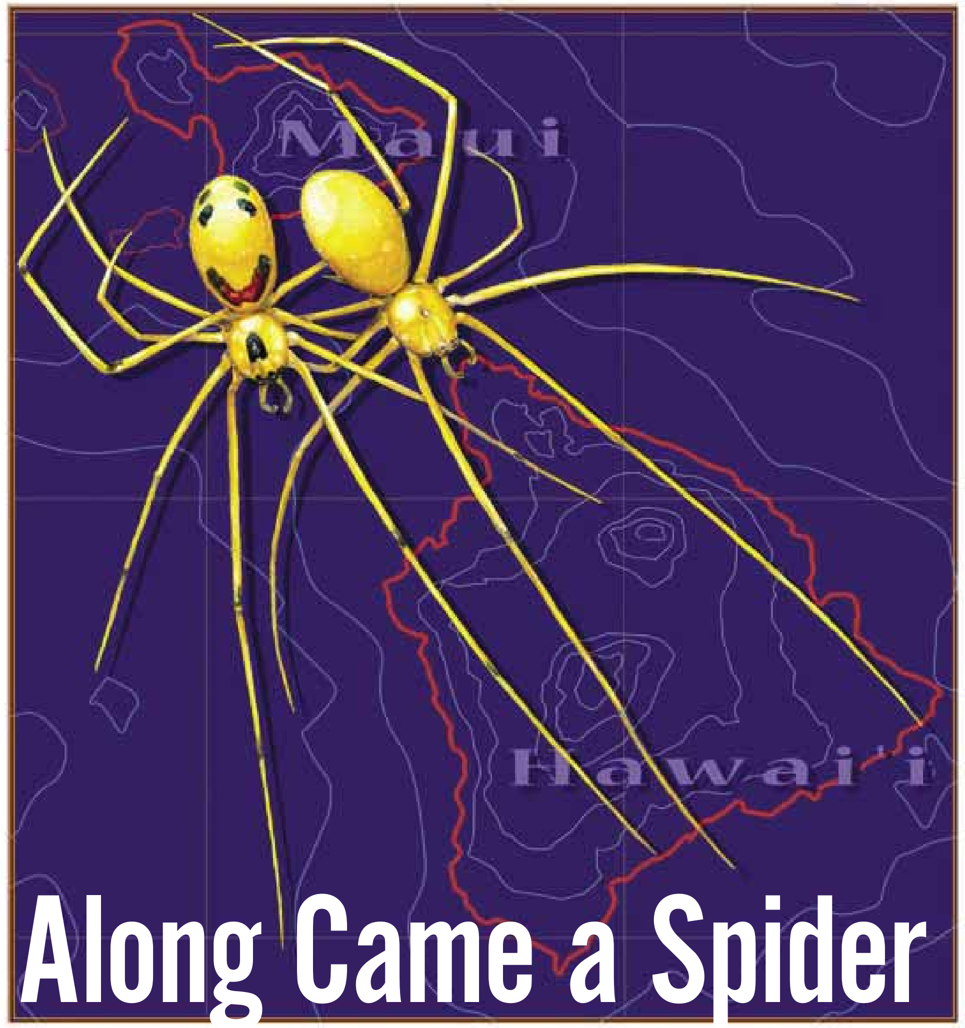
Kate Ramsayer ("Along Came A Spider") graduated from Williams College with a degree in biology. After two years of honing her pipetting skills at Massachusetts General Hospital in Boston, she opted for a career in science writing. She is spending the fall of 2003 as an intern at Science News. Although she enjoys Washington, D.C., she would jump at the chance to investigate Hawaii's flora and fauna—even if it involves bugs.

Emily Singer's ("Mind Over Stomach") fascination with pioneering women scientists dates back to a high school paper she wrote on Madame Curie. She studied biology at the University of California, Santa Cruz, and completed an M.S. in neuroscience at the University of California, San Diego. For her summer internship, she worked at New Scientist in London.

Nicole Stricker ("Fish Tales") has a B.A. in biochemistry from the University of Colorado, Boulder, and a Ph.D. in neuroscience from Johns Hopkins University. Although she is living the rootless life of an aspiring newspaper reporter, she can always be reached at nstricker@nasw.org.

Ernie Tretkoff ("The Light of Dr. Jean Brodie") majored in physics at Princeton University. She spent her summer internship writing for the media relations office at the California Institute of Technology.

Shawna Williams ("Recipe for Life") has been pondering the mysteries of the universe as a writer intern in Geneva, Switzerland, at CERN, Europe's most important center for particle physics research. She is essentially a nomadic science writer with family roots in Colorado. Williams majored in biochemistry at Colorado College.



Along Came a Spider

The colors of Pacific island spiders tell a story of evolution in action.

By KATE RAMSAYER / ILLUSTRATION by EVAN BARBOUR

ROSEMARY GILLESPIE'S desk at the University of California in Berkeley is dwarfed by a gigantic spider web—made from an intricately woven string of Christmas lights. A large model of a yellow and black spider lurks beside her computer on the desk.

Her bookcase is lined with texts on insects and arachnids—a class of creepy crawlers that includes not just spiders but also ticks and mites—and Lonely Planet guides to exotic locales. Few professors would post a flyer of the David Arquette movie *Eight-Legged Freaks* on their office door. But Gillespie is an arachnologist, and her interest in her research subjects extends even to campy horror flicks.

Real-life versions of those research subjects are everywhere in her office: Blanketing a desk and the bottom shelves of bookcases along the wall are little vials, shaped like perfume samples but a bit bigger. Floating in each one are multiple spiders, legs entwined to form big arachnid clumps.

"The problem with these things is that in alcohol they really don't look very good," says Gillespie, a slight woman with short curly hair. "Insects you can pin, but spiders you just have to dump in alcohol, so it's really hard to preserve anything good looking about them."

Still, the intricate red and gold colorations stand out on a spider with a body no bigger than an eraser head.

This little creature belongs to an arachnid species from the Hawaiian Islands called *Theridion grallator*, or happy-face spider, which is aptly named: The two black dots and red smudge on its yellow back can resemble a "Have a Nice Day" smiley face sticker. But other arachnids of the same species sport completely different markings—any combination of red, black, or white patches on a yellow background. In fact, around 70 percent of these spiders are plain yellow, with a few black spots. These color patterns decorating the backs of many spiders gave Gillespie and her colleagues insight into the incredible power of evolution on the Hawaiian Islands.

Gillespie is on a quest to uncover all she can about the happy-face spider and another group of Hawaiian arachnids, the *Tetragnatha* spiny-legged spiders, as well as new species from the remote French Polynesian Islands. She has been collecting and characterizing all the specimens that she can scoop up, investigating how they colonize an island and adapt to its different niches. By studying how varying coloration patterns have evolved in these Pacific island spider species, she and her colleagues have uncovered intriguing new examples of "parallel" evolution—the tendency of nature to come up with the same solutions over and over again, albeit via different routes.

The evolutionary patterns she has discovered confirm the general theory of speciation, in which one group of critters branches off from their relatives to form a separate species. Gillespie and her colleagues also hope to track the evolution and movement of spider species between regions, and shed light on the incredible biodiversity that is unique to each small tropical island—information important to future conservation efforts.

Gillespie has no fear of spiders, although she was not always an aficionado of the bugs herself. As a zoology major at the University of Edinburgh in her native Scotland during the late 1970s, she wanted to study seabirds with a behavioral ecologist. The year she signed up to work with him, though, his research focused on spiders, so she ended up investigating how these arachnids decide where to put their webs.

This led to graduate work on spider ecology at the University of Tennessee, and ultimately to a postdoctoral stint studying the feeding habits of the Hawaiian happy-face spiders. While doing her field research, she noticed various species of the spiny-leg Tetragnatha spiders.

"The more I looked, the more I found that basically everything there, all the whole diverse spider fauna, was all this one genus," says Gillespie. "So I became very interested in that group and how it diversified."

ISLANDS HAVE BEEN the choice destination for evolutionary biologists ever since the days of Darwin, who in the 1830s began to formulate his seminal theories on evolution by studying the differences in beak shape and body sizes among finches of the Galapagos Islands. Such isolated pockets of land provide a defined habitat where organisms gradually evolve to adapt to a specific environment.

When separated from the population of their founding ancestors over many generations, critters acquire genetic differences—random mutations that may prove advantageous to survival in their habitat, be it an open grassy area or a wide-leafed tree—and eventually diverge from their kin into new species. In a large landmass, such adaptation could be squelched if two or more closely-related animals invade and compete for the same habitat; the losers never have the chance to populate and adapt to that particular locale. But in islands these colonization events are so rare that species have time to evolve without interruption.

Because colonization in islands was rare before people started moving goods from place to place, island animals provide prime opportunities for evolutionary biologists to study scenarios of evolution uncomplicated by the influences of invading species. The Hawaiian island chain, for example, is an optimal location to study spider evolution and the relationships between species. The islands were formed sequentially, starting around five million years ago with Kauai, and progressing to the big island, Hawaii, which is still forming. And for the most part, the oldest spider species exist on the most ancient islands.

To investigate the roots of diversity in the color patterns of the happy-face spider, Gillespie and her collaborator Geoff Oxford, a geneticist at the University of York in England, collected and interbred Maui spiders with different markings. They determined a basic pattern of inheritance to explain how the happy faces might have originally developed.

"You get this tremendous diversity of color forms on each of these islands, and it's all inherited in that very straightforward way," says Gillespie as she searches for a pen and scrap paper on her desk. She sketches out the genetic crosses, diagramming the different combinations of genes that baby spiders could inherit from their parents. "So we got it all figured out," she says, her excitement shining through. In Maui, the yellow form is most common, but if a yellow spider mates with a multicolored spider, half of their offspring will be yellow and half will be patterned.

Straightforward enough. But the scientists then looked at the same species of spiders on the big island of Hawaii. Here, the overall ratios of yellow to patterned happy-face spiders were the same as on Maui, with similar color variations. But surprisingly, some of the patterns could be found only on the female spiders, while others were unique to males. This finding implies that genes on a sex chromosome play a role in determining the color design for the Hawaii spider that isn't found in its Maui cousin.

When it comes to the family tree of species, appearances can be deceiving.

While the variations in color seem identical on each island, at a molecular level the patterns are "actually supported by a different genetic architecture," says Oxford. "We've demonstrated a shift in the genetics of this color variation." In other words, the researchers found that nature had devised the same color patterns for the two groups of happy-face spiders, but through separate genetic mechanisms—an example of convergent evolution.

How could this happen? Gillespie and Oxford have a theory: Maui is the older island, so when it formed around 800,000 to 2 million years ago, color patterning evolved in the happy-face spiders as a backup camouflage method. Yellow spiders are the most common, apparently because they can hide under leaves and blend in as the sun shines through, making the critters all but invisible to predatory birds peeking under the foliage. But when the yellow spiders become too numerous, the birds begin to see through the arachnids' disguise and start eating more of them. Now, the multicolored spiders then have an advantage; the further away from plain yellow they are, the better their chances of surviving and thriving. Consequently, over generations, the ratios of yellow to multicolored members of the species remain virtually constant, Gillespie says.

Later, when the big island of Hawaii was forming, some happy-face Maui spiders would have migrated to the new environment. Because there's such an extensive range of patterns in Maui, and because colonization is so rare between islands, Gillespie and Oxford assume that representatives of every color variation didn't make it to Hawaii. For the few specimens that did complete the trek, however, once they reached the newer island they were subjected to similar pressures of natural selection from the same species of birds. Over time, that threat coaxed the Hawaiian population to evolve the same color patterns that had surfaced in Maui—but with different genes. "[The Hawaiian group] basically put together another genetic way of achieving the same end product," says Gillespie. "At least over evolutionary time, there would have been strong selection to get back the diversity they had originally."

While the happy-face spiders exemplify evolution within a single species, Gillespie also studies the gradual adaptations that cause members of one group to branch off into an entirely new species. She is able to conduct studies now that wouldn't have been possible during her graduate school days—the tool kit for studying evolution has changed dramatically since Gillespie made her first field trip to Hawaii in 1987.

Now, by studying minute changes in DNA, the genetic blueprint for life, researchers can determine how closely related different spider species are to each other. Each species is placed on a branch of a "phylogenetic" family tree, illustrating when one type of spider separated from the crowd, and who its closest relatives are, based on their genetic similarities. "You collect spiders, extract and sequence a section of DNA, and you build a phylogenetic tree based on who's related to whom, so you get a whole pattern of relationships," says Gillespie.

Gillespie used these methods to deduce the relationships between the brown, green, and maroon spiny-legged spiders she had first noticed when she arrived in Hawaii. At first glance, one might assume that spiders of the same color are most closely related to each other, irrespective of which island they call home. But after collecting specimens of each type from each island, sequencing their DNA, and constructing a family tree, Gillespie discovered yet again the hand of convergent evolution at work: She found that the three different species on each island were more similar to each other than they were to their color-matched counterparts on other islands. She concluded that when a spider of one color originally colonized a new island, it adapted to the varied ecologies in the same way every time–by evolving the two other colors.

"Basically you get communities evolving and just throwing up the same kinds of ecological forms over and over again on each island," says Gillespie, "so this tells you how speciation happens."

Gillespie's work is "clearly the best example of ecological divergence driving the speciation of spiders," says arachnologist Marshal Hedin of San Diego State University in California. "We don't have that many solid empirical examples, but I think Rosie's is certainly some of the nicest in the invertebrate world."

Her research also demonstrates what Gillespie calls a "race between colonization and evolution." If a green spider, which blends in well with leaves, moves into an area formerly inhabited only with brown spiders, the new neighbors will fill the green-spider ecological niche. There will be no time, and no need, for the brown spider to adapt and evolve into a green spider, so colonization trumps evolution.

BEFORE ALL THE evolutionary work and genetics can be done, however, the spiders and other critters need to be collected. "Getting out in the field and finding the animals is the most challenging, and the most fun too," says Elin Claridge, a graduate student in Gillespie's lab who is studying the evolution of beetles.

In recent years, Gillespie has expanded her research to the French Polynesian Islands–2600 miles south of Hawaii–where she's searching for new species and beginning to describe the relationships between them. Whereas the Hawaiian Islands have been mapped out and are easy to reach, her new collecting grounds are full of obstacles.

"Getting to some of these islands is extraordinarily hard," says Gillespie, who went to a tiny island in the Southern Australs called Rapa before Christmas. To get there, Gillespie flew to Tahiti, took the once-a-week flight to Raivavae, an island 450 miles to the south, and then waited for a day-long boat ride to Rapa.

"They put out a special boat for us. Usually you have to stay for a month, and even then it's not exactly clear–it might be shorter or longer. The boat ended up being four days late, but it got us there," says Gillespie. "The boat ride to Rapa was wretched, it was just awful."

Once she arrived, she went hunting for spiders. Other colleagues from Paris searched for snails, a scientist from Hawaii collected insects, and a French Polynesian colleague sought out plants. Because the islands aren't well characterized, Gillespie doesn't yet know where the best places to find spiders are. The most promising spots are on the tops of mountains, where native spiders don't have to compete with new invasive species. Mountains pose their own problems, though. "They're volcanic and they've eroded away, so you get lots of knife-edged ridges, and that's how you have to get to the top of the mountain," says Gillespie. "They're not the most fun things to climb."

> **Gillespie hopes to collect — and protect — undiscovered insects before they go extinct.**

Gillespie is in the first stages of her research on the spiders of French Polynesia, collecting, identifying, and sequencing the DNA of the specimens she has brought back. She's gradually fitting them into their proper place on family trees, and will look for patterns similar to those that she described in Hawaii.

Scientists have long theorized that the Hawaiian spider species could be traced to ancestors that originated in Southeast Asia and skipped across the Pacific island chain to Hawaii, populating French Polynesia along the way. But Gillespie's latest observations, along with studies by others, hint otherwise. The French Polynesian spiders that she has found are considerably different from the Hawaiian breeds, which suggests that the groups of species in the two regions don't share a common ancestor after all. In fact, the spiders from the 50th U.S. state instead seem to be most closely to related to species from the lower 48, or at least from North America.

In all, Gillespie has discovered more than 50 species of spiders throughout her 17-year career, and has described 19 of them in depth. Identifying all of these varied arachnids gives a sense of what's out there that needs to be protected. Because of their sheer number, spiders are some of the most important natural predators, says Gillespie, and if they start disappearing it could affect the whole community.

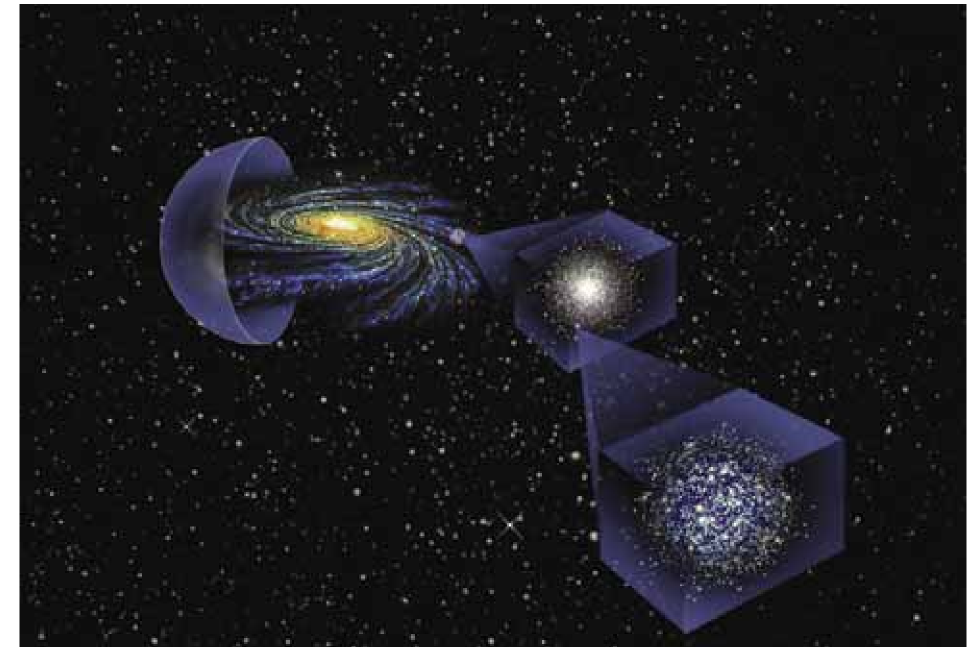
"We've got this wealth of diversity in the world, and it all plays a role in how ecosystems operate. Exactly what role we don't know, and exactly what the impact will be if it were lost we don't know," says Gillespie. "Basically, what's happening in the world at the moment is that we're mowing over all of the diversity that has taken millions of years to evolve."

She hopes that her work in French Polynesia will help to bring attention to the native species on the island that are vulnerable to extinction. Graduate student Claridge fears that some of the species she described on previous expeditions could be already wiped out. Claridge is documenting the forests of French Polynesia as she hunts for beetles, in the hopes that it will inspire the French government to accelerate its conservation programs. The state of many of the islands hasn't been described since the 1930s, and with the advent of tourism, much has changed since then.

To Gillespie, conservation and evolution are intertwined topics. It's not enough to only preserve habitats for spiders and other creatures that exist now; it's also necessary to accommodate species that might exist in the future, she and other researchers say.

"A lot of conservation is aimed at protecting a particular species, but I think [it's] far more important … to be able to preserve the ability of plants and animals to respond to changes in the future," says entomologist Dave Kavanaugh of the California Academy of Sciences in San Francisco. "Extinction is a fact of life, [but] there are succeeding organisms that fill in behind things. One of the dangers is we're eliminating the ability of other things to do that."

By studying how species evolve, scientists hope to gain a sense of the environmental factors that are necessary to maintain healthy ecosystems where future life forms can bloom. Toward that goal, Gillespie continues to juggle the trio of fieldwork, lab work, and descriptions of new species. She surveys her office, looking at the boxes and Tupperware containers filled with vials or suspended spiders. "I haven't looked at a lot of those yet–it's kind of daunting," she says. "I could retire from everything I'm doing and spend the rest of my life just looking at these samples, and keep myself perfectly occupied forever." SN



The Light of Dr. Jean Brodie

Dense clusters of stars might illuminate how the galaxies of the universe were born.

By ERNIE TRETKOFF / ILLUSTRATION by NADIA STRASSER

JEAN BRODIE COLLECTS light from some of the oldest objects in the universe. An astronomer at the University of California in Santa Cruz, Brodie recently spent a week of evenings in Hawaii peering through the enormous Keck telescope at globular clusters–dense clumps of stars that hang out in just about every galaxy in the universe, like blueberries in a pancake.

For astronomers, globular clusters are like the fossils that paleontologists use to track the evolution of life. The star-clumps provide Brodie and her colleagues with a window through which they can watch galaxies evolve. They believe that the stars in a given cluster formed at the same time as their host galaxy billions of years ago, making them among the oldest radiant objects in the universe.

The universe contains billions of galaxies, yet scientists don't know much about when and how they form, grow, and break apart. Astronomers have determined that most galaxies formed within a couple of billion years after the Big Bang, the explosion that gave birth to the universe around 14 billion years ago. "After the Big Bang, the universe was a uniform soup. Now we see all kinds of structure," says Brodie.

Indeed, the universe today bubbles with galaxies of all types: beautiful spirals, with their central bulge of stars surrounded by a disk with long, curved arms; blobby, football-shaped ellipticals; and amorphous irregulars that don't fit into either category. There are also stars, clumps of gas and dust, and groups of galaxies.

Astronomers have been baffled for decades as to how all these celestial structures took form out of the uniform soup. They have some theories, and now they have a telescope powerful enough to test them. Indeed, Brodie has developed a promising new hypothesis of her own.

Previous theories of galaxy formation, developed over the past few decades, were based mainly on older, less-detailed telescope observations and computer simulations. Each hypothesis has its own advantages and problems. The scenario that most cosmologists prefer is known as the hierarchical model, which proposes that most galaxies formed early in the history of the universe, over a period of a few billion years, through the clumping together of larger and larger gas clouds. According to some scientists, galaxies are still being formed today by this method.

Another model posits that while spiral galaxies arose through the hierarchical scenario, the majority of elliptical, or football-shaped, galaxies form when spiral galaxies crash into each other. This "mergers" model has the clear advantage that astronomers actually do observe spiral galaxies in the process of colliding to form ellipticals. But such mergers are rare, and in order for mergers to have played a dominant role in galaxy formation, they would have had to occur much more frequently in the past than they do now, which researchers agree is unlikely.

Until recently, there hasn't been enough data to test either of these theories. Part of the difficulty stems from the fact that galaxies are complex mixes of stars of different ages and chemistries, as well as all kinds of dust and gas. Trying to study such a disorderly mess from billions of miles away is an extremely tough task, even for scientists armed with the biggest telescopes and most powerful computers in the world. Further complicating matters, the newest, brightest–and thus most visible–stars tend to dominate the light streaming out from a galaxy. But they make up only a small fraction of its mass, so these young stars are useless for looking at the galaxy's formation.

Scientists therefore needed a less complicated object that would still tell them something useful about the galaxy. Globular clusters fit the bill. Although up close, they look like a confusing jumble of stars flying every which way, compared with galaxies, they are simple. Because all stars in a given globular cluster formed from the same gas cloud at about the same time–give or take a few million years–they tend to be composed of the same chemical elements. This uniformity makes the clusters relatively easy to study. For Brodie's kind of research, "they're better than galaxies themselves," she says.

Globular clusters typically contain between 100,000 and a million stars in a glob extending 60 to 150 light-years across, with one light-year–the distance light travels in one year–equal to about 6 trillion miles. From a distance, the clusters appear as tiny specks in galaxies, which usually are made up of 100 billion stars and run 100,000 light-years in diameter. Because they are so densely packed, the stars in a globular cluster are influenced by the pull of each other's gravity and zoom about in complicated patterns, in all directions. Occasionally, stars are even expelled from the clump.

Globular clusters live almost everywhere in the universe, in every type of galaxy, from the elegant flat spirals like our own Milky Way to the footballish ellipticals. The Milky Way is home to 150 clusters, while some elliptical galaxies are known to harbor over 10,000 of them. A few clusters can even be found in the tiniest dwarf galaxies.

The amateur German astronomer Abraham Ihle observed the first globular cluster in 1665, but he mistook it for a nebula. The first scientist to correctly identify one of the star-clumps was the British astronomer William Herschel, who coined the term "globular cluster" in 1789. But only in the last decade have these entities become an area of intensive research, as more powerful telescopes have come on line to study them in great detail.

BRODIE IS ONE of the leading researchers in the U.S. in using globular clusters to study galaxy formation. She works on a project called SAGES, Study of Astrophysics of Globular clusters in Extragalactic Systems, which uses images from the Hubble Space Telescope and the huge 10-meter Keck telescope in Hawaii—the largest in the world—to learn more about these celestial objects and the galaxies they inhabit.

The SAGES group looks at three or four galaxies and around 50 globular clusters per year. It can take several hours of telescope time to look at a single cluster. To find out exactly what each one can tell us about its parent galaxy, Brodie carefully analyzes the light emanating from its stars to determine its age and composition.

The brightest stars in globular cluster M15 are the orange-hued red giants, about 12 billion years old. The dimmer stars are hotter with a blue-white color. The cluster is 40,000 light-years away. (Space Telescope Science Institute)

All stars, like our sun, emit a continuous rainbow of light, from short-wavelength blue light to longer-wavelength red light. In general, bluer stars tend to be hotter and more massive than redder stars, and they tend to burn out more quickly. So if all the stars in a globular cluster were born at about the same time, a cluster will start to look redder as its blue stars die off. All else being equal, this would mean that a globular cluster dominated by blue stars is younger than one dominated by red stars.

But all else is not equal. Different stars contain different chemical elements, which can change their colors. Each element can absorb light of certain precise wavelengths, creating a sort of chemical signature that astronomers can read to identify which elements a star contains.

This information is important, because chemical composition is also a clue to age. In the early days of the universe, only the lightest elements, hydrogen and helium, made up all the gas that ultimately became stars. All stars begin their life cycle by burning hydrogen into helium; when they use up all their hydrogen, most of them die out, but a few are large and hot enough to burn helium into heavier metal elements. When these stars finally die, they eject those metals out into space, where they can be incorporated into any new stars that form.

Because heavier elements are better at absorbing short-wavelength blue light, stars containing metals will appear redder than metal-poor stars. So in general, based on chemical composition, older stars—which formed before there were many heavy elements in the universe—look bluer than younger ones.

The question is: How do you tell whether a cluster is blue because it is young and hot, or because it is old and metal-poor? Steve Zepf, an astronomer at Michigan State University, explains the question with this analogy: "You gain weight if you eat candy or if you eat potato chips. How do you tell why you got fat?"

Brodie thinks she has found a way to sort things out. When a star is hot enough, the electrons in its hydrogen atoms can jump to higher energy levels, emitting light of a particular wavelength, known as a Balmer line. Strong Balmer lines indicate hotter stars, and therefore can identify younger clusters. This dating method is somewhat like looking at the cluster's color, but it's much more precise because it doesn't depend on chemical content. "You can't do better than Balmer lines," says Jay Strader, a graduate student who works on SAGES with Brodie. Still, the UCSC researchers admit getting an exact age is extremely difficult.

After carefully analyzing spectra from dozens of clusters, Brodie and others found that all galaxies seem to have exactly two populations of globular clusters: one redder, younger, and metal-rich, and the other bluer, older, and metal-poor. "It's a clear distinction you can see by taking out telescope and looking," says Strader.

So far, Brodie's team has found the two populations in about 50 galaxies. In almost all cases, spectral analysis indicates that the red and blue clusters differ in age by about 2 billion years, though both are at least 10 billion years old, supporting the widely accepted notion that most galaxies formed very early in the history of the universe. Recently, however, researchers have found a few galaxies that have younger red clusters that are between 3 billion and 7 billion years old, Zepf says. These "teenagers," as Zepf calls them, have further confused the galaxy formation picture.

Regardless of when galaxies formed, astronomers need to figure out why there would be two distinct eras of globular cluster formation, rather than one, or ten, or a continuous history of them. The answer depends on how galaxies formed.

The two distinct populations of globular clusters recently prompted Brodie to help develop a new theory of galaxy formation. This model holds that galaxies formed in two distinct stages within a few billion years after the big bang. First, dust and gas coalesced to form galaxies. This initial collapse was followed by a quiet period of about a couple of billion years, during which a few stars generated some of the heavy metals. Then all of a sudden, the galaxy exploded, Brodie conjectures, shooting out all its material, including those metals. Much of this material fell back towards the center of the galaxy, pulled in by the strong gravity of the galaxy.

In Brodie's two-stage collapse model, the red population of globular clusters was born with the galaxy, whereas the population of blue globular clusters formed during this second collapse. This model gives a neat and easy way to explain why every galaxy has precisely two populations of globular clusters. But the hypothesis has its shortcomings.

For starters, Zepf raises a note of caution over the two populations Brodie's group has identified: "One thing to remember—it's sort of like dividing up people. There's two different kinds of people, men and women, but that doesn't mean everyone in each group is identical."

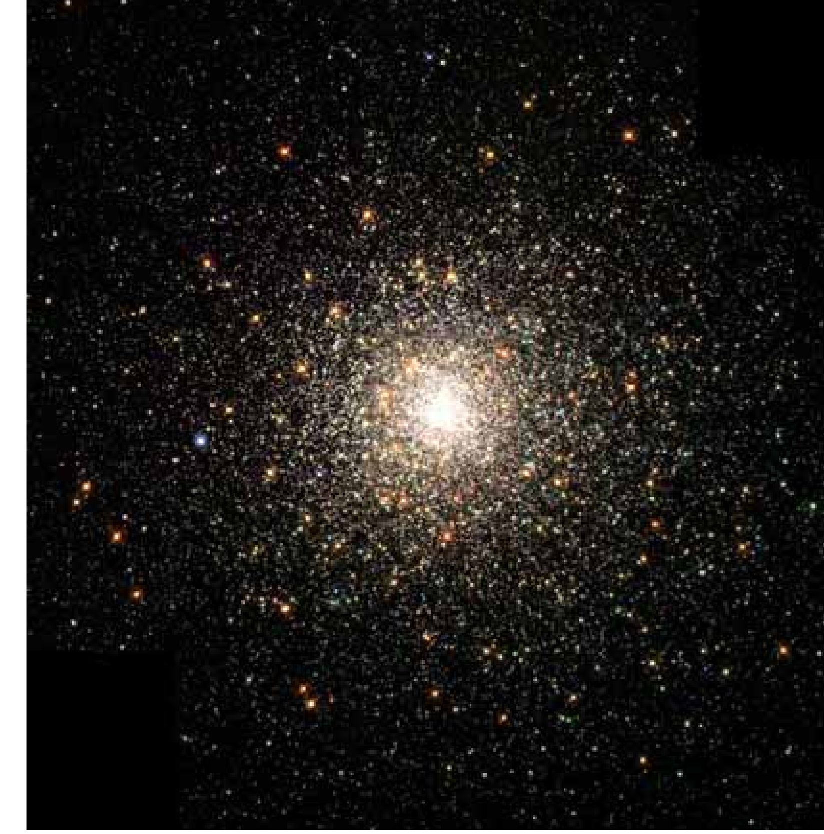
Moreover, no one understands exactly what physical mechanism would cause a two-stage collapse—and no one has ever observed a galaxy undergoing this process. This is one reason Zepf, who favors the mergers model, says that though he admires Brodie's observations, he is skeptical about her theory. Admits Brodie, "It's not at all clear why that would have happened. We don't know what triggers formation." She is also searching to explain what could cause a galaxy to suddenly explode.

TO GATHER MORE support for her theory, Brodie is now collecting additional data. In particular, she is focusing on measuring the ages of a large sample of clusters—a difficult task. Zepf says that the best dating methods today are accurate only to within 30 percent of the correct age, although other scientists think they are achieving better estimates than that. But obtaining reliable ages for many globular clusters could be the key to the galaxy formation puzzle, since the different theories predict different ages for the clusters.

Whereas Brodie's two-stage collapse model calls for two distinct cluster populations, both very old and nearly the same age, the hierarchical model predicts this alternate scenario: Since most galaxies formed early, most globular clusters should be very old; but each galaxy should have clusters with a range of ages, rather than two distinct populations. "It's hard to get two distinct populations of globular clusters from this model—but it's been proposed that you can," says Zepf.

One way to do so, according to Brodie, is if the blue population developed from the original gas clouds, while the red clusters were born when some of those clouds merged, assuming that most of the activity happened in the first few billion years after the Big Bang. This would put the red population about two billion years younger than blue, which matches real-life observations well. Unfortunately, this scenario is hard to distinguish from the two-stage collapse theory on the basis of globular clusters alone.

The mergers model suggests, on the other hand, that the globular clusters should have just a few age brackets, which would vary in age from galaxy to galaxy, depending on each one's exact merger history. In this model, the first, blue population came with the spiral galaxies. The second, red population is created when shock waves caused by the colliding galaxies produce bursts of star formation. The question is whether mergers happen often enough to create all the elliptical galaxies we see. These crashes would have been more likely in the first half of age of the universe, when it was much denser and its structures were closer together.



This cluster, M80, is located about 28,000 light-years from Earth and with hundreds of thousands of stars, it is among the densest of the 147 known globular star clusters in the Milky Way galaxy. (Space Telescope Science Institute)

But Brodie isn't convinced by this model, pointing out that if mergers were more common billions of years ago, then many galaxies would have undergone more than one merger, leading to more than two distinct populations of globular clusters. And of course, the merger model leaves open the question of how the spirals formed in the first place. Nonetheless, says Zepf, "My opinion is that mergers are dominant, just because we actually see it happen."

The mergers model is the only one that predicts a significant number of clusters younger than about ten billion years. This aspect was a strike against it until recently, when the small number of 3-billion- to 7-billion-year-old red clusters was found. These are young enough to have formed during mergers, though astronomers don't know yet how common these younger clusters are.

All in all, the data offers support for each theory. Current evidence points to some mix of these hypotheses being correct, says Brodie. "My real feeling is it's a hybrid thing," she says. But how many of the billions of galaxies in the universe formed by mergers? How many by two-stage collapse, or through the hierarchical model? Which model is the dominant method? Though each theory has promise, in order to finally sort out how galaxies formed, astronomers will need to look at many more of them and those fossils of their evolution, globular clusters. And that means Brodie will be making trips to Hawaii for years to come. SN

A Battered Mollusk

(Also Steamed, Stir-Fried, and Eaten Raw)

Overfishing and disease drove California's abalone to near extinction. Science may bring them back.

By HELEN FIELDS / ILLUSTRATION by RACHEL ROGGE

IN THE LATE 1960s and early 1970s, white abalone became a popular target for fishermen diving into the deep waters off southern California. Inside each flattish, dome-shaped shell, nestled in an opalescent lining, was a snail that spent its life eating drifting pieces of kelp. The white is said to be one of the most tender, delicious abalone. Its muscular orange foot, delectable raw or fried, was selling for about a hundred dollars apiece by the 1990s, when the whites had become so rare that the state made it illegal to fish for them.

> "It's like coming onto an accident scene. The first order of business is to prevent extinction."
> – Gary Davis, Channel Islands National Park

Tom McCormick is passionate about white abalone, but he has never eaten one and doesn't want to. An aquaculturist who has been breeding abalone in captivity for 20 years, he sees personality in the snails. "They're a beautiful animal," he says. "If they don't want to be some place they just pick up and they take off. They just start walking, and they kind of waddle back and forth as they walk," he says. Eating an abalone is a waste of the snail's life, he says. "That took 10 years to get to that [size], and you're going to have it for one dinner?"

In 2001, the white abalone made the federal endangered species list, the victim of overfishing. Whereas the deep waters near the Channel Islands, located off the California coast near Santa Barbara, teemed with thousands of white abalone per acre of ocean floor in the 1970s, the most recent state survey uncovered only a handful of the snails per acre.

McCormick, who founded the Channel Islands Marine Resource Institute in Port Hueneme, California, to study the white abalone, has been working to restore their population. Two years ago, he and his coworkers managed to get a few adult white abalone to spawn, and the scientists are now raising 16,000 young snails from that union. Several thousand snails are growing now from a second spawning this January. Some day, McCormick may be able to release the whites into the wild.

A century ago, white, black, red, pink, and green abalone flourished along the California coast. Hundreds of fishermen made their living fishing the abundant snails. But by the 1990s, the fisheries in California were closed because the abalone population had been decimated by fishing and disease. Now, black abalone could soon join the whites on the endangered species list and the outlook is dim for the green and pink as well. Other species of abalone around the world have suffered similar problems, as have many other marine animals.

Alarmed by the decline, researchers such as McCormick and biologists with the California State Fish and Game Department are working to bring abalone back, not just to save the snails with the opalescent shells, but also to someday revive the fisheries. Like most conservation measures, the efforts to save the tasty abalone from extinction are part nursery, part dating service and part hospital care.

Fish and Game scientists recently drafted a recovery and management plan. Goals are first to restore enough of the shellfish in the ocean so that they can reproduce, then eventually to grow the populations large enough to support fishing again. The department will survey the existing numbers of each abalone species at sites off the California coast, look into culturing and planting the shellfish in the ocean, and continue researching abalone genetics and disease. The department also recommends setting up zones where abalone will never be fished.

The rescue plan covers red, green, pink and black abalone and two rarer species; white abalone are included as well, but because of their endangered status, they are also being managed by a special federal recovery team. "Abalone recovery will probably take many decades," managers wrote in the report.

"It's triage," says Gary Davis, a marine biologist at Channel Islands National Park, of the abalone rescue efforts. "It's like coming onto an accident scene. The first order of business is to prevent extinction."

TWO DECADES AGO, when Davis strolled at low tide along the shores of the Channel Islands, he saw hordes of black, oval shells everywhere. "There were probably more than ten million black abalone in the park in the early 1980s," he says. But today, it takes him up to 45 minutes of looking under rocks to find a single black abalone in the pools where the creatures used to flourish. The culprit–which Fish and Game marine biologist Carolyn Friedman identified in the late '90s–is withering syndrome, a bacterial disease that has made millions of abalone shrivel up and die.

The abundance of abalone off California in the 20th century came about, indirectly, because of people. In addition to withering syndrome, the shellfish have an age-old foe. Sea otters, which used to live in great numbers along the Pacific coast, from Baja California to Alaska and Japan, are voracious abalone eaters. In the early 19th century, when otters were thriving, they kept the abalone populations small; the shellfish could only be found in cracks and crevices of underwater rocks, or above the low-tide line–places where otters couldn't get them.

By the late 1800s, however, people had hunted the sea otters to near-extinction for their luxurious pelts, and abalone populations exploded, taking over rocky surfaces underwater and along the shores. But about 50 sea otters survived off the isolated, steep Big Sur region of the central California coast. By the middle of the 20th century, under federal protection, they were spreading up and down the coast again and competing for abalone with a new rival–the fishing industry.

Native Californians harvested the snails for food, but Chinese-Americans in Monterey, just north of Big Sur, had been the first to catch and export abalone, a delicacy in Asia, in the mid-1800s. After World War II new diving equipment, which let fishermen breathe air from the surface, had made abalone easier to catch, driving a boom in the fishing industry. With the rebound of the otter population, though, the situation began to change.

"The otters would move in and the fishery [catches] would drop," says Peter Haaker, a senior marine biologist for the California Department of Fish and Game who has been studying abalone since the 1960s. Fishermen were permitted by law to only take larger abalone, but the otters were gobbling those down. So the abalone industry shifted its center to Southern California. Fishermen kept moving ahead of the otters, and the abalone catch boomed, with hundreds of people collecting abalone by the late 1960s.

But suddenly, in the late 1980s, disaster struck: The industry was reporting that the shellfish had all but disappeared, Haaker recalls. By the end of the 1990s, California law prohibited all commercial abalone fishing to protect the few remaining animals.

Scientists now recognize that what happened to the abalone is an all-too common tale in modern fisheries. When catching abalone was still legal, commercial fishermen had to report how many abalone they caught, with state Fish and Game employees checking the numbers each year. About the same harvest numbers came in year after year, so the abalone population looked as though it was holding steady. But the constant catch data masked what was really going, Haaker says. When he and his colleagues looked back at the data in the late 1990s, they saw a different picture.

What the fishermen were doing, the researchers realized, was moving from place to place and species to species, clearing out all the abalone and moving on. Fishermen had originally started out hunting red abalone, the world's largest kind, and expanded to the pink variety. By the early 1970s, the red and pink abalone catch were down to about half of what they'd been in the good years in the '50s and '60s. So the industry started going after the green abalone in their blue-green shells, then the black, then the tastiest of them all–the white, which had escaped fishing for decades because they live farther from shore, in deeper water than the other species. Each species and fishing ground was knocked out in turn.

The abalone's story is an example of what biologists call serial depletion, and it has been repeated countless times with different marine creatures. In parts of the Atlantic Ocean, fishermen fished one cod sub-species after another, clearing each one out. They caught the same number of cod each year, so no one noticed a problem until, suddenly, there were no more cod to catch. The same thing has happened with species of Alaskan crabs and whales. When the tastiest or easiest-to-find animals run out, fishermen move on to the next best species. Better technology and better boats let them go farther and farther out, reaching areas that were once refuges where animals could reproduce and replenish the near-shore populations.

Currently, serial depletion could also be happening with sea urchins, another lucrative California fishery, and sea cucumbers, which people only started fishing a few years ago, Haaker says. Now, people can go out and start fishing anything, whether or not state managers know anything about it, Haaker says. Their data comes from asking commercial fishermen how much they catch, not from going out and counting the number of animals in the ocean. "If you're just operating your fishery from the commercial landings, you're going to be surprised some day," Haaker says.

But even when managers realized that the abalone were in trouble, there was little they could do, Haaker says. Until a few years ago, the state legislature had to approve any fishery closings. Abalone fishermen lobbied hard against shutdowns, the state Fish and Game managers worked to make the snails off-limits, and it wasn't until 1993 that the first of the fisheries, the black, was completely closed–but by then, disease and fishing had killed most of the black abalone.

Commercial catches of all abalone species were prohibited in 1996 and 1997. Now the only abalone fishing allowed is for sport in Northern California, with no scuba gear and strict daily and annual limits on the number of abalone people can take. Managers know poaching is still a problem, but have no idea how many abalone poachers take every year.

Despite the political conflict between Fish and Game and the abalone fishery, Haaker says that fishermen were not to blame for the serial depletion of the shellfish. "They were only doing what society, the Fish and Game commission, all of us let them do," he says. Zeke Grader, executive director of the Pacific Coast Federation of Fishermen's Associations, says that the industry was just following the regulations set by Fish and Game. Fishermen can invest tens to hundreds of thousands of dollars in a new fishery, and they don't want to see it collapse in a few years. "It's not just an investment in money; it's an investment in their lives," Grader says. Recently, California fishermen have even argued for stricter state regulations on squid fishing. "We weren't going to sit back and let what happened to the abalone fishery happen to the squid," he says.

BIOLOGISTS ARE NOW STUDYING a number of strategies to rescue the abalone. One way is to help the animals reproduce. Like many marine invertebrates, male and female abalone mate by spitting out clouds of sperm and eggs–through a string of small, volcano-shaped vents in their shells. Once ejected into the water, the eggs from a female have to bump into the sperm from a male to achieve success. "If there aren't a fairly large number of individuals within a meter of each other when they spawn, the probability of successful fertilization is nearly zero," says Gary Davis. Scientists used to think that because abalone are "broadcast" spawners, the shellfish would never go extinct from fishing because there would always be enough left to breed. But the experts guessed wrong: Fishing thinned out the snails until it was impossible for the few survivors in many areas to reproduce.

Given the logistics of abalone mating, one solution is to collect a few thousand abalone and plop them down in the equivalent of a big dating pool. In the early 1980s, scientists collected 4,500 mature green abalone and seeded them in waters off Palos Verdes Peninsula south of Los Angeles. The transplant worked for a while. In 1985, juvenile green abalones were a common sight. But the plan had a key flaw: poaching. By 1989, a survey by the Fish and Game department found no adults; poachers had taken every one, Haaker says. This method might work better today–since all abalone fishing is illegal in southern California, wardens know that anyone toting around a bag of the snails has broken the law.

Another conservation tactic is to grow abalone in captivity, then release them in the wild. A few commercial abalone farms in California raise red abalone to sell to restaurants Near the Channel Islands, marine biologist McCormick has worked with other scientists in planting red, green, and pink abalone out in the ocean before as part of his work as president of Proteus SeaFarms, an aquaculture company near Santa Barbara. Raising abalone takes considerable time and patience. For instance, McCormick is waiting for the thousands of white abalone in his nurseries to grow to about 4 inches long before he releases them. They're growing at about one-half to three-quarters of an inch a year, so it could be another three or four years until they're ready for the ocean.

Babysitting thousands of abalone is neither cost-free nor well funded. "A lot of people assume that if a species has endangered species status, then the heavens open up and money issues forth from some federal agency," McCormick says. In fact, research money for abalone conservation is scarce. McCormick and other researchers have been donating time, equipment, and snail feed to help the white abalone. They also have funding from foundations and corporations, such as a local power company. "I'm always working on grants," he says.

Scientists hope to develop captive breeding techniques for white abalone in hopes of replenishing the declining populations in the wild. (Kevin Lafferty/USGS)

Even if efforts at replanting abalone in the ocean succeed, another menace lurks. Withering syndrome, caused by a kind of bacteria referred to as *Rickettsia*-like prokaryote, is now endemic in Southern California. The bacteria flourish in warm weather, so in warm El Nino years, the disease can break out farther north. No one knows where the disease came from. It hits black abalone worst, but it can make reds and whites sick, too, says Fish and Game biologist Thea Robbins, who studies withering syndrome at Bodega Marine Laboratory, in Bodega Bay, 60 miles north of San Francisco. Operated by the University of California, the lab's low, angular modern building sits out at the end of a spit of land forming one side of Bodega Bay.

Sick abalone live there in hospital-green tubs, with seawater continuously cycling through, in a dim concrete room. Robbins uses a kitchen spatula to pry a green abalone off the side of a large bucket so that she can show off its frilly epipodium, the rim of tissue that edges its shell. The disease is caused by bacteria that infect a snail's gut, changing the structure of its digestive organ so that the host wastes away. "It's a bummer to be a snail," Robbins says. The disease doesn't hurt people, so infected animals are safe to eat, but they look shriveled and unappetizing. On the way out of the disease lab, Robbins brushes the soles of her shoes over a tub of disinfectant to keep the disease from the rest of the lab. After seawater passes through the abalone tanks, it gets treated with chlorine before being piped back into the ocean.

Robbins and her colleagues are studying drugs that could treat sick abalone in collaboration with an abalone farm in central California. The drugs couldn't be used in the wild–there's no way to convince a wild abalone it wants to eat some tasty medicated kelp, or to keep the drugs from getting to other animals. But antibiotics could help scientists raise healthy abalone for transplanting to the ocean. Farmers shouldn't use the drugs continuously, says fish pathologist Jim Moore, one of Robbins' colleagues, because they could create antibiotic resistance. "We're hoping the industry will use it as a tool to get through El Ninos or periods when the water is warm," Moore says.

"RIGHT NOW, I don't foresee having any kind of an abalone fishery in Southern California in, probably, any of our lifetimes," Fish and Game's Haaker says. "Probably all of them, greens, pinks, blacks, and whites–but not reds–could be very close to a situation where they would be extirpated from California or literally go extinct."

Along with black abalone, the green and pink varieties may eventually be listed as an endangered species, Haaker says. In the Channel Islands, according to Davis, so little information currently exists on the green abalone, it's hard to know if it, too, is in trouble. In the last few years, there haven't been enough greens in the park to keep track of their numbers.

But even Haaker admits to some moments of optimism. For the whites, the outlook actually might not be as bad as it once was. "After our surveys in July, I feel a lot better about the future expectations for white abalone than I do about the other species," he says. The surveys found the white shellfish clumped in deeper water, probably close enough together to reproduce, yet out of the reach of otters. Haaker sees some signs of hope for the black abalone as well. On San Nicolas Island, one of the smaller Channel Islands, he and others found all sizes of black abalone last February, which suggests that the snails are reproducing and growing.

The good news is, of course, tenuous. If the sea otter population, which has been facing troubles of its own, were to come back and recolonize Southern California now, Haaker says, it would wipe out any white abalone gains and probably drive a few other species of the snail to extinction. And Haaker can only hope that the black shellfish on San Nicolas are resistant to withering syndrome. The odds are undoubtedly stacked against California's abalone. Nonetheless, in the fight to save them, every single survivor counts. SN

The Creativity Conundrum

Research hints that crankiness stokes artistic inspiration.

By GRETA LORGE / ILLUSTRATION by CHRIS FIELD

The creative mind can be a chaotic place. History offers numerous examples of writers, artists, and musicians who danced at the edge of sanity. The list reads like a *Who's Who* of the world of literature and the arts: from wordsmiths Plath and Poe to painters Gauguin and van Gogh to composers Berlioz and Berlin.

British novelist Virginia Woolf's journals and correspondence bear witness to her lifelong struggle with mental illness. Woolf suffered her first breakdown at age 13, following the death of her mother. Years later, she wrote of the "terrific high waves, and the infernal deep gulfs, on which I mount and toss." The ups and downs Woolf described are hallmarks of manic depression, or bipolar disorder, an illness characterized by dramatic, periodic mood swings alternating between euphoria and the debilitating gloom of depression.

Woolf could scarcely write at all when she was either depressed or manic, but she grew convinced that the ideas for most of her books came to her at times when she was ill. Woolf once wrote to a friend, "as an experience, madness is terrific I can assure you… in its lava I still find most of the things I write about. It shoots out of one everything shaped, final, not in mere driblets as sanity does."

The idea that artistic talent and mental instability are linked is not new. Ancient Greeks believed that Muses possessed the artist, stoking the creative fires. Aristotle quoted his teacher Socrates as saying, "If a man comes to the door of poetry untouched by the madness of the Muses, he and his sane compositions never reach perfection, but are utterly eclipsed by the performance of the inspired madman."

Today, centuries later, the synergy between genius and madness remains a tantalizing mystery. Why is it that so many works of great art, music, and literature have arisen from tormented minds? It's a question that captures the imagination: Creative people excite our curiosity and envy. Perhaps we hope that by understanding what makes them different, we can find a way to tap into our own inventiveness.

Connie Strong, a psychologist at Stanford University, has an additional reason for being fascinated with this question. Mental illness wreaks havoc in peoples' lives and touches everyone close to them. Strong has experienced this firsthand. Around the time when she began her research at the Stanford Bipolar Disorders Clinic three years ago, Strong had to hospitalize one of her closest friends. The friend had disappeared without a word, and when she resurfaced three weeks later–wearing a fur coat, bedroom slippers, and living in her car–Strong recognized the signs of bipolar disorder.

According to the National Institutes of Health, at least 1 percent of Americans over the age of 18 experience bipolar symptoms in any given year–more than 2 million adults in this country alone. "There is so much pain and suffering and social cost to this illness," Strong says. "I feel it's compelling to look at all aspects of it." Society stigmatizes bipolar disorder, yet a flair for creativity might well be a positive facet of the illness, she says. "If there's something good about bipolar disorder, we want to understand that too."

Strong and a colleague, Stanford psychiatrist Terence Ketter, have been probing the creativity connection. They don't believe that the highs and lows of bipolar disorder in themselves fuel innovative thinking; the picture just isn't that simple. Instead, they propose a new, and more subtle, explanation of how certain aspects of temperament–the basic operating principles that shape our attitudes and behavior–that underlie the bipolar personality might enhance creativity. In a recent study, Strong and Ketter compared the temperament traits of creative graduate students with those of patients at the Stanford Bipolar Disorders Clinic. The results suggest that one peculiarity shared by artistic types and manic-depressive individuals is irritability. And that quirk, the investigators say, might be an important factor in fostering ingenuity.

People suffering from depression have described it as a mental ice age in which the world goes cold and grey; they become trapped inside themselves. Depression strips away pleasure and purpose. Everyday tasks, even getting out of bed, become insurmountable. By contrast, mania unleashes a flood of energy and banishes the need for sleep. Sometimes mania brings intense focus and concentration; at other times the mind veers haphazardly from one thought to another.

Mania or depression alone is more than enough to disrupt work and interfere with relationships. But in bipolar disorder, mood oscillates between the two extremes. Psychiatrist Kay Jamison, of the Johns Hopkins University in Baltimore, who has written extensively about mental illness and art–and her own struggle with bipolar disorder–explained in a 1995 *Scientific American* article: "In a sense, depression is a view of the world through a dark glass, and mania is that seen through a kaleidoscope–often brilliant, but fractured." Each phase may last several weeks to several months. The disorder is incapacitating, and frequently destructive: One in five bipolar patients commits suicide, a rate around 20 times the frequency in the general population.

At the Stanford Bipolar Disorders Clinic, standard drug therapy–such as lithium and other mood-stabilizing medications–permits most manic-depressive patients to function well at their jobs or their studies. Ketter estimates that a quarter of the clinic's patients–many of them university students–are exceptionally creative; they are studio artists, authors, and architects. However, he notes that his patients are not representative of bipolar disorder in general and probably represent the "best possible outcome scenario" for living with the illness. That's because the Stanford clinic serves a particular population that is generally well-off, educated, and insured.

About three years ago Ketter and Strong recognized that their clinic provided an ideal laboratory for exploring the intersection of creativity and mood disorders. Not only did they have a group of bipolar patients that they were closely tracking, but it also happened that the researchers were following a group of healthy people as part of a separate study. "We thought, what an opportunity to approach the question from the standpoint of the bipolar patients versus healthy controls, and ask, Are the patients really more creative?" Strong says.

Ketter and Strong knew that previous scientific explorations in this area had turned up a number of intriguing results. For instance, in 1992 psychologist Arnold Ludwig of the University of Kentucky identified 1,004 deceased individuals in a wide range of occupations who had been profiled in biographies that were reviewed in the *New York Times Book Review*–an indication, presumably, that these people were all at the top of their profession. Ludwig scanned the books for clues that their subjects suffered from mental illness. He found that those in creative vocations, such as literary and visual arts, were two to three times more likely to have psychiatric symptoms than those in non-creative professions such as business, science and politics. However, critics of the study have pointed out that trying to diagnose mental illness posthumously is tricky at best.

In other work, over a period of 15 years during the 1970s and 1980s, psychiatrist Nancy Andreasen of the University of Iowa interviewed 30 faculty members appointed to teach at the university's prestigious creative writing workshop. All were distinguished authors; many were household names. She assessed the frequency of mood disorders in the literary group versus a comparison group of 30 faculty members in non-creative disciplines. She found that 80 percent of the writers showed signs of either depression or bipolar disorder, whereas only 30 percent of the non-creative controls experienced any symptoms. But Andreasen's study has come under fire because it didn't include an independent verification of the psychiatric diagnoses, throwing the results into question.

In 1988, psychiatrist Ruth Richards of Harvard University took a different approach; she attempted to quantify inventiveness in patients with mental illnesses using a scale she developed, the Lifetime Creativity Scale. The scale, based on lengthy structured interviews, is designed to capture originality in the accomplishments of everyday people over their lifetime. Richards found that bipolar and depressed patients were more creative than healthy individuals. But the interview process is time-intensive, and scoring the scale requires expert training, so other researchers have shied away from using the Lifetime Creativity Scale. As a result, Richards' results have never been replicated.

Compared to the earlier research, Ketter and Strong's work at Stanford differs in a number of respects. Theirs is the first attempt, within a single study, to converge on the creativity conundrum from two complementary vantage points: assessing artistic ability in manic-depressives, and screening healthy creative individuals for temperament traits associated with bipolar disorder. And whereas previous studies focused primarily on famously innovative personalities, Strong and Ketter were more interested in regular people who are creative in their day-to-day lives, even if they aren't well-known.

The researchers recruited four groups of people for their study: 48 patients whose bipolar illness was stabilized with medication; 47 healthy volunteers; 32 creative individuals from three Stanford graduate programs in fiction writing, fine arts, and product design; and 25 depressed patients, who were also medicated and in remission. Strong and Ketter put everyone through a battery of tests consisting of questionnaires that identified temperament traits and paper-and-pencil tests that assessed creativity.

The temperament portion of the study revealed that creative, bipolar and depressed subjects all expressed more negative emotions – they were more melancholic, neurotic, and irritable – than the healthy group. And creative and bipolar people tended to be more open to new experiences than either depressed or healthy individuals. Overall, Strong says their study showed that the creative graduate students shared more traits with bipolar patients than with the healthy controls.

Strong says certain features of temperament, such as having a melancholy outlook or a cranky disposition, seem to dominate in bipolar people long before they are diagnosed–and persist even after they recover with medical care. And those traits, the researchers theorize, might enhance creativity. "Our sense is that there is something about bipolar disorder that confers an advantage in people who are creative already," Strong says.

The creativity portion of the study seemed to bear out that hypothesis, particularly the results from one well-established measure called the Barron-Welsh Art Scale. This scale consists of 86 black-and-white drawings that range from simple shapes, such as a circle or an arrow, to others that look like chicken scratchings or notebook doodlings. "It's just all these ugly little pictures," Strong explains. All the subjects have to do, she says, is indicate whether they like them or not. The test doesn't require any degree of artistic sophistication; all it takes is a gut-level reaction.

Bipolar patients and creative individuals tested similarly on the scale, scoring almost 50 percent higher than did the depressed or healthy study volunteers. A high score is supposed to reflect a preference for complexity and asymmetry. But Strong noticed that the high scorers disliked more pictures than they liked. Both bipolar patients and creative individuals were more apt to say, "I don't like that," she says. And that ability to summon negative emotions, she hypothesizes, may help the creative process. "The advantage doesn't seem to be from a selective liking of complexity or asymmetry; it seems to be more related to an ability to dislike things and act on [that feeling]," Ketter says. If an artist is happy with the way things are, there's really no impetus to make changes. Discontent, he reasons, may be the mother of invention.

Five years ago, psychiatrist Charlotte Waddell of the University of British Columbia reviewed the results of 29 reports published between 1925 and 1995 that examined the link between creativity and mental illness. She criticized many of the studies' authors for "enthusiastically promoting an association…despite a lack of scientific evidence." One major shortcoming, she found, was that most of the early studies failed to use standard diagnostic criteria for mental illness. But Waddell's biggest beef is that the scientists couldn't seem to agree on a definition of creativity. At least two-thirds of the modern investigations looked at well-known individuals who society deemed creative, such as Nobel laureates. Commenting upon Strong and Ketter's new study, Waddell says: "It's unclear how 'creative' people were defined or selected,…[which leaves] the possibility of bias from the outset."

Ketter concedes that there is an advantage to studying the "eminent" creativity of celebrated artists: "There is wide agreement based on obvious success in the arts. These are people who have pictures hanging in the National Gallery of Art." Although he agrees that everyday creativity is indeed harder to define, Ketter says the advantage of his and Strong's approach is the potential to apply the insights to real-life situations. The researchers say their study is one of the better attempts to date at taking the question into the realm of everyday creativity. "We looked for people who are bright, innovative, and not only have interesting ideas but actually produce something," he says.

The Stanford investigators walked into their research "with open eyes," Ketter says–fully aware of the methodological challenges. As difficult as it is to define, creativity is even more difficult to quantify. There are literally hundreds of creativity tests, measuring different aspects of the complex intellectual and emotional concept of creativity. Some, like the Torrence Tests of Creative Thinking, or the Guilford Battery, purport to assess "pure" creativity. These tests identify styles of thinking–like the ability to produce novel ideas and unusual responses to questions–that are judged to be important to the creative process.

The Barron-Welsh scale captures some facets of creativity, but not the whole picture, Strong says. Still, in the Stanford study, the scale was able to distinguish their creative graduate students from the other groups, which gives the findings more credibility. And Barbara Kerr, a psychologist at Arizona State University who has reviewed many of the standard creativity tests, says that the Barron-Welsh scale "is probably one of the best measures of artistic ability, and to some degree artistic originality."

Strong and Ketter's results suggest that the Barron-Welsh scale is picking up on affective, or "feeling" aspects of creativity rather than cognitive, or "thinking" components. In both bipolar patients and healthy creative individuals, their emotions are closer to the surface, giving them readier access, and in some cases facilitating inventiveness. But, Ketter adds, "there are many pathways to creativity."

Because the popular association of manic-depression with creativity is so pervasive, many artistic bipolar patients resist treatment, fearing that the mood-stabilizing drugs will rob them of their inspiration. But Strong and Ketter say their study indicates that these fears may be largely unfounded. Being successfully medicated, Ketter says, does not have to be an impediment to creativity.

The underlying problem in bipolar disorder seems to be a neurochemical imbalance. Different parts of the brain communicate with each other via chemical messengers called neurotransmitters. In such a sensitive system, things can easily go wrong: If there's too much neurotransmitter, or not enough, communication breaks down. Neuroscientists have found that in bipolar patients, the parts of the brain that regulate mood make too much of a class of neurotransmitters called monoamines.

Lithium and other classic mood-stabilizing drugs for treating bipolar disorder, such as the anticonvulsants Depakote and Tegretol, work by normalizing monoamine levels in the brain. While they level out the emotional highs and lows, keeping patients on an even keel, they don't fix the fundamental neurochemical problem. Most patients have to be medicated for the rest of their lives. And these drugs have side effects, including sluggishness, weight gain, and sexual dysfunction.

Strong says many of their patients, some of whom earn their living as writers and artists, report that the medicines also blunt emotion and stifle their brainstorming abilities. "It's a huge concern for people who are creative," Strong says. "These folks can deal with sexual side effects and weight gain, but if they lose their creativity they may lose their jobs"

Ketter points out that while some medications may flatten emotional range, ongoing depression has the same effect. Although it's important for doctors caring for bipolar artists or writers to be mindful of the effects of drugs, he says, the top priority has to be getting patients healthy. When they are left untreated, their manic and depressive episodes become more frequent and more severe over time, and they also become less responsive to medication. Ketter does note that patients taking the drug Depakote tended to have higher creativity scores than patients taking other combinations of drugs. But the numbers were far too small to draw any conclusions, he says. Nonetheless, the finding suggests that some medications may preserve productivity better than others.

And, even medicated, the bipolar patients in Strong and Ketter's study were much more creative than the average person, as measured by the Barron-Welsh scale. Yet one wonders how they might have scored if they hadn't been taking the drugs at all. In the early days of studying mental illness in creative people, researchers proposed that the ability to produce art was tied to the ups and downs of manic depression's emotional rollercoaster. The theory was that thoughts flow more freely in mildly manic states, and that a lack of the usual self-censorship allowed novel associations to be made; and moderate depression could later play an editorial role, tempering the excesses of mania. Certainly, that may be one path to creativity. But there's a tradeoff. In severe mania, thoughts become disordered which can lead to dangerous behavior and acute depression can paralyze thought processes.

The nexus between madness and genius is far too complicated to be explained by the idea that euphoria simply sets the stage for brilliant brainstorming. After all, most bipolar patients don't possess extraordinary artistic gifts, and most artists don't suffer extreme mood swings. The Stanford work suggests that underlying temperament traits could either predispose a person to developing bipolar disorder or incline them toward accomplishments in the arts–or both. Temperament is something people are born with–it may even be hardwired in the brain–and it doesn't change over the course of a lifetime. Bipolar brains may be wired to be more emotionally volatile than normal. And while that may be painful at the extremes of the emotional spectrum, manic-depressive patients who are stabilized may be able to harness those emotions and pour them into creative pursuits.

The key seems to be finding the right medication, in the right dose, to control extreme mood swings while still allowing the patients access to their emotions. Strong and Ketter believe that new and better treatments can alleviate psychic distress without snuffing the creative spark. In the meantime, the researchers say, patients and their loved ones can take heart. Says Strong, "There is something about the disorder that is a silver lining." SN

Virginia Woolf's note to her husband

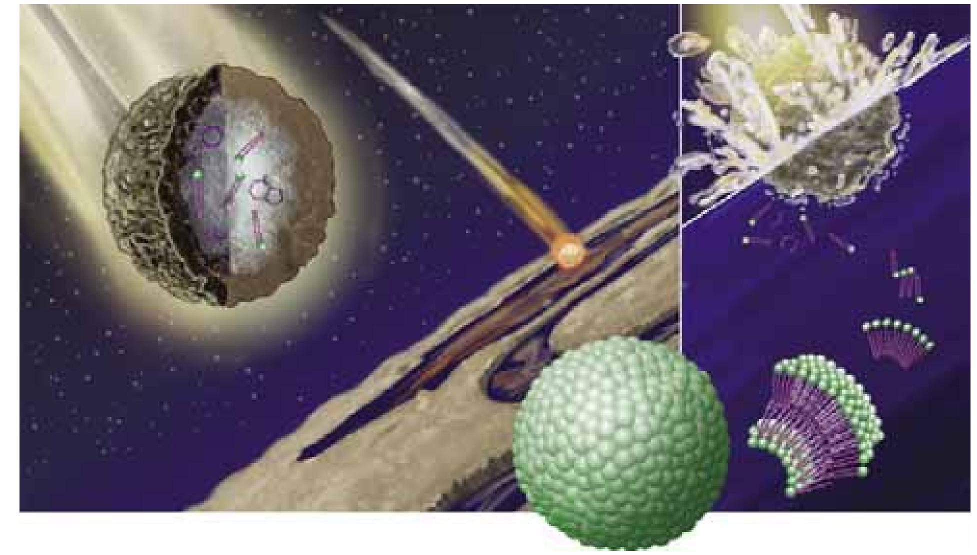
On March 28, 1941, Virginia Woolf put a large stone in her coat pocket and drowned herself in a river.

Dearest,

I feel certain I am going mad again. I feel we can't go through another of those terrible times. And I shan't recover this time. I begin to hear voices, and I can't concentrate. So I am doing what seems the best thing to do. You have given me the greatest possible happiness. You have been in every way all that anyone could be. I don't think two people could have been happier till this terrible disease came. I can't fight any longer. I know that I am spoiling your life, that without me you could work. And you will I know. You see I can't even write this properly. I can't read. What I want to say is I owe all the happiness of my life to you. You have been entirely patient with me and incredibly good. I want to say that — everybody knows it. If anybody could have saved me it would have been you. Everything has gone from me but the certainty of your goodness. I can't go on spoiling your life any longer.

I don't think two people could have been happier than we have been.

V.



Recipe for Life

The building blocks for life on Earth may have come from someplace far, far away.

By SHAWNA WILLIAMS / ILLUSTRATION by NICOLLE RAGER

FIFTY YEARS AGO, a graduate student named Stanley Miller tried to create life–or something like it–in a chemistry lab at the University of Chicago. To approximate the ocean of primitive Earth, he filled a glass bulb with water, methane, ammonia, and hydrogen, the chemicals that scientists speculated had dominated the early atmosphere. Then Miller hooked two electrodes to the bulb to simulate lightning, and flipped the switch.

Miller let the mixture brew for a week. The "ocean" bubbled, converting to vapor that rose to the "atmosphere," where a continuous current zapped the gas, imitating an electrical storm. Inside the glass bulb was a condensing column that worked like a cold soda can on a hot day: When vapor hit the column, the gas turned into liquid. Then it trickled back into the ocean to start the process again.

While Miller didn't find a growling monster bursting out of the flask at the end, what he did find was almost as exciting: The flask contained amino acids, vital components of every living thing.

The implications were huge: If biological chemicals were so easy to make from scratch, many researchers believed that the other steps to generating life would soon fall into place. "It's maybe hard for us to really appreciate how big the [experiment's] impact was at the time," says Max Bernstein, a chemist at the NASA Ames Research Center near San Jose, California. Miller and his colleagues "were seeing what we think of as the absolute basic components of life. So it seemed like it would be a short time before the origin of life would be understood." Instead, 50 years later, Bernstein says, "In a way we know more–but we think we know less."

Researchers soon found that adenine, one of the bases of DNA, could form under similar conditions. And in 1969, a meteorite chock-full of amino acids fell near Murchison, Australia, hinting that some of life's ingredients might have come from space. Yet try as they might, scientists have been unable to use these ingredients to create even the most lowly of organisms in the lab.

Half a century of exploration has called into question Miller's original premise that life began in the oceans, and alternative explanations remain unproven. The idea that the orchestrated complexity of life could have come out of random non-life is totally counterintuitive. "Most scientists find it too daunting a problem," says Dave Deamer, a biochemist at the University of California at Santa Cruz. Though modern science can put a man on the moon and split the atom, the recipe for pond scum remains stubbornly elusive.

The puzzle is made more intimidating by the fact that, with no physical record of the first organisms, there's no way to definitively test theories of how they came about. At best, says Deamer, scientists will be able to set up model systems to show how life might have arisen.

Bernstein and Deamer are among the scientists engaged in this quest. Rather than focusing on the planet's early oceans for answers, they have both looked to outer space for clues. They are exploring the idea that we may owe our lives to crucial compounds that formed in tiny ice particles and rode down to the Earth on meteorites or space dust.

The tallest hurdle to tracing the origin of life is that even the most basic form of self-sustaining life imaginable would have had to perform many tasks at the same time, such as harvesting energy from sunlight, chemicals, or heat, and using that energy to reproduce itself.

It also must have had a genetic code to outline the basics of these processes, and a way of passing that code on to its descendants that allowed for some genetic change, but not too much. It must, in other words, have been able to evolve–otherwise life could never have gotten past that primitive first step. That's a tall order for something that came together by chance, because it requires a melange of complex chemicals.

The organic chemicals needed for life could not form from scratch in today's oceans and ponds, because our atmosphere holds too much oxygen; oxygen reacts with organic molecules, ripping them apart before they have a chance of doing anything interesting. Fifty years ago, scientists conjectured that primitive Earth had an atmosphere rich in hydrogen rather than oxygen, one that would have favored the formation of long organic molecules, like amino acids, from carbon and hydrogen.

However, geologists now think that although the Earth's atmosphere contained less oxygen during the planet's early existence than it does today, it still had too much oxygen and too little hydrogen to favor production of complex molecules. Thus, large amounts of organic molecules could not have formed in the ocean, as Miller thought, to form the rich "primordial soup" that he simulated in his experiment.

SINCE 1953, a boggling cacophony of other hypotheses has arisen to explain life's origins. Besides those who think we owe our lives to cosmic dust, some scientists subscribe to a modified version of the primordial soup theory, while others think life sprang from biochemical reactions at heat vents deep in the sea.

Biochemist A.G. Cairns-Smith, of the University of Glasgow in Scotland, argues that the first genetic material might have been a self-replicating crystal. Gunter Wachtershauser, a German patent attorney who's become a respected origin-of-life theorist in his spare time, postulates that life initially came about not in cells, but developed on the surfaces of special minerals that promoted crucial reactions. Francis Crick, one of the discoverers of the structure of DNA, even suggested that intelligent beings elsewhere might have "seeded" the Earth with extraterrestrial bacteria.

Rather than crediting little green men with our existence, Bernstein has been studying a more prosaic breed of space invader: meteorites. On a recent afternoon at NASA Ames, Bernstein pauses in front of a display case of meteorites in the lobby of the building where he works. Most of them look like ordinary rocks; a dime-sized square of Martian rock mounted on a piece of wood resembles concrete.

For Bernstein, meteorites are far more than museum curiosities. He is particularly interested in those known as carbonaceous chondrites, which bring organic chemicals with them to Earth. "When a meteorite falls to Earth, you can pick it up and analyze it, and be looking at perhaps a piece of the same asteroid or comet that fed the early Earth. These are things, literally, that are 4.5 billion years old, and you can hold them in your hand," he says. By "fed," he means that organic molecules from carbonaceous chondrites might have served as the starting materials for Earth's first life forms.

In his first-floor lab down the hall, Bernstein runs a deep-space version of Miller's famous experiment. Instead of the relatively warm environment of the primordial soup experiments, he creates a cold, harsh vacuum simulating conditions in outer space to see what kinds of reactions might happen there. Common chemical sense dictates that very little will happen in a frigid environment (which is why food doesn't spoil in the freezer). That's because reactions require some energy to get started, usually from heat. Still, molecules frozen in ice crystals in space do get regularly zapped by strong ultraviolet and other radiation from stars—much more than what we get on Earth, where our atmosphere protects us. Such jolts might jar a molecule into reacting with its neighbor, prompting them to stick together, Bernstein says. This bigger new molecule may later bond with third molecule, and so on and so forth, until a complex molecule emerges.

Such a process could take up to tens of millions of years in space, but Bernstein compresses the timescale into less than an hour in his studies. The first step is to look at telescope scans of the distant dust cloud whose conditions Bernstein wants to recreate. Different chemicals give off different colors of light, providing him clues to the gases that make up the dust cloud.

He then allows a similar mixture of gases to slowly leak into the vacuum chamber, where they freeze onto an extremely cold surface. The temperature inside is about -445°F, cold enough that the ice doesn't even form crystals—just an amorphous blob. Then Bernstein bombards the frozen goo with UV radiation. After allowing time for reactions to take place, Bernstein analyzes the ice for substances such as the amino acids that make up proteins, and quinones, molecules that harvest energy in the cell—and has found that they're there, though in vanishingly small amounts.

Bernstein aims to find out where the organic molecules in carbonaceous chondrites come from. They may have formed in comets or meteorites with cores of ice, or even of water. Alternatively, the molecules could have been spawned billions of years ago in the fledgling solar system, when it was just a massive gas cloud infused with tiny grains of ice. To Bernstein, the difference between the two scenarios is crucial. It's a question of universality: All solar systems condensed from interstellar gas clouds, so if biological chemicals formed within those gaseous mixtures, then "your starting materials are there in all the solar systems in the whole galaxy," he says.

But even if meteorites provided the seeds to the first complex biomolecules, how did those amino acids and quinones transform into life? Assuming that early life did build itself from space chemicals, then some scientists have simply traded distant dust clouds for warm oceans. The gap between non-life and life, after 50 years of conjecture and experiments, looms as large as ever.

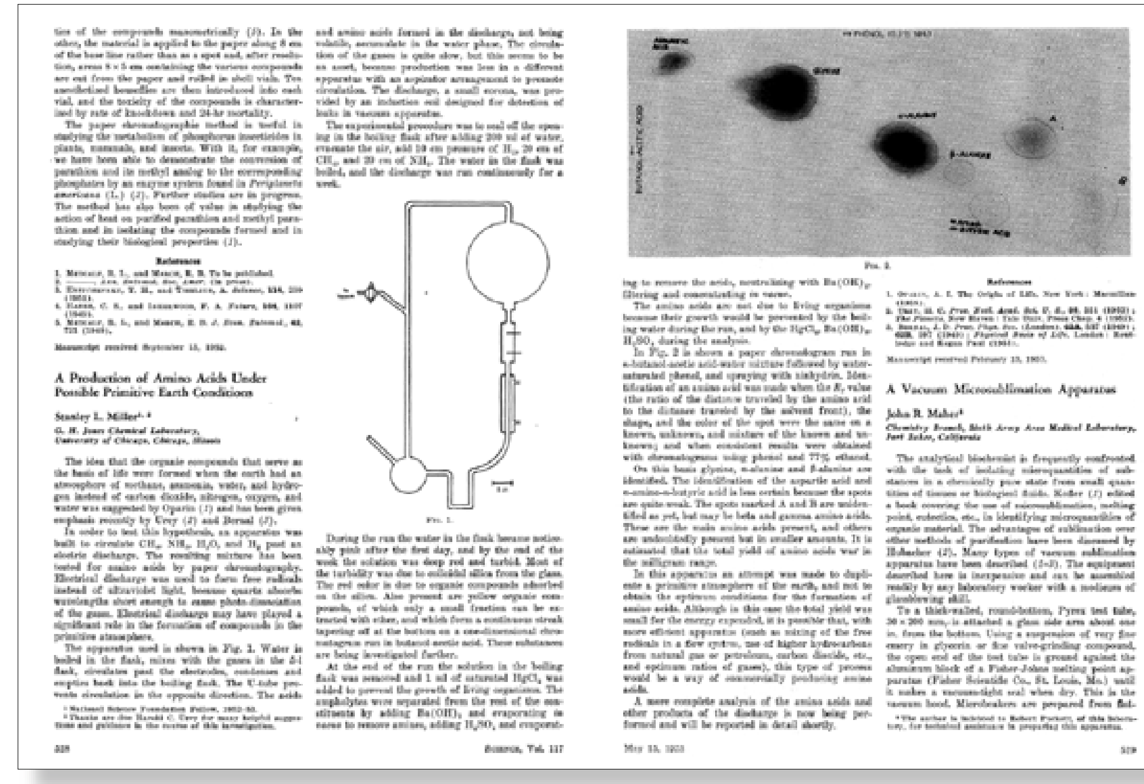
Enter Dave Deamer's research. Deamer brings an unusual approach to the origin-of-life problem: Instead of focusing on how the inner workings of the cell fell into place, he's working from the outside in—starting with the cell's housing, components of which he believes might have come from meteorites.

"Life as we know it began when it became cellular," he says. In other words, the first organisms had to have a barrier separating themselves from the chaotic outer world. They needed skin, a membrane. With this idea in mind, Deamer decided to see whether membranes could spontaneously arise from the raw materials in meteorites—which isn't as wacky as it seems. Certain molecules, detergents, have one end that likes to mingle with water and one end that, like grease, does not. When mixed with water, these detergents assemble into tiny spheres, lining themselves up into a double-layer barrier with their water-soluble ends facing out and their insoluble ends protected on the inside. These self-organizing molecules are the main components of cell membranes.

Deamer theorized that if these kinds of spheres could form easily from extraterrestrial molecules that fell into water, that might be the kind of jump-start life needed. So he extracted organic molecules from a carbonaceous chondrite, added them to water—and found that spheres about the size of bacteria formed. Here was proof that the meteorite contained detergent molecules.

Deamer found that the most prevalent detergent molecule in the meteorite was one called nononoic acid. His recipe for bacteria-sized membranes has the simple elegance of a middle school science fair project: Put one drop of nononoic acid in a drop of water on a slide, then add one drop fluorescent dye. A glimpse at the mixture under the microscope reveals round hollow spheres of different sizes, drifting around like bacterial ghosts. Under ultraviolet light, some of the spheres glow green because they contain the dye, while others loom darkly. The black spheres are intact membranes that have excluded the dye, Deamer explains, while the glowing spheres have slight flaws that allow some exchange with the environment. Such flaws would have been needed to allow the flow of nutrients into the very first cells, he believes.

Mix water with amino acids from an asteroid and some naturally occurring detergent molecules, and you might have the beginnings of a living cell.



Stanley Miller's 1953 paper in *Science*.

Using membranes as a starting point, Deamer is now trying to create an artificial cell in the lab. Scientists have long theorized that a molecule called RNA functioned in early cells as the carrier of genetic information before DNA evolved, so he did another experiment: He mixed building blocks of RNA—called nucleotides—with water, and found that freezing the solution could actually bring the pieces together in short chains. These chains could be coaxed to grow only as long as eight nucleotides each—a promising result, although the smallest useful RNA chains are at least 50 to 100 nucleotides long.

Deamer concedes that RNA probably did not arise *ab initio*, but instead evolved from a simpler molecule. "There must have been some scaffolding, we call it, that provided a kind of sequence information for this, but we simply haven't discovered it because it no longer exists," he says.

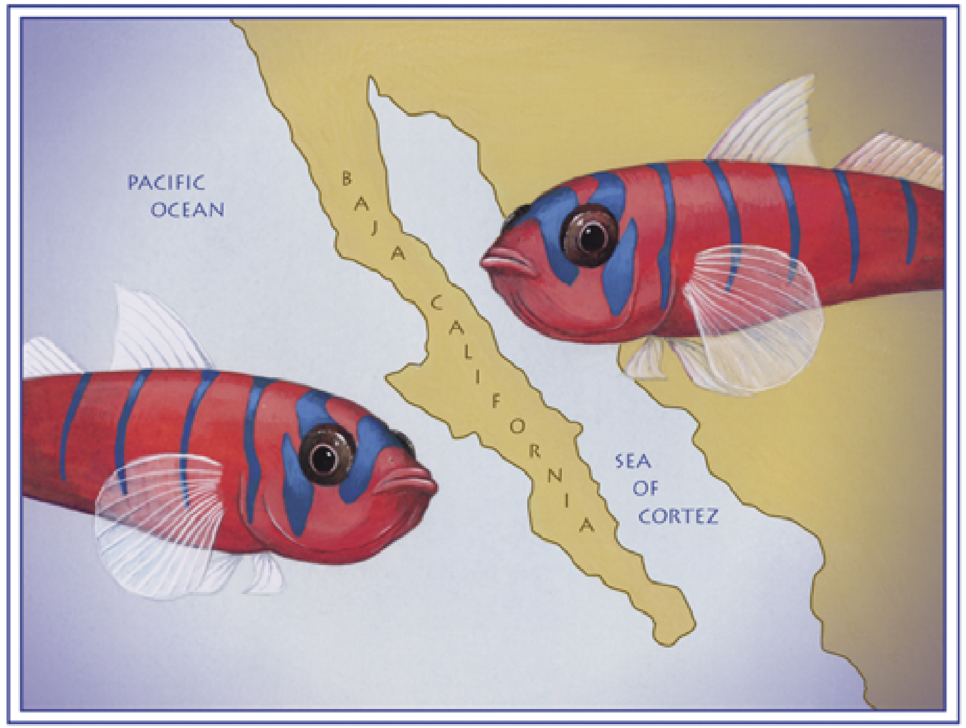
Deamer's experiments have led him to question the supposition that life originated in the ocean. He has found that in saltwater, detergents form clumps, not spheres, so he theorizes that a freshwater pond would have been a more hospitable environment. And from his RNA experiment, he surmises that the pond where life originated would probably have been cold, not warm.

As he sees it, meteorites could have fallen in or near a pond, bringing chemicals with them. Evaporation might have concentrated the chemicals, making them more likely to react with each other. Detergent spheres and short RNA strands would have formed separately, but over time, he thinks, a few RNA molecules would have been enclosed within some spheres by chance. And after many false starts, a stretch of RNA that could reproduce itself could have ended up inside a sphere. That would leave one more major hurdle to make Deamer's hypothesis viable: To replicate itself, this promising sphere would have needed to produce its own detergent molecules.

Fellow origin-of-life scientists aren't holding their breath. Leslie Orgel, a Salk Institute biochemist, calls the idea that life's building blocks came from space a "perfectly good theory," but says, "at the moment there isn't enough evidence to choose where molecules came from." Similarly, evolutionary biologist Carl Woese of the University of Illinois says that no origin of life theory will convince him unless it produces a system of self-replicating chemical cycles, such as those that make energy or copy genetic material. "I don't think we know enough to be sure of any of these suggestions," he says.

The origin of life is a fascinating problem, one that A.G. Cairns-Smith, the Scottish biochemist, has compared to a Sherlock Holmes story. But this greatest of scientific mysteries is far more complicated than any murder. Fifty years after Miller's famous experiment, it's impossible to say whether any of the detectives are on the right track. Judging by the current state of the origin-of-life field, it seems unlikely that the year 2053 will find children using high-tech chemistry sets to generate primitive organisms in ice cube trays in their freezers. Perhaps the origin-of-life field itself is stuck in a self-replicating cycle, a succession of red herrings and disappointments.

Or maybe not. If nothing else, over the decades biologists have gained a much greater understanding of—and appreciation for—life's awesome complexity. The double-helix structure of DNA was discovered in 1953, and just 50 years later, scientists have mapped the entire human genome and possess a basic understanding of how cells work. If life does not yield all its secrets in the coming decades, we can be sure that what we do learn will continue to astound us. SN



Fish Tales

Strange goings-on around Baja California.

By NICOLE STRICKER / ILLUSTRATION by ANDREW RECHER

"THIS IS AN ANIMAL that lives inside the anus of sea cucumbers," says Giacomo Bernardi, holding an oblong bottle at eye level to examine the white, 10-inch-long, snakelike specimen inside. Bernardi—a tanned, balding scientist clad in a sweatshirt, shorts, and sneakers—is showing off the fish he has collected around the world, from the anal albino inhabitant to colorful coral reef dwellers.

Jars of pickled fish line the shelves in Bernardi's office and the countertops in his lab at the University of California's Long Marine Laboratory in Santa Cruz. Bernardi moves to a refrigerator, opens the door, and produces a clear plastic tube. Inside, several quarter-sized tropical damselfish float in alcohol. These adult fish are black with a small white dot near the eye, the remnants of a white streak that fades with maturity, Bernardi explains. He then opens one of many boxes to reveal rows of vials—each one encasing a miniature, M&M-sized juvenile damselfish, white stripe and all. Although these critters look identical, a peek at DNA harvested from their gills can reveal a surprise: that a group appearing to comprise only one type of fish might actually harbor several species.

Bernardi is an evolutionary biologist who ponders marine creatures for the same reason Darwin scrutinized finches: to learn what drives the diversity of life. "There are 25,000 species of fish, which is more than all the land vertebrates put together," Bernardi says. "But people don't exactly understand how species of fish are created." Gaining insights into that process could help scientists estimate the variety of fish in the sea. These estimates are important because the number of species and the abundance of each animal help scientists decide which ocean zones deserve protection.

By analyzing tiny differences in DNA, Bernardi can determine how closely related members of a given species are—and even detect when some members have begun to split off into new subspecies. "Our tools allow us to uncover things you can't really see," he says.

Indeed, Bernardi has recently captured molecular snapshots of evolution in action among fish swimming in the waters off the Baja California peninsula. His laboratory trove includes a haul of sandbass, rockfish, and other marine creatures. DNA analyses of the specimens suggest that some types of fish began forming new species when the Baja peninsula rose from the ocean millions of years ago, dividing a single population into two distinct groups, one on each side of the wall formed by the peninsula. The research is a prime example of how geologic events can produce new species—and also underscores the fact that the ocean harbors far more variety in its denizens than anyone realized.

CATALOGUING the planet's inhabitants is the mother of all census projects. Scientists have so far documented nearly 2 million species of bacteria, plants, fungi, and animals. Yet the globe hosts 5 million to 30 million species of organisms, biologists estimate. Every time scientists discover new life forms, taxonomists toil to properly categorize the creatures. Part of the challenge lies in the definition of a species—there is no hard-and-fast rule. Looks and lifestyle can offer a clue; animals that generally look alike, live in a similar habitat, and prey on the same food source are typically classified together. But comparable appearances and lifestyles can be deceiving. For example, sharks and dolphins are both large, finned swimmers that eat smaller fish, yet sharks are a type of fish and dolphins are a type of mammal. The two groups have completely separate ancestral lines.

Among animals that are closely related, the task of categorizing species can be even more daunting. Creatures that look and act similarly sometimes belong to different classification groups—consider the 450 species of North American ladybugs. Conversely, one group can comprise many creatures that seem very different from one another. Rottweilers and poodles, for instance, are members of the same species. Mating success or failure can additionally help scientists to properly classify animals; a species is often defined by the ability of members to mate and produce fertile offspring. Yet biologists cannot always assess breeding feasibility, especially when different populations of the same species don't normally encounter each other in nature. For example, the bottlenose dolphin species contains Atlantic and Pacific varieties, yet it's unknown whether the two groups can actually breed with each other.

The presence of the Baja peninsula is causing new species to form.

While such questions may have confounded Darwin's peers, modern scientists have an advantage—they can scrutinize the molecular makeup of organisms for fresh insights. The more genetic differences that exist between animals within a species, the more likely it is that the population has split into subspecies that can no longer interbreed.

Such subgroups are most likely to form within a "disjunct" species—a species whose populations have been geographically separated from each other into two discrete regions. The human species experienced small-scale disjunction, for instance, when the demilitarized zone of Germany's Berlin Wall divided families for three decades. On the evolutionary scale, barriers such as mountains, oceans, or simply large distances can suddenly split land-dwelling populations. Such obstacles are so vast and permanent that disjunct creatures sometimes eventually evolve into different subspecies.

In the sea, land masses, water temperatures, or ecological niches such as reefs or tide pools can corral marine life. One well-studied barrier is the Isthmus of Panama, connecting North and South America. When this strip of land jutted out of the ocean 3.5 million years ago, it divided populations into Pacific and Caribbean groups. Today, several species are found on both sides of the divide. Yet biologists have detected molecular changes revealing that a number of those disjunct species have began to diverge into distinct subgroups.

HOPING TO DISCOVER more emerging subspecies, Bernardi recently headed to Baja California, a region chock-full of known disjunct species that have not yet been studied on a molecular level. The Baja peninsula is a narrow land strip extending 800 miles south of California. The Pacific Ocean laps at its western shores, while on the east, the Sea of Cortez separates the peninsula from mainland Mexico. The waters surrounding the peninsula teem with fish, but only a handful of species are sharply divided by the geography. Those species reside in the cool water around the northern portion of Baja California, and two barriers fence them in: the land itself and warm southern waters.

Baja California represents one of the rare regions where genetic surveys of disjunct species are possible. "There are very few places where you have all the good things to study—[where] you can sample the species, you know what they are, you know what the currents are, you know the geologic history of the place, you happen to find an abundance of individuals," Bernardi says.

So Bernardi braved chilly waters at 19 locations up and down both sides of Baja California to gather his gilled guinea pigs. Sometimes he used a snorkel and a handheld net, other times he speared his quarry while scuba diving. Occasionally he needed only to wade in tide pools. Bernardi collected fish representing nine disjunct species, including variations of sandbass, rockfish, perch, and grunion. He nabbed anywhere from one to 44 fish at each site and hauled more than 200 pickled specimens back to his laboratory for genetic analysis.

After harvesting DNA from the fish he'd collected, Bernardi compared the genetic sequences of individual fish within a single species. Although genetic makeup is bound to vary among individuals of one species, more than 99 percent of their DNA is estimated to be identical. The amount of DNA variability among organisms is a little like the differences and similarities among automobiles. Non-essentials such as color and carpeting vary widely among cars, just as genes for coloring or personality differ in individual animals. More fundamental aspects such as engine and frame design will be common to a particular class of car; likewise, related species share many fundamental genes, such as those dictating size and shape. And essentials like pistons and tires vary little, just as certain genes are virtually identical from mice to men. To effectively study the differences between his disjunct fish, Bernardi needed to focus on a genetic region known to foster just the right amount of variability.

He chose a narrow segment of DNA called the D-loop control region. The D-loop resides within the mitochondria, the energy generators of the cell that harbor their own miniature set of genes. But the D-loop itself doesn't encode a gene—it instead serves as sort of genetic filler. So, in the same way that the upholstery inside a car doesn't affect its performance, random mutations within this stretch don't help or hinder the survival of a fish species through the forces of natural selection. As a result, D-loop DNA changes are less likely to sicken or kill an animal (and thus more likely to be passed to the next generation) than mutations in sections that encode genes. An average animal gene might accumulate eight mutations over a million years, whereas the D-loop could chalk up as many as 40.

Sequences of D-loop DNA are similar among animals that are breeding and exchanging genes with each other, but genetically isolated populations rack up differences quickly on an evolutionary timescale. So this rapidly changing region serves as a sort of molecular clock: The greater the number of DNA differences, the longer it has been since the groups have diverged.

FOR EACH of the nine disjunct Baja species, Bernardi scrutinized and compared the DNA of at least five fish from the Pacific side of the Baja peninsula and five that had swum in the Sea of Cortez. A computer analysis of their genetic differences helped him rank how closely related the fish in each species were to each other. This information then allowed Bernardi to build a kind of evolutionary family tree, which clusters the fish into branches according to their similarities.

His results show a genetic divergence brewing within several of the groups. For example, the evolutionary tree he generated for the grunion species showed a rift was forming between fish from the Pacific Ocean and those from the Sea of Cortez: The grunion living on one side of the peninsula were more closely related to each other than to grunion from the other side. He saw a similar pattern in two-thirds of the species overall. "The population used to be continuous, and then the geologic formation of Baja California physically separated them. And then they slowly diverged genetically," Bernardi explains.

For some of these diverging species, the number of DNA discrepancies suggests that the animals have been accumulating differences for about 2.5 million years–dating back to around the same period when the Baja peninsula formed. The data also hint that other species started branching apart less than 1 million years ago, roughly the time when an inland seaway closed, preventing marine life from crossing the peninsula. Bernardi's findings suggest that the presence of the Baja peninsula is in fact causing new species to form.

At the same time, Bernardi found that four of the species he studied are genetically uniform across the Baja; those species don't seem to be splitting. That finding suggests that fish in those groups aren't truly separated and might be migrating around the southern tip of the peninsula. Alternatively, the uniform distribution could simply mean that those populations haven't been separated long enough to accumulate DNA differences.

Bernardi wonders if recent glacial events, which temporarily chilled the ocean about 10,000 years ago, could account for the consistency of these animals across the peninsula. A cooling of the seas surrounding the southern peninsula would allow migration of the cold-water fish, which would be restricted again when the waters warmed back up. Because separations occurring less than 150,000 years ago are virtually invisible to the genetic technique, Bernardi can't distinguish recent splits from ongoing migrations.

Whatever the explanation, Bernardi's work paints a clearer picture of the diversity of fish around Baja California. Although he is not petitioning to reclassify the Baja's eastern grunion in a different species from its western grunion, he says it is important to realize that the two populations are not homogeneous. "We have to acknowledge the fact that we're talking about two general groups that are separated from each other–not only in space but also in time, by 1 million years," he says.

YET IT IS THE DISTANCE in time that worries some evolutionary biologists, who consider molecular clock analyses troublesome. Ideally, the DNA region chosen as a molecular clock (the D-loop, in Bernardi's case) incurs random mutations that don't affect the animal's survival. Any mutation that confers a detriment or benefit would skew the timepiece.

But researchers disagree over which regions of DNA, if any, accumulate harmless mutations regularly over time. "One of the problems is that people who use these molecular data as clocks have to make a number of assumptions," says William Fink, an evolutionary biologist at the University of Michigan in Ann Arbor. "What they're assuming is that the molecules they're looking at are basically evolving randomly…. That's hard to be sure about."

Also, DNA changes are not as predictable as the ticks of a clock–mutations do not necessarily occur once every so-many years. "It doesn't always change regularly with time," says geneticist Carol Stepien of Cleveland State University in Ohio. "That gives you slop in your clock." But, she adds, the technique is widely accepted among evolutionary biologists, and she herself uses it. "You can tell a very interesting story if you use a molecular clock."

Fink and Stepien both agree, however, that scientists can bolster this kind of data by verifying how fast their clock ticks. One way to do that is to compare the estimated dates of species-branching events with those of known geologic events, such as creation of the Isthmus of Panama. If the molecular clock predicts that the branching happened around the same time as the shift in geology, researchers can be more confident that their timepiece ticks accurately. "When groups are separated on either side of the isthmus, we know when the door closed," says Stepien. "When we have a clear separation of groups, we can calibrate a molecular clock."

In the case of Bernardi's disjunct Baja fish, one lucky finding enables an extra measure of calibration. Unlike the Isthmus of Panama, the Baja peninsula is more like a door left ajar–it formed a "leaky" barrier that did not completely separate marine populations. This leakiness makes it more difficult for Bernardi to establish a firm timeline when using DNA mutations to estimate the years gone by. Bernardi would need to compare D-loop mutations among fish separated by a firmly closed door to calibrate the tickings of his molecular clock. It just so happens that one type of fish that's forming subspecies across the Baja peninsula, the sargo, has cousins that were separated by the Isthmus of Panama. This rare find–two closely related disjunct species–enables Bernardi to compare his estimates of mutation rates to two geologic events. With his precisely calibrated molecular clock, Bernardi is confident that formation of the Baja peninsula triggered subspecies evolution.

SUCH INVESTIGATIONS allow scientists to peer beneath the sea's surface and take stock of what's living there. "We have a system that allows us to understand how new species are being created," Bernardi says. "If you don't understand that, it's really difficult to understand how biodiversity is generated in the ocean."

Understanding aquatic diversity is critical when scientists decide the boundaries of federally protected marine reserves. Conservation goals can change when scientists learn that one species of, say, rockfish, is in fact two populations that no longer exchange genes with each other.

"We use that [type of] info to try to decide how we want to manage those areas," says Steve Palumbi, a biologist at Stanford University's Hopkins Marine Station in Pacific Grove, California. "If there's plenty of gene flow, we would manage in a different way than if that gene flow were impossible." In a region such as the northern Baja Peninsula, for instance, if biologists worked toward conserving critters on only one coast, they would be neglecting the closely related, yet distinct subspecies on the other side.

Research such as Bernardi's gives evolutionary biologists a glimpse into how and when new species begin to form. "It provides a great road map into the past," says Palumbi. The study of animal species on a molecular level offers modern scientists a window into evolution that Darwin would envy. Bernardi, for one, does not take this power lightly.

In fact, it sometimes leaves him feeling like he's discovering evolution all over again. Says Bernardi with a wink, "I am Darwin … reincarnated!" SN

Fifty-five million years ago, the Earth heated up dramatically. That's when the evolution of modern mammals really got cooking.

Global Fever

By ELISABETH NADIN / ILLUSTRATION by HOLLY GRAY

IT'S HARD TO BELIEVE that crocodiles used to swim in warm waters off Greenland, or that our primate ancestors once chattered among broad palm fronds in a tropical forest within northern Wyoming. But scientists paint exactly this picture of the world circa 55 million years ago in the Eocene epoch, just 10 million years after the demise of the dinosaurs. During this time, the planet heated up in one of the most rapid and extreme global warming events recorded in geologic history. Sea surface temperatures on Earth rose almost 15 degrees Fahrenheit over a period of a few thousand years–a mere instant in the geologic timescale. And according to geologists Jim Zachos and Paul Koch of the University of California in Santa Cruz, this temperature spike triggered a wholesale reshuffling of life on the planet.

Zachos and Koch study chemical clues in the ocean and land, searching for evidence of how past climate changes altered Earth's ecosystems. Zachos has connected the Eocene heat wave to drastic changes in ocean chemistry that caused a massive die-off of marine microorganisms worldwide. On land, Koch and his colleagues discovered that the global warming spike brought many newly evolved mammals to North America. Oddly enough, the mammals were strikingly smaller than both their ancestors and descendants. The first horse that whinnied in the subtropical forests of Wyoming, for instance, was the size of a modern Siamese cat.

What's more, based on fossils recently unearthed in Asia, the researchers' work has recently provided the first substantive evidence for a controversial theory of where modern mammals came from: Animals living in the hot Eocene world took advantage of warming northern latitudes to make their way from Asia to North America and Europe. These dwarfed creatures went on to evolve into the most common mammals on the planet today, Koch says.

In light of such discoveries, many earth scientists believe that the state of the planet at the beginning of the Eocene era could hold lessons for Earth's future. With greenhouse gases locking in the sun's warmth and global temperatures rising, the planet is heating up at least as fast as it did 55 million years ago, say Zachos and Koch. If global warming continues at its current rate, they speculate that future generations may well see a similar major impact on land and ocean ecosystems.

SIXTY-FIVE million years ago, at the end of the Cretaceous period, an asteroid impact brought an end to the dinosaurs and the Age of Reptiles. The fossil record indicates that mammals, which had lived in obscurity in the shadows of the dinosaurs, flourished soon after the giant reptiles died out. With no large competition for resources, little critters suddenly had a fighting chance to dominate the world. These first

mammals were strange shrewlike creatures with sharp, jagged teeth. But by 55 million years ago, some of these diminutive beasts had grown to 6 feet tall or greater. Though bigger, these were still primitive mammals with short, thick limbs, clumsy feet and hands, and simple teeth capable only of easy maneuvers, like tearing. At the beginning of the Eocene, however, several new mammal groups arrived on the scene, bearing modern features like long, thin legs, feet and hands capable of grasping, and advanced teeth adapted for chewing. We recognize these new animals' direct descendants today–in horses, camels, sheep, cows, and humans.

To zero in on how quickly this evolutionary transition occurred, paleontologists in the early 1900s turned to layers of sediment in northern Wyoming's Bighorn Basin. The basin hosts a dazzling array of plant and animal remains from around 62 million to 52 million years ago that were preserved as sediments slowly filled an ancient river valley. Over 150 years of fossil collection from the site reveals evidence of a warm Eocene world with tropical animal and plant life, like crocodiles and palm trees.

But something changed in the Wyoming habitat, dramatically altering its inhabitants. The mystery of what caused the transition to modern mammals was impenetrable–until pieces of the puzzle were pulled out of the earth in other parts of the world.

The modern oceans hold one of the crucial keys to understanding what had happened long ago. Until the 1960s, little was known about the record of Earth's history stored in seafloor sediments. Then, scientists began probing ocean basins and studying the cores of sediment layers they pulled out. In 1990, a literally groundbreaking analysis of marine sediments showed that the Antarctic Ocean actually heated up, a lot and quickly, in the Eocene.

In an article published in the journal *Nature*, marine scientists James Kennett and Lowell Stott, both then at the University of California in Santa Barbara, reported that not only had the surface of the Antarctic ocean heated up about 20 degrees, but the entire depth of the ocean had warmed, changing its chemistry. The warming coincided with an extinction of almost 40 percent of microorganisms that lived in deep ocean waters, Kennett and Stott wrote.

Zachos, who was doing postdoctoral work at the University of Michigan at the time, reviewed the then-new Kennett and Stott paper. He remembers his reaction: "It was unlike anything I'd seen before." Even after the asteroid crash that wiped out the dinosaurs, says Zachos, the ocean responded less drastically; only surface water chemistry changed. But whatever caused the Eocene warming altered the chemistry of the entire ocean, top to bottom. Zachos decided to investigate, and he's still at it 13 years later, puzzling out the cause of the global warming.

THE TRICK TO tracking the chemistry of ocean water lies in studying two forms of carbon, called isotopes, which have slightly different weights. Most of the carbon in the carbon dioxide we breathe is dubbed ^{12}C, or "light" carbon. It is the most abundant carbon isotope in water, air, and plants. A tiny portion of all carbon in nature is the slightly heavier isotope, ^{13}C. Carbon dioxide dissolved in magma and fossil fuels like methane has a distinctively low amount of the heavy isotope.

Scientists examine ancient sediments and fossils for the relative amounts of heavy and light carbon they hold, in order to figure out where gases in the air and the ocean came from at different times. Marine critters keep great carbon isotope records because they build their shells from the carbon in the water they live in. When these organisms die, their shells settle on the ocean floor, accumulating hundreds of feet of sand grain-sized skeletal remains –a silent testimony to the environment the animals once lived in.

Kennett and Stott found a sharp decrease in the amount of heavy carbon in 55-million-year-old marine fossils, a decline that caused the relative ratio of ^{13}C to ^{12}C to plunge. Most scientists agree that in order to drop the ratio so sharply, a gas with very low amounts of ^{13}C must have literally flooded the atmosphere. Some researchers theorize that numerous volcanoes spewed carbon dioxide directly into the atmosphere.

But in 1995, Gerry Dickens, then a graduate student at the University of Michigan, instead argued that only methane gas had enough light carbon to produce the early Eocene plunge. He proposed that a belch of methane escaped from ice in seafloor sediments as the Earth warmed.

Zachos' studies over the past dozen years support the methane-belch theory. Based on his own and colleagues' recent work, Zachos calculated that up to 2 trillion tons of methane bubbled out of the oceans. Zachos and Dickens say that methane combined with oxygen in the air and water, forming carbon dioxide and essentially suffocating marine life. But whether volcanic activity or a methane belch was the culprit, the greenhouse gas locked in the sun's warmth, sending global temperatures soaring.

Zachos and other experts of past climate change have studied, in excruciating detail, evidence of this heat spike, which they call the Initial Eocene Thermal Maximum. After the Kennett and Stott paper was published, recalls Zachos, "that basically set off a flurry of activity, with people running to all these existing outcrops and cores." They found that the sharp drop in carbon isotopes is recorded in every ocean sediment core that scientists have collected dating to 55 million years ago. Ocean cores from seafloor locations as farflung as Blake's Nose in the north Atlantic off Florida and the Kerguelen Plateau in the southern Indian Ocean all recorded the event. "It was almost within a year or two that we pretty much knew that this was a global signal," Zachos says. "This was not something unique to one ocean."

With the isotope record in hand, paleoclimatologists could link the extinction of seafloor-dwelling critters to increased temperatures in the ocean. "It was exciting: There was a connection that we could attribute to this global warming event," says Zachos. Later, in 1999, researchers from Bremen University in Germany, and the Woods Hole Oceanographic Institution in Massachusetts, showed that the sharp drop in the carbon ratio took place in less than 10,000 years. On a geologic timescale, this shift is virtually instantaneous.

WHILE MARINE SCIENTISTS were busy looking for the carbon isotope signal in ocean cores, earth scientists searched for similar evidence in the land fossil record. Back in 1991, Zachos met Paul Koch, then a new graduate student in Michigan, and the two joined forces. "Paul and I came up with this idea to correlate the marine and terrestrial records using carbon isotopes," recalls Zachos.

Shifts in ocean chemistry directly impact the land because the atmosphere acts as a big conduit, shuttling carbon between ocean and land habitats. On land, plants take up carbon from the air and soil. Animals incorporate that carbon into their teeth and bones through the plants or other animals that they eat. Decay of animals and plants returns the carbon to the soil.

To investigate the land record, Zachos and Koch went to the Bighorn Basin of Wyoming, 100 miles east of Yellowstone National Park. Fossilized plant parts tell us that 55 million years ago, Bighorn Basin was a hot, humid subtropical forest with a river snaking through it. Elm-like trees related to species living today in Panama, Texas, and Oklahoma shed pits on the ancient riverbed. Dawn redwoods, large sequoia related to those now found mainly in central California, sprouted from the fertile floodplains.

Today, the Bighorn Basin is a maze of bare, red-striped gray mudstone hills as far as the eye can see. Each stripe represents an interval of time, composed of sediment that cemented millions of years ago. "You can just see time laid out in front of you," says Gabe Bowen, a graduate student working with Koch in Santa Cruz.

When Koch himself first set to picking apart the sediment layers ten years ago with Zachos and University of Michigan paleontologist Phil Gingerich, they sampled the stripes at 5-meter intervals. They collected preserved teeth and pieces of soil carbonate, in which Koch found the same drop in carbon isotope ratios recorded in marine fossils.

"Organisms on land and in the oceans were responding to this climate change, like, boom, dramatically," remarks Koch.

The land record revealed a few new crucial pieces of information absent in the marine record. First, according to Koch's data, after heating up, the Earth *remained* warm for about 80,000 to 200,000 years. More importantly, digging within a 40-meter sediment stripe that marked this interval of global warming, paleontologists found dramatic changes in the animals living in Bighorn Basin at the dawn of the Eocene. Whole new orders of mammals–groups of closely related families of animals–appeared, including many families never before seen in North America.

Koch and Gingerich were astonished to find that the chemical change recorded in land sediments coincided with one of the most bizarre events in the fossil record: the dwarfing of early mammals. Based on fossil tooth size, paleontologists discovered that within the 40-meter layer representing the hottest temperatures of the early Eocene, animals were half the size of both the mammals that came before them and those that followed. "Before it, there are animals characteristic of the Paleocene. In the 40-meter [layer] there are strange, small animals. Above it, you find normal-sized animals again," says Koch. "There's this genealogical evolution that's dropping forms on the landscape." Animals' weights, estimated from fossil tooth size, were 60 percent lower.

While paleontologists already knew that animals of the Eocene substantially differed from those of the preceding epoch, no one had been able to pinpoint exactly when the transition occurred, or why. The discovery of the carbon isotope shift in Bighorn Basin sediments is the first evidence to unequivocally correlate any stage of mammal evolution to climate change, according to Gingerich.

Why animal size shrank during the heat wave is anybody's guess. Koch and Gingerich, among others, speculate that body size is related to temperature or food supply. Koch says that animals in warm climates tend to have smaller bodies. "Look at white-tailed deer from one end of their geographic range to the other," says Koch. "There's little tiny ones in Guatemala, there's big honkin' ones in Michigan. And this happens in a lot of different species." Still, he says no one knows what the evolutionary mechanism behind the dwarfing is. Some have suggested lack of nutrition made the animals smaller. Plants may have been to blame.

According to Scott Wing, curator of paleobotany at the Smithsonian's Natural History Museum in Washington, D.C., the fossil record shows that plants stayed put during the initial temperature spike. He thinks they forsook the opportunity to spread to new habitats in favor of soaking up the abundant carbon dioxide where they already lived. "It's very odd that so little seems to have happened to plants at that time," says Wing.

Plant resilience during the climate shift may have been bad news for animals, according to recent investigations by Wing and Gingerich. When plants take more carbon into their tissues, they produce less protein in their leaves, so their nutritional value for animals drops. Plants also use the extra carbon to produce more compounds that herbivores find hard to digest. As a result, the researchers speculate, animals grew more slowly.

Not only were early Eocene mammals remarkably small, they were also extremely successful. "These animals are basically the evolutionary roots of a huge radiation in the tree of life. They started whole new branches," says Koch."What's interesting is that not only are there lots of first appearances [of mammals], but they're all first appearances that are going to go on to do lots of business," he says.

The Bighorn Basin research documents the introduction of three entirely new orders of mammals to North America–a major development, considering that there are only 21 orders in total today. The trio includes artiodactyls, or hoofed mammals with an even number of toes, whose direct descendants are cows, pigs, sheep, deer, and camels; perissodactyls, or hoofed animals with an odd number of toes, which gave rise to modern horses, rhinos, and tapirs; and perhaps most meaningful of all, because we are their direct descendants, the primates. Chris Beard, curator of paleontology at the Carnegie Museum of Natural History, agrees with Koch. "What happens right at the boundary, at least in North America, you get modern types of mammals. They're still primitive, but at least they're things we can place on a family tree: ancestral primates, horses and such."

The standing theory is that these mammals were immigrants. Going into the early Eocene, the planet's continents were arranged differently than they currently are; although they sat at roughly the same latitudes as today, continents were bunched closer together. The polar regions weren't covered with ice, but they were still too cold for comfort for mammals. But as the globe warmed during the heat pulse 55 million years ago, researchers speculate, land animals that had been living in mid-latitudes migrated northward in search of cooler haunts. The poles warmed up too, enough to make them more inviting to wandering animals, who moved into northern latitudes. Europe was covered by a shallow sea, leaving only one link–the Bering land bridge–to fresh territory in North America.

Recently, Koch and his student Bowen, working with collaborators at the American Museum of Natural History in New York City and Louisiana State University, unearthed evidence supporting the controversial idea that creatures from Asia made their way across that bridge to North America, giving rise to the modern mammals. That theory was first proposed by 19th century paleontologists Roy Chapman Andrews and Henry Fairfield Osbourne, because they believed evolutionary innovation happened at high latitudes and then spread southward. The Eurasian continent, the biggest landmass positioned at such a high latitude during the Eocene, fit the bill.

Andrews and Chapman failed to find evidence for their theory. Beard, the Carnegie paleontologist, remarks, "Some people have parodied it as a Sherwin Williams model," referring to the paint company's logo that shows paint dripping down over a globe.

Although scientists agree that the same mammals appeared in Asia and North America around the same time, there was no way to know where the creatures had evolved first.

The new findings by Koch's group and his collaborators shed light on that question. They've detected the same initial Eocene carbon isotope signature in fossil soils from China and Mongolia. And from their excavations, they discovered that at least one dwarfed animal type–a creodont, a now-extinct carnivorous, hoofed animal with an odd number of toes–that first showed up 55 million years ago in Bighorn Basin also appeared earlier in two different parts of Mongolia. This work suggests that hoofed, odd-number toed creatures existed in Asia at or before the beginning of the Eocene, says Koch.

Beard says the findings confirm that Asia was the birthplace of modern mammals. "The climate warmed, and that allowed all these animals that had evolved in Asia … to leave Asia and basically take over the world," he says. But other researchers urge caution. "I think the truth is we don't exactly know where most of these animals are coming from," says Gingerich. "The only thing we know for sure about them is that they are coming from somewhere else."

Koch is now busy in Asia trying to find more predecessors of the North American Eocene mammals. He is also trying to link climate change to evolution during other time periods, using fossil teeth and soil minerals to figure out past rainfall and air temperature, and animal diet and migration patterns. Meanwhile, Zachos just returned from a two-month ocean expedition, sampling ancient sediments off Venezuela from the JOIDES Resolution, an ocean drilling vessel. Zachos was looking not only for more evidence of the global impact of warming 55 millions years ago, but also for its cause. He and his shipboard colleagues believe they found more evidence of a giant methane burp at the start of the Eocene.

WHY LIFE ON EARTH would respond so dramatically to climate change remains unclear, but the planet's unique qualities provide some clues. Earth, as far as we know, is the only place in the universe supporting complex life forms. Water may have once flowed on other planets, and some planets may even host simple organisms, but only Earth has been able to maintain the delicate balance of air, mineral, and water chemistry vital to all living beings. When this balance is disturbed, the consequences can be major.

Zachos and many of his colleagues theorize that the Earth's temperature can change slowly, incrementally, with no visible impact–to a limit. They call that limit a climate threshold, and once it is crossed there is no going back. "Several of us suspect that the … rapid release of methane was initiated by gradual warming that pushed the climate system across a physical threshold," Zachos says. According to Zachos, crossing the threshold could mean facing a climate system gone haywire. With air and water temperatures and pressures and ocean salinity all playing roles on the climate stage, it is hard to pinpoint when and where that line is crossed. But Zachos thinks the climate system begins to crumble when polar regions warm up.

The ocean is much like air when it comes to circulation. As blowing winds stir up air, swirling water currents stir up the seas. Water on the surface of the North Atlantic warms, shimmies north and south to the poles, cools and sinks. But if polar waters warm, too, the relocated water would fail to cool, and would remain on the surface. The pockets of water that once warmed and cooled, rose and sank, would stop flowing. Ocean circulation would slow down.

Imagine stagnant, humid, unmoving air: It's hard to breathe. That may be what oceans were like to their resident organisms once the warming took hold. Zachos thinks that an extra-warm push at the poles was enough to cross the climate threshold, which in turn triggered a bizarre response in land and sea creatures.

And it could well happen again, he warns. Up to 2 trillion tons of greenhouse gas were released into the atmosphere 55 million years ago. Today we pump 7 billion tons into the air each year from the burning of fossil fuels alone. As a result, Zachos points out, the carbon isotopic signature of ocean surfaces today has already begun to shift. Since the same kind of shift was the precursor to upheavals in the planet's ecosystems in the past, the current trend might foreshadow similar changes in the future. But according to Gingerich, climate lessons from the past are not all doom and gloom. "The good news coming from Wyoming is that the Earth's biota worked its way out of it," he says. "The bad news is that it took about 80,000 to 200,000 years." SN

Mind Over Stomach

A NASA scientist believes astronauts can overcome space sickness through willpower.

By EMILY SINGER / ILLUSTRATION by KATHERINE RIZZO

IN THE WAKE of the Columbia tragedy, NASA and the public are keenly focused on getting astronauts into space and back home again as safely as possible. But scientists can't ignore what happens to the astronauts on even the smoothest of space journeys–the extreme stress that space travel imposes upon the human body.

During launch, the space shuttle accelerates by 33 miles per hour every second–25 times faster than an average race car. Gravity becomes magnified to three times the Earth's pull, about the same degree of force that plasters riders to the wall inside spinning carnival rides at amusement parks.

Meanwhile, within the body, the "fight or flight" response goes into hyperdrive. Blood weighs more under the drag of gravity, so the heart must pump faster to push blood to the brain. Blood pressure and heart rate skyrocket, making those on board miserably dizzy, nauseated, and prone to passing out.

And after surviving the launch phase, astronauts face other major dangers: quick losses in bone density and muscle mass from long stays in outer space, and a potentially dangerous drop in blood pressure during the rapid return to Earth and its higher gravity.

If humans are ever going to fully colonize the International Space Station or fly a mission to Mars, scientists must find a way to overcome these physiological changes. NASA researcher Patricia Cowings believes she has a solution. In fact, she would like to make life in space a routine reality. Cowings, a psychologist at NASA Ames Research Center in Northern California, has spent the last 30 years designing a technique to rid astronauts of their peskiest of problems–air sickness–as well as long-term effects associated with extended stays in space. "Our primary mission is to enable a permanent human presence in space–not just to visit but to stay and to function and to thrive," Cowings says.

Cowings hopes to prepare astronauts for these strange new environments by teaching them to control the physiological responses that lead to motion sickness and blood pressure problems. In these training sessions, astronauts wear a specially designed vest that measures physiological responses like heart rate and blood pressure. Cowings then uses a method called biofeedback to train people to control the autonomic nervous system–the part of the body in charge of the fight or flight response.

The technique is a kind of physical workout, but instead of doing weight-lifting reps to strengthen muscles, she says, "we're exercising the control over heart rate." The treatment could have earthbound applications as well. Mae Jemison, a former astronaut, recently licensed the technology and plans to market it for common medical problems such as nausea and anxiety disorders.

When the space shuttle program first began in the '70s, air sickness was a huge problem for astronauts. Approximately 50 percent of shuttle crews experience symptoms of motion sickness during space travel. Cowings first began working on a cure when she landed a job at the space agency's Ames center as a postdoctoral researcher in 1973. Five years later, she joined the staff as director of its psychophysiology lab.

By the mid-1980s, the agency began using the drug promethazine to control air sickness, but Cowings continued the line of work she had started. She collaborated with Russian scientists who were interested in finding an alternative to promethazine, which could cause fatigue. Cowings had always approached the problem with a philosophy very different from a pharmaceutical fix, partly because she had wanted to push the limits of human ability since childhood.

As the only girl among brothers in her family, Cowings grew interested in human potential–the uniqueness inherent in each person and their individual promise. "With three brothers, I noticed at nine years old that white men get all the jobs, she says. "I figured, I'm not a man and I'm brown." But her father, a grocery store clerk, told her she could transcend her gender and skin color. She recalls him saying, "You're a human being–look at it from the point of what you can do." He inspired her to study psychophysiology, the interaction between the mind and the body, which Cowings views as an exploration of human potential. For instance, she asks, "How can you make yourself do better? What keeps you from getting ahead? How do you fix it?"

Cowings' interest in psychology was partnered with a fascination with outer space. "I discovered science fiction in high school and emptied the library," she says. Her role models were communications officer Uhura on TV's *Star Trek*–and astronaut Jemison, who was the first African-American woman to fly a space mission

Cowings went on to study psychology in graduate school at the University of California in Davis. She describes herself at that time as "a *Star Trek* woman and a paranoid black child," referring to her love of space and the lingering fear of how difficult it would be to succeed in the white male world. Then in 1969, U.S. astronauts landed on the moon. Inspired by such a landmark achievement in human potential, Cowings decided to bring her fascination with space travel into her psychology studies. She talked her way into an aeronautics course in the school of engineering.

"They probably only let me in because I read so much science fiction," she says, laughing. The course objective was to propose a new tool for the space shuttle. Cowings wrote a paper exploring 12 ways that psychophysiology research could be applied in space flight. She got an A. That class would seal Cowings' future at NASA. "We went on a class field trip to NASA Ames, and I've been here ever since," she says.

AS SHE TACKLED the challenge of air sickness, Cowings figured that since people adapt very differently to stressful situations, the best cure would be one that was tailored to the individual. To devise such a remedy, she would first need to know how a person responds to stress, and the most accurate way to measure that would be to mimic the stressful event as closely as possible.

So Cowings headed to the lab, where space physiology researchers were devising ways to recreate the harsh stresses of space. One of the tests NASA uses to see how a person will respond to the conditions of outer space is called the "G-test": A volunteer spends hours inside a small, spinning room designed to create conditions mimicking the Earth's gravity and 1.5 times Earth's gravity. The result is a sort of human centrifuge, like the contraption in the movie *The Right Stuff*.

Four hardy volunteers braved the centrifuge–which was outfitted with a bed, a TV, computer, and food–for 22 hours, acting as guinea pigs for Cowings and other researchers who wanted to study how long periods of high gravity affect the body. Researchers knew from shorter spin tests that tolerance to high gravity varies: Some people pass out at 1.5Gs, while others could handle 4 or 5Gs. Under high-gravity conditions, blood is pushed out of the head, causing people to black out or faint.

Cowings wanted to know what causes the varied tolerances, so during the marathon spin she measured skin temperature, blood flow, heart rate, and respiration rate. Subjects also took tests in typing and word comprehension to measure cognitive and motor function. Cowings further tortured these spinning souls by asking them to lie down, sit up, and stand up for a few seconds at a time to see how their bodies would react under high-gravity situations.

When you stand up, gravity draws blood to the feet. The body compensates by increasing heart rate and blood pressure to pump more blood to the brain. Cowings found that the best "adaptors"–those who could withstand the highest gravitational forces–were physiologically flexible. The most adaptable person in the experiment had a heart rate that jumped from 60 to 120 beats per minute when he stood, allowing him to compensate for changes in the stresses of gravity–but also making him more susceptible to motion sickness.

The results from the G-test confirmed what Cowings suspected: that a successful solution would be one that works for everyone, adaptors and non-adaptors alike. During development, Cowings tried all the tricks in her psychologist's toolkit–yoga and transcendental meditation, hypnosis, and most promising of all, biofeedback.

Biofeedback might sound complicated, but it's a simple idea. People can elicit physiological responses in different ways, says David Shapiro, a psychologist at the University of California in Los Angeles who has been researching biofeedback for the last 40 years. Walking fast and thinking about emotional memories can each drive up heart rate and blood pressure, two involuntary reactions. Biofeedback uses monitors to show people exactly what their body is doing, so they can learn to control the otherwise automatic responses.

Cowings combines biofeedback with a tension-reducing technique called autogenic therapy, which is similar to self-hypnosis. She uses visualization exercises to show the trainee how to focus their attention on different muscle groups and learn to control them. For example, she might ask the astronaut to focus on the fingertips of the right hand. "Think about your hand getting warmer, and it will increase blood flow," she says.

With only a few hours in the astronaut's busy schedule available for biofeedback training, Cowings had to make her technique quick to learn. She streamlined the training to six half-hour sessions. "You only have 30 minutes, and you have to get the astronaut to forget about the arguments he had with his wife, or the fact that he's launching on Tuesday," Cowings says. So she figured out how to make those short spurts as productive as possible–she uses hypnosis throughout the sessions to focus the subject's attention.

When training, the astronaut wears a special close-fitting white vest made from a cotton polyester blend that Cowings and her team designed. It's loaded with wires and sensors that monitor everything from heart rate to skin tension. The trainee sits in a modified dentist's chair, facing a series of computers that will display the body's every reaction.

Cowings then gets to indulge her sadistic side by yelling at the astronauts to get their heart rates pounding. In the first few training sessions, she determines how a person responds to stress and figures out which of the feedback displays work best for them. "You're like a director in a band," she says. "There are 20 different displays happening and you have to direct the person which one to pay attention to." The process is similar to learning to use a joystick in a video game, where players get feedback by watching their performance on the screen and then correct their movements to improve their score.

In the next session, trainees are sent on yet another carnival-like ride, this time in a rotating chair built to induce motion sickness. Blindfolded and strapped into the chair, each astronaut is then spun around to see how well he or she has learned to control the changes in blood pressure and heart rate without looking at the biofeedback monitors.

In the following sessions, trainees return to the biofeedback monitors and work on further honing their skills–to see how quickly they can, say, increase their heart rate, hold it steady, and bring it back down. The last stage of training is to introduce environmental distractions, and that means more shouting from Cowings. "It's fine if you can control physiological responses in a dark quiet room, but what about in the real world?" she says.

After training with Cowings for six to eight hours, 85 percent of people can reduce their motion sickness, she says. And while most people learn to control their physiological responses to some degree, some truly excel. It's impossible to predict who will be the "autonomic athletes," as Cowings calls them, but one in four people qualify, learning to completely suppress motion sickness in just six hours. The ability doesn't correlate with age, athletic ability, or education, and like any physical conditioning, it improves with practice. "It's a talent–like playing music," she says. And although astronauts seem to be a little bit better than most people at almost everything, when it comes to autonomic training, they are the same as everyone else. "A high school kid could come in and perform better than an astronaut," she says. Only one in 20 people are "autonomic duffers," those who can't control their responses.

The 20-g centrifuge at NASA Ames Research Center in Mountain View, Calif. (Photo courtesy of NASA)

COWINGS' TECHNIQUE is still experimental. Her research is promising, but more in-flight research is necessary to determine if her technique is practical, says Malcolm Cohen, a branch supervisor at NASA Ames who also studies adaptability to high gravity. Extensive testing of her system in space isn't likely to happen soon; with limited flight time and small crews, getting clearance to conduct an experiment in space can take years. "When you do experiments in space, you get in line behind the rest of the world," Cowings says with a sigh.

NASA also needs to determine if the technique is something the astronauts want to learn. Cowings says she has encountered some resistance against using the vest from pilots and astronauts. "They think it's silly, and they don't want to have anything to do with psychologists," Cowings says. But when she portrays the technique as just another type of physical training, like a bench press, they seem to be more accepting, she says. Interestingly, Russian cosmonauts are more open to the biofeedback technique, probably because they're more familiar with behavioral conditioning, says Cowings, noting that Pavlov, the psychiatrist who made dogs salivate at the sound of a bell, was Russian.

For Cowings, the roadblocks are frustrating. In a study published in the *Journal of Clinical Pharmacology* in 2000, she found that her training exercise was much more effective at controlling motion sickness than promethazine. NASA gives the same drug treatment to everyone, regardless of their size, she says. "That's not the scientific method, that's the shotgun approach." Whereas the drug can cause drowsiness, the benefit of the biofeedback technique is there are no side effects and it can be tailored to meet a person's needs, she added. "One guy says he's fine but faints, and another guy who is a good adaptor throws up. You can't tell who is going to be susceptible to different disorders," Cowings says. "We're just now getting to agree that not one treatment works for everyone."

Cowings sees a place for her biofeedback vest beyond the astronaut world, in helping ordinary people handle anxiety or nausea. "There are lots of situations where your heart rate goes up–[such as] before a test or a speech," she says. We've only touched the tip of the iceberg in the number of medical applications," Cowings says.

Cowings is working with Jemison, whose Houston-based medical technology company, Biosentient, is developing a portable, commercial version of the monitoring vest and display system for mainstream medical use. Biosentient researchers have been taking advantage of advances in wireless communication and power efficiency "to make a truly portable garment," says Jemison, who is a doctor and chemical engineer. "It's something people can wear over the course of the day, under a suit."

They now have a prototype which different research groups will take for a test drive in the upcoming year. Scientists or doctors could use the future biofeedback outfit–consisting of both a shirt and shorts–to track the activities of a person's autonomic nervous system for different purposes. For instance, psychologists could use it during therapy session to help patients learn to manage their anger. Or patients with fear of flying or other phobias could wear the garment in a plane or whatever environment triggers their fears.

Jemison says the outfit could be useful even without the biofeedback training. Professional athletes could wear the garment and have their vital signs monitored by trainers, who could spot the early warning signs of, say, heat stroke, from overtraining in the summer.

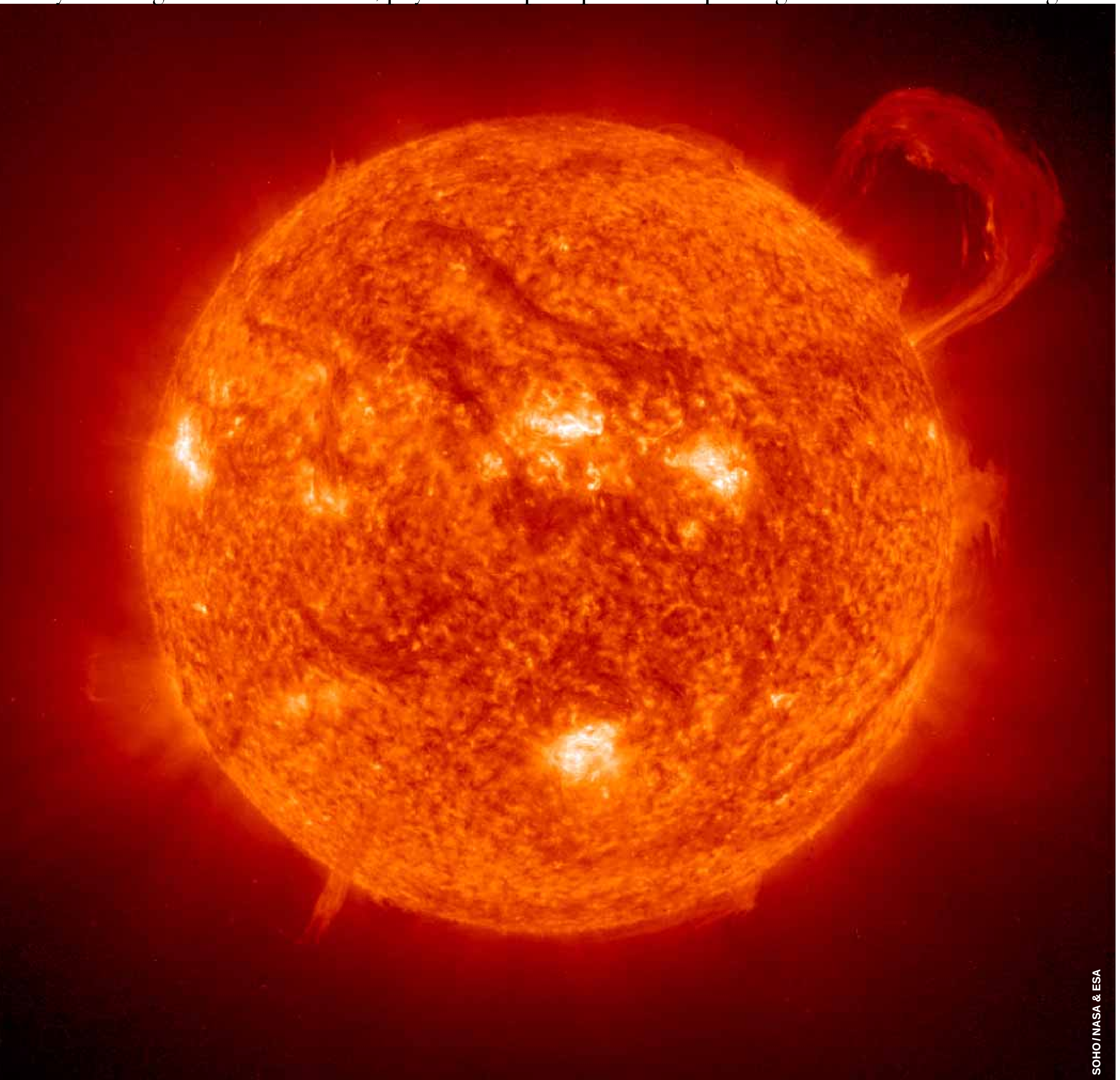
Once the monitoring system is available, Jemison's next step will be to conduct clinical trials testing whether a reliable and easy-to-use biofeedback protocol could help treat ailments that are tied to the autonomic nervous system, such as motion sickness and some anxiety disorders.

Whether or not the tool developed for astronauts will find a market on Earth is unclear. Biofeedback first became popular in the '60s and '70s, but later fell out of favor partly because of a lack of research proving its effectiveness. Compared with existing biofeedback systems, the new NASA technology offers the important advantage of portability, but it still might come up against the same roadblock that Cowings had with pilots–a prejudice against what is often viewed as a "touchy-feely" treatment.

Although the technique is used in treating a variety of conditions, from anxiety disorders to tension headaches to temporomandibular joint disorder, biofeedback has never really moved into the medical mainstream, says UCLA's Shapiro. "It can be useful in cardiac arrhythmias and hypertension, but it's not part of standard medical practice." As a result, clinical use is holding steady rather than expanding.

For now, Cowings says her number-one clients are the astronauts. She's trying to get one of her vests up to a cosmonaut aboard the space station, but can't get through the NASA bureaucracy. "I just keep working away in the basement," she says. "I'll keep doing this until I die or we get to Mars, which ever comes first." SN

By learning more about the sun, physicists hope to predict cell phone glitches and the next ice age.



A huge, handle-shaped prominence emerged out of the sun on Sept. 14, 1999. Prominences are huge clouds of relatively cool dense plasma suspended in the sun's hot, thin corona. At times, they can erupt, escaping the sun's atmosphere.

STARING AT THE SUN

by Jyllian Kemsley
illustration by Megan O'Dea

Your mother told you never to look at the sun, because if you did it would ruin your eyes. But even if you gazed directly into our star's glare, odds are that all you'd see is the yellow surface of a big ball of burning hydrogen gas, 865,000 miles across. It's what you can't see that's important: the 30,000-mile dark patches known as sunspots, and solar storms that shoot gusts of charged particles toward Earth at a million miles per hour. Such solar spectacles create a combination of events that can knock out pagers and cell phones, and trigger power outages for millions of us here on Earth. Since 1996, solar weather has caused nearly $2 billion worth of damage to satellites.

Scientists have been studying sunspots for millennia–extremely large spots are sometimes visible to the naked eye, and were recorded by Chinese astronomers as far back as the year 301. The invention of the telescope in the early 1600s allowed astronomers to observe the sun in more detail. In recent decades, investigators have turned to satellite technology to create three-dimensional pictures of the star.

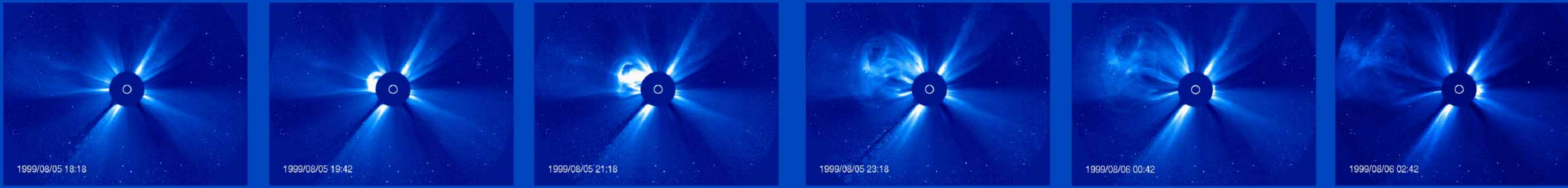
Since 1995, physicists at Stanford University, Lockheed Martin, and NASA have been using one satellite, the Solar and Heliospheric Observatory (SOHO), to illuminate the sun's inner workings. And they are preparing to launch a new satellite in 2007 that will give them even better insights. Currently, some of SOHO's instruments analyze the spectrum of light emanating from the sun–from infrared to X-ray frequencies–to investigate its atmosphere. But another instrument, designed by Stanford physicist Phil Scherrer, allows him and his colleagues to fathom the depths of the fiery ball by "listening" to sound waves generated from within.

"Every time we look at the sun with a new instrument, we find something surprising," says Karel Schrijver, an astrophysicist at Lockheed Martin's Solar and Astrophysics Laboratory in Palo Alto, California. For instance, this year researchers unlocked the secret to how irregular bright patches on the sun, called supergranules, appear to move across its face. Ultimately their mission is to understand and predict the behavior of magnetic fields roiling below the sun's surface that trigger the solar storms and wreak havoc for us at home. The researchers also want to understand the intricacies of solar weather patterns over decades and centuries. Increases in sunspot activity have been linked to warm spells on earth, whereas quiet periods may correlate with ice ages. Insight into solar cycles may therefore provide clues to planetary climate change.

Just as the Earth has layers–an iron core and molten mantle, topped by a rocky crust–so does the sun. The star has an inner core, a 15-million-degree sphere of gas. There, a nuclear reaction converts hydrogen atoms into helium, producing the energy that makes life on Earth possible. But Scherrer and his collaborators are more interested in the sun's outermost layer, also composed of hydrogen and helium gas but at temperatures ranging from about 2 million degrees near the core to 6,000 degrees at the surface. Gas atoms at such searing temperatures become separated from their electrons, creating a collection of charged particles known as plasma.

As a result of the temperature gradient, the outer layer "boils" like a pot of water: Bubbles of plasma called granules–which are about the size of Texas or California–rise up from the bottom. At the surface, the plasma cools and spreads to the sides, then it drops down again to the bottom of the layer. Such a cycle of movement driven by warming and cooling is called convection, which is why the outer solar layer is known as the convective zone.

Granules and convection are the key to how the Stanford physicists "listen" to the sun. Think of placing your hand on the surface of the water in a swimming pool, and pulling down suddenly. The water comes in over the top of your hand, and then waves go out from the sides.



The same thing happens when the cooled plasma drops back down from the sun's surface, except the downdraft in this case creates sound waves. The waves travel through the sun and are affected by whatever they encounter along the way.

Millions of granules on the sun's surface produce millions of sound waves. "It's like a bell in a sandstorm," Scherrer says. The waves start bouncing around inside the sphere, and some of them wind up back where they started and create repeating patterns, or resonance. These patterns are similar to what you hear when you pluck a guitar string–the sound reverberates for a while before it dies off. As sound waves continue to form from new granules, they overlap to reinforce and stabilize each other, so the sound doesn't die off. And the resonating waves cause the sun's gaseous surface to actually pulse. As a result, the sun becomes a huge pulsating ball.

The SOHO satellite, launched in 1995, carries instruments designed to measure those pulses. "People can make models all they want, but there's nothing like having data," Scherrer says. The satellite moves in a "halo" orbit balanced 1 million miles from the Earth and 92 million miles from the sun. Scherrer and colleagues rely upon an instrument aboard SOHO called the Michelson Doppler Imager (MDI), which monitors slight changes in wavelengths of light rays emitted from the sun as it pulses toward and away from Earth.

From those pulses, the scientists then use computers to calculate information about the sun's overall sound resonance and the original sound waves making up that repeating pattern. In the process they get details about the sun's interior–information that typical light-viewing telescopes can't reveal. For example, they can pinpoint areas of higher temperatures or stronger magnetic fields, which are produced by the flow of charged particles in solar plasma, because sound waves travel faster through such regions. And because sound waves also come from the back of the sun, they can get a picture of activity there as well.

The satellite data have shed light on several of the sun's secrets. One mystery centered around bright, 20,000-mile-wide swaths of plasma–known as supergranules–that were thought to move horizontally across the solar surface faster than the sun rotates. Scherrer and colleagues, analyzing data obtained from MDI, found that scientists had it all wrong: The data demonstrated that supergranules don't actually move; rather, the plasma is just rising up and down, like sports fans doing the wave in a stadium. The next challenge is to figure out what's generating the supergranules in the first place. Scherrer thinks the cause is some sort of interaction between smaller granules and the sun's rotation.

Imager data has also revealed another surprise for solar physicists: Sound waves travel through the sun at speeds different than expected–moving more slowly in the core, but accelerating significantly at the boundary where the inner and outer layers meet. Because the speed of sound depends on the compactness of the material it passes through, this means that the scientists' original estimates of the sun's internal density are incorrect. "There's something in the core that our model has wrong–some sort of mixing that our model doesn't have" says Scherrer, who plans to investigate further.

Snapshots of a coronal mass ejection from the sun, observed over an eight-hour period on August 5-6, 1999 by the Solar and Heliospheric Observatory. The dark disk blocks the sun so that instruments can observe the structures of the corona in visible light. The white circle represents the size and position of the sun. (SOHO/NASA & ESA)

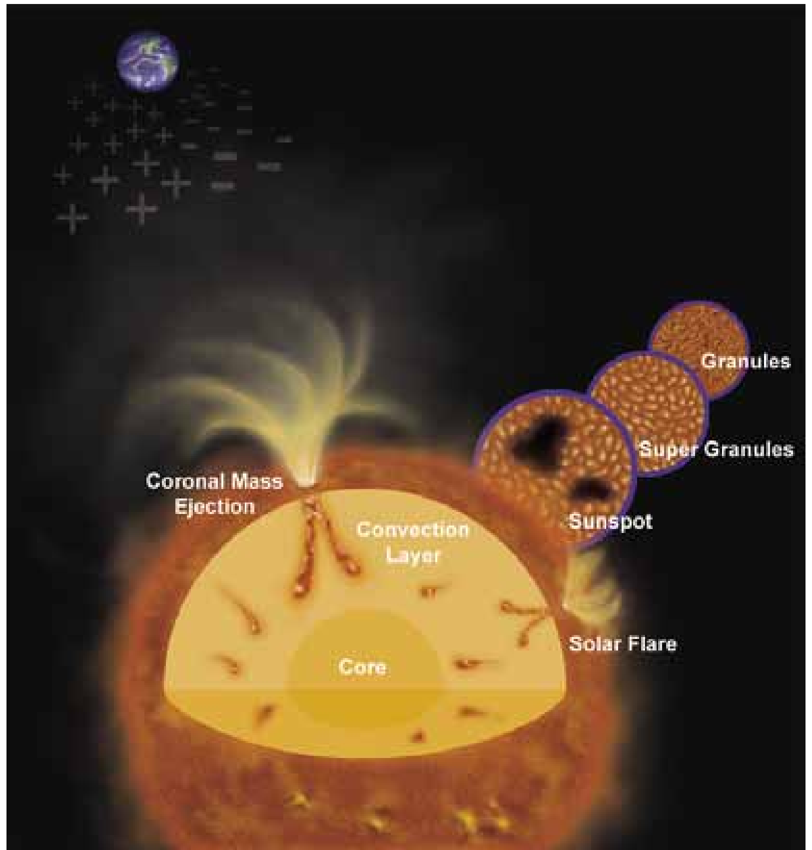
In the meantime, Scherrer has also been busy studying sunspots, which can produce effects felt 92 million miles away on Earth. A sunspot forms when a cluster of magnetic field builds up at the bottom of the convective layer. Then, because plasma is less dense in a strong field, the cluster becomes buoyant and rises to the surface, forming a dark blotch on the face of the sun. Sunspots can last for days or weeks, and occur in pairs: Like two ends of a bar magnet, one will have positive polarity and the other will be negative.

Sunspots cause trouble on earth when two sets of them interact. Underneath one sunspot pair, another will eventually form and rise to meet the spots already at the surface. The charged particles in the plasma within sunspots produce strong electric currents. So when two spots meet, it's like two crossed wires short-circuiting to blow a fuse or start a fire–but on a massive, violent scale. The two spots actually annihilate each other, releasing large amounts of energy, charged particles, and magnetic field into the sun's atmosphere and beyond–a solar flare. A very large flare is called a coronal mass ejection.

A coronal mass ejection is like a very strong gust of the solar wind that regularly carries energy to Earth in the form of light and charged particles. "Ejections to the side are fine, it's those in your face that are a problem," says astrophysicist Juri Toomre from the University of Colorado, Boulder. The amount of energy released by a flare can equal up to a billion million tons of TNT. Earth's magnetic field guides charged particles into the atmosphere, where they encounter gas particles and start to glow. This is the source of the aurora borealis, or Northern Lights. A super-size coronal mass ejection may wreak havoc on cities, because power grids can act like antennas for the electrical currents generated by the charged solar particles. A solar storm in 1989 knocked out Quebec's power system and plunged six million people into darkness. The damage took months to fix.

The Space Environment Center (SEC), operated in Boulder, Colorado, by the National Oceanic and Atmospheric Administration, tries to forecast such events, providing information to telecommunications companies, the military, and NASA. Not only are power grids in danger of damage from ejected particles, but so are telecommunications satellites cruising above the earth's protective atmosphere, says Joseph Kunches, chief of space weather operations at SEC. A 1998 storm caused a blackout of service for nearly 40 million pagers. The government's program to locate cell phones through global positioning satellites would also be vulnerable to solar storms, Kunches says. And airplanes and the Space Shuttle are susceptible to solar storm radiation. The instruments on solar research satellites "have made us forecasters a lot smarter," Kunches says. He would like to see a better warning system, so that power grids and satellites could be operated in "safe"–albeit less profitable–modes and airplanes rerouted as necessary. When a big solar storm struck in July 2000, he notes, it caused only minor damage partly because scientists had issued an advisory that a major sunspot region could turn deadly.

Scherrer and Schrijver believe that better forecasting will come through deeper understanding of the magnetic fields and flows that produce sunspots. Such knowledge could lead to predictions of when a second spot will rise to produce a flare or ejection, and of just how big an ejection might be. Currently, however, the orbit of the SOHO satellite only allows Scherrer and colleagues to get nonstop data from MDI for two months of the year. MDI's view of the sun is also not very detailed, offering high magnification of an area that's only about a fifth of the visible surface, allowing them to observe a spot only for a day or so. "It gives us snapshots," says Scherrer. He'd much rather have a movie.



That movie is where a new satellite and new instrumentation come in. Four years from now, Lockheed and NASA are planning to launch the Solar Dynamics Observatory (SDO), which will carry MDI's successor, the Helioseismic Magnetic Imager (HMI). HMI will download solar data 24/7 for all but a couple of days of the year. It will also have high magnification of the entire sun, roughly the equivalent of going from a 14-inch to a 56-inch television. The new technology will allow the researchers to follow sunspots throughout their typical 10-day journey across the solar face. Scherrer also wants to track sunspots over longer periods. For reasons that aren't understood, the number of sunspots regularly waxes and wanes over an 11-year cycle. During periods of maximal activity, sunspots are found closer to the sun's equator, whereas they migrate to the poles as the cycle winds down into a minimal period. Scherrer wants to know what's in the convective layer that leads to this behavior.

Another question scientists want to explore is the connection between sunspots and climate. From the 1100s to the 1500s, astronomers observed a period of extremely intense sunspot activity, corresponding to a global warm spell. If you've ever wondered how Greenland got its name, this is why: At the time it was discovered, it had grass. This greening of the Arctic was followed, however, by the "little ice age" in Europe, a period marked by only a handful of sunspots instead of hundreds. These climate cycles appear to correlate with a 0.1 percent change in solar luminosity between periods of intense and lackadaisical sunspot activity. Understanding–and predicting–these patterns may provide insight into global climate change.

In the long run, Scherrer's goal is to put all of the pieces of the puzzle together–the mysteries of magnetic fields in the convective layer, how sunspots form and interact, whether a solar flare is imminent, and the secrets fueling the solar cycles. "We want to understand the effects on a technological society due to a variable sun," Scherrer says. "If we can understand how the material underneath drives the process, then maybe we can predict the process better."

Now and then, even those of us without access to NASA satellites can witness one of the solar events that inspire his work. Despite your mother's admonitions, it actually is safe to look at the sun when it touches the horizon at sunset. Perhaps one day, you'll manage to see a giant sunspot–as Scherrer himself did a few years ago–and get a first-hand glimpse of the activity that forms the heartbeat of our solar system. SN

Teaching an Old Owl New Tricks

The barn owl shows how the brain works.

By RACHEL EHRENBERG / ILLUSTRATION by LUCY READING

OVER THE COURSE of a year, according to one study, a single barn owl eats approximately 115 meadow voles, 226 pocket gophers, 167 white-footed mice, 83 house mice, 3 kangaroo rats, and 101 roof rats—along with occasional starlings, moths, crickets, and frogs. Not impressed? Consider this: Most of these critters were caught in total darkness.

Barn owls can pinpoint the location of a noise with such precision that even on a moonless night, the rustle of leaves can be a scampering rodent's death knell. Like most animals, soon after birth, owls are able to recognize where a sound is coming from. As they grow up and go through the motions of hearing and catching their prey, the networks of neurons in their brains that interpret sound becomes increasingly refined, reinforced by the experience of hunting. In the parlance of those who study how the brain learns, this window of time when neural connections can still be calibrated by experience is called the sensitive period.

Scientists have long investigated sensitive periods in the context of research questions ranging from how babies pick up a language to the development of binocular vision in young mammals. Until recently, conventional wisdom said that little could be done to extend the brain's "plasticity" once the sensitive period had passed. The adage about old dogs actually has a basis in neuroscience.

Now, however, research is challenging that notion. Stanford University neuroscientist Eric Knudsen is using the barn owl's exceptional aural ability to explore how and when brains do their best learning. For the past 30 years, he and his colleagues have been untangling how the bird's brain crunches incoming sensory data to create and synchronize mental maps of both the auditory and visual world. The twists and turns through the owl's neural circuitry have recently led Knudsen to a surprising discovery. He's finding that even after the critical window of early learning closes, an old brain that is fed information in the right way can still learn new tricks.

The key, it turns out, is in the packaging. When new information is received in small doses, or in an especially stimulating environment, the brain is much more likely to incorporate it. These findings are consistent with recent studies of how infants learn language, and suggest promising strategies for enhancing learning ability in adults.

Knudsen has been investigating how the brain processes information since he was a graduate student at the University of California in San Diego in the late '70s. His early studies focused on catfish, which have inner ears that hear vibrations in the water and also detect the electric fields of nearby living things. Knudsen found that the catfish brain processes these two types of sensory information—auditory and electric—in separate, but parallel, pathways. That research raised a question: "I wondered, is the auditory system in terrestrial animals organized the same way?" Knudsen recalls. "Does it separate out what a signal is from where it is located in space?"

Sipping from a John Deere coffee mug in his Stanford office, Knudsen explains how his research focus moved from catfish to owls. Tall and blond, with piercing blue eyes, he looks more like a Norwegian bachelor farmer than a neuroscientist. He gestures at a poster on the wall, a stunning time-lapse photograph in black and white: A barn owl, its wings and talons extended, appears against a midnight black backdrop, swooping down towards an unseen mouse. A colleague, neuroscientist Mike Konishi, took the picture with an infrared video camera. "It was basically a completely dark room, and he just opened the shutter and strobed an infrared light," Knudsen explains. "He's showing how the owl uses hearing to find its prey."

Knudsen was finishing his Ph.D. when he first heard about Konishi's investigations of barn owl behavior. Konishi, who had video-recorded barn owls reacting to sound in a totally dark room, was struck by the speed and accuracy with which the bird turned its head towards a noise—its response was as swift as the flick of a human eye shifting its gaze. Knudsen realized that the owl's auditory prowess would make it an ideal study subject for investigating how the brain processes sound and integrates it with visual information. Not long after the two met at a conference, Knudsen began a postdoctoral fellowship working with Konishi at the California Institute of Technology in Pasadena.

Their early experiments showed how the barn owl, like humans, merges the information from its two ears to locate a sound. By comparing differences in the timing and intensity of, say, a mouse squeak or rustle of leaves reaching the two ears, the bird's brain makes a rapid computation that pinpoints the source of noise—and calculates the precise flight trajectory that will land it dinner.

The differences in the auditory information that reaches the two ears are amplified by the architecture of the barn owl's head. The bird's face is asymmetrical: Its left ear, which sits higher on the face than the right, is surrounded by feathers that are oriented downward, enhancing sounds from below. The inverse is true for the right ear, which is more sensitive to sounds from above. The birds' filamentous facial feathers are arranged in such a way that they form the equivalent of satellite-receiving dishes on either side of the beak. These facial discs collect sound, focusing it towards the ears.

In the late 1970s, Knudsen and Konishi began a series of experiments hoping to pinpoint which neural networks in the owl brain distinguish where a sound is located. The researchers first looked at the forebrain—the seat of higher, complex functions in vertebrate animals—but soon moved on to the midbrain, a region responsible for orienting the eyes and ears to important events in the environment. After connecting tiny electrodes to the anesthetized brain of a barn owl, they moved an audio speaker around the bird's head while playing a variety of noises, and tracked the neuron firing patterns.

To the investigators' astonishment, the pattern of firing changed dramatically. "The neurons were really sharply tuned for sound location," recalls Knudsen. "They didn't much care about how loud the sound was or what kind of sound it was, but they cared very much about where it was coming from—it was pretty surprising."

Scientists had known that the vertebrate brain builds a visual map with information coming from the retina, but how it interprets auditory information was largely unexplored. Like a surveyor, the owl's brain was taking measurements of sounds and crunching the numbers to map the outside world of sounds depicting actual space, Knudsen says. "The auditory system was going to great lengths to create a representation of space that was very like the visual representation, even though it was starting with very different information. It was mapped topographically—very much like a regular map, and very much like the visual map."

With his own graduate students at Stanford, in the late 1980s Knudsen found that this auditory map is sent to a specific region of the midbrain, the optic tectum, where it is aligned with the visual map. So when an owl hears a mouse in a certain location, a cluster of neurons fires in a specific area of the optic tectum; and when it sees the mouse in the same place, neurons in that area are triggered again.

THE DISCOVERY of this combined visual-auditory map led Knudsen to pursue another question, he says: "How much could we distort the sounds, and still have the owl accurately reconstruct the world in its head?" To find out, the researchers took advantage of a quirk in barn owl anatomy. The eyeballs of these creatures actually aren't balls at all, but elongated, piston-like tubes.

Pulling a barn owl skull off a bookshelf, Knudsen explains how each empty eye socket has a cylindrical structure that gives the birds highly sensitive vision. But the eye's mobility is relatively fixed. To move its eyes to the left or right, the bird must turn its head. In fact, some species can rotate their heads 270 degrees and look behind them.

Upon hearing a noise, an owl instinctively looks for its cause. If the sound is coming from anywhere but directly in front, the bird must swivel its head to see the source—and it does so as quickly as the human eye darts to an unexpected noise. Because head movements are much easier to see and count than the flicker of an eyeball, Knudsen could test whether the owl's audio and visual maps remained in sync when he exposed the animal to distorted sensory cues.

Even with one ear plugged, owls were able to compensate and home in on a noise.

He and his colleagues manipulated the auditory information reaching the bird's brain by stopping up one ear with a plug. Then the researchers compared neuron-firing patterns in the hearing-impaired birds versus the normal birds. Initially, the birds with an earplug misjudged the location of a sound, repeatedly swiveling their heads to look for a noise source off to one side when it actually was straight ahead. But over a period of weeks, something remarkable happened. The owls' auditory maps actually compensated for the earplugs, so they accurately oriented to the sounds.

These behavioral experiments with the earplugs provided the first evidence that a sensitive period might influence the birds' ability to adjust the brain pathways from noise to neuron. "We had no idea that there would be a developmental component to learning in the auditory pathway," Knudsen says. "But the young birds were able to make sense of the altered cues caused by the earplugs very easily, and the adult owls could not."

Alfredo Kirkwood, who studies neural plasticity in rats at the Mind/Brain Institute at Johns Hopkins University, says the results make sense when cast in a developmental light. "You want the plasticity when the body is growing. When your head and eyes and ears are growing, you have to adjust all the time to keep the sensory system working with high precision," says Kirkwood.

Much of the brain's circuitry is established before birth, guided by genetics. Since many of the interactions between body and surroundings are predictable—pain is bad, for instance, whereas food is good—the nervous system has evolved to cope with an environment that is, in many ways, consistent. But many neural connections remain malleable, allowing the brain to adapt to the body's environment. While that developmental window is open, experience dramatically shapes which neural connections are established in the brain, and the networks laid down during this period are strong.

As we age, however, those networks become much more difficult to adjust. For instance, the neural connections between the eye and the brain's visual cortex normally grow stronger during early development. Landmark experiments showed that kittens with one eye blindfolded at birth never strengthened those networks—and when the patch was removed in adulthood, the eye was permanently blind. "As the brain matures you get specificity and lose plasticity," says Kirkwood.

KNUDSEN'S investigations of the barn owl noggin next delved into figuring out which mental map the brain trusts when its audio and visual systems aren't in sync. In a set of experiments in the '90s, Knudsen again distorted the auditory signal with an earplug, and once the birds had adjusted to the situation, he put blinders over their eyes—little spectacles covered in masking tape.

Curiously, the results showed that once the earplug was removed, the owls that were wearing spectacles couldn't relearn the original, correct map for sound. "They got stuck with the altered map," he recalls.

Somehow, the visual system was overriding and correcting the auditory system with what Knudsen calls an "instructive signal."

"The only time the signal raises its head is when there is disagreement," Knudsen says. While very little is known about the instructive signal, the findings suggest that over the course of evolution, sight has proved a more reliable indicator of spatial information than sound. The implications are powerful, he says, because this executive order from the visual system seems to drive changes in neural plasticity, telling the brain when it's got it right. "If we can figure that out, then we can exploit it," he says.

To find out more, Knudsen tried a different experimental strategy. By manipulating only the birds' visual information, he found he could shift their response to sound. Knudsen fitted his owls with goggles made of special prismatic lenses that shifted their visual world 20 degrees horizontally to either the right or left.

In a dark room he exposed the birds to a sound stimulus, a burst of noise from a loudspeaker positioned off to the side. Initially, trying to look directly at the sound, the spectacle-wearing birds relied upon their unaltered auditory map and turned their heads to the same degree as they normally would without the goggles. But after six to eight weeks, their brains recalibrated, adjusting to the visual distortion caused by the glasses. Now, when the birds heard the noise, they swiveled their heads even farther than before, because the new visual map had apparently instructed the auditory map to shift as well.

While experimenting with the prismatic lenses, Knudsen again found that young birds had an easier time compensating for the distorted visual cues than older birds did. When they wore prisms that shifted their field of view 23 degrees, juvenile owls adjusted to the distorted cues after just a few months. By comparison, adult birds achieved at most only a quarter of the adjustments that their younger counterparts did. Electrodes recorded neural activity in two different areas of the older birds' brains–indicating that their maps weren't realigning.

The difficulty adult birds face when trying to adapt to the lenses fits with the current understanding of critical periods. Later in life, the brain is better at recalling learned information, rather than learning itself. "Your brain becomes more committed when you are older," explains Knudsen. "There is a tremendous advantage in reliability."

But Brie Linkenhoker, a graduate student in Knudsen's lab, wondered if there wasn't still some latent malleability in the adult birds brains, so she decided to try teaching these older owls in small steps. Rather than shifting their vision a full 23 degrees, Linkenhoker started the owls with shifts of 6 degrees, then 11 degrees, and finally 17 degrees. To her surprise, the incremental learning made a big difference. Although the mature birds still didn't compensate by correcting their mental maps as much as the juveniles did, they were far more malleable than when faced with one big visual shift.

Linkenhoker's experiments offer a new research regime for those studying how adult brains learn. The results also suggest that whatever the instructive signal from the visual system is, it operates over a small range, yet could still be exploited. "We have to ask, what is the relative practice step for [learning in] a given system, and then repeat that step," she says. "The idea now is repeat, repeat, repeat."

Brains of babies can adapt more quickly, but adults can still learn if they have a need to.

Within the barn owl system, the small step was easy to figure out: shorter, incremental shifts in the visual field. But Knudsen says that if we can figure out the small steps for absorbing other kinds of information, adult brains might be able to learn much more than scientists previously thought. He hopes that someday, that kind of knowledge could help improve the recovery of patients with brain injuries.

Sascha du Lac, a former grad student of Knudsen's who now works at the Salk Institute in La Jolla, California, agrees. "The dogma is that synaptic connections between neurons change," says du Lac, "But the change may be in the firing of the neurons."

If that's the case, the neural architecture may still be present. If scientists could find the right stimulus to wake the latent neurons, it would be possible to revive forgotten or unused connections. Additional experiments by Knudsen suggest that in barn owls, once the neural architecture is laid down, it persists. He's recently homed in on a type of a nerve cell that has already been implicated in learning processes in other parts of the brain. These cells play an important role when the birds are actively learning a new mental map, and seem to suppress the old map when it is no longer useful.

Studies of how infants learn languages support the notion that the brain's learning capacity depends not only on the amount of new information at hand, but also on how it's packaged. Linguist Tobey Nelson and her colleagues at the University of Washington in Seattle recently conducted a study in which they exposed two groups of 9-month-old infants to Mandarin Chinese.

One group of babies listened to a CD of someone speaking Mandarin, while the other group heard the language spoken in person by four adults. Both groups were then tested for their ability to distinguish between two Mandarin sounds. The children who listened to the CD were no better at recognizing the sounds than a control group of kids who'd only listened to English. But the infants who heard the language live, and from different speakers, fared significantly better on the test.

"Even at very young ages, we are aware of a connection between visual and auditory information," says Nelson, who works at the university's Center for Mind, Brain and Learning. "What you are doing while hearing–the social interaction, making eye contact–it makes a difference."

Nelson's work suggests that the brain pays attention to a lot more than just sound when learning language. "The brain really is quite plastic," she says, "But we have to figure out how to package the information, to tailor the training in the most effective way."

Preliminary data from the latest work in Knudsen's lab lends further support to that idea. Prism-wearing owls seem to adjust their mental maps more quickly if they have to catch their dinner, rather than being fed–in other words, when it really matters to their survival. "If you care about something, you learn more than if you don't care about it," he says.

So in addition to packaging new information in small bites, the context within which the learning occurs seems to be critical. Says Knudsen, "It's a combination of making the information graspable, and the amount of arousal–the amount of attention you engage the animal with–that will determine how much information it can gather." SN

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Science Notes is a publication of the Science Communication Program at the University of California, Santa Cruz.

The program consists of two separate graduate certificate tracks: science writing and science illustration. Each accepts 10 students a year for a one-year curriculum. More information is available at scicom.ucsc.edu.

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