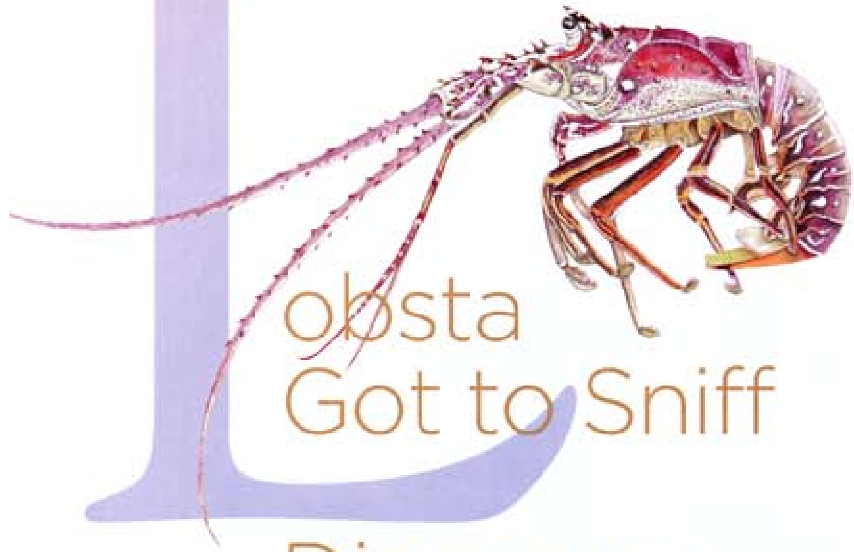
Nature's way: Koehl's research combines biology and engineering to better understand the natural world; opposite, Caribbean spiny lobster, *panulirus argus*.

Photos of Mimi Koehl by Jim Wilson '74 / Illustrations by Ippy Patterson



Lobsta Got to Sniff

Dinosaurs Got to Fly

In the field of comparative biomechanics, Mimi Koehl is an audacious pioneer whose success stems from a willingness to challenge assumptions. The Mr. Potato Head models don't hurt either.

By Barry Yeoman

THE WEEK WAS NOT GOING WELL FOR RASTA LOBSTA or for its creator, Mimi A.R. Koehl.

The robotic crustacean—built from the molted, epoxy-filled shell of a Caribbean spiny lobster—was the centerpiece of an experiment funded by the U.S. Office of Naval Research. The Navy was looking for answers to a life-or-death problem: how to defuse the unexploded mines that lurk in shallow marine waters without putting sailors' bodies at risk. Would it be possible to create a machine that could "smell" these underwater explosives with artificial noses? If so, what could scientists learn from spiny lobsters, which sniff out their food, mates, and predators with more precision than anything engineers have ever invented?

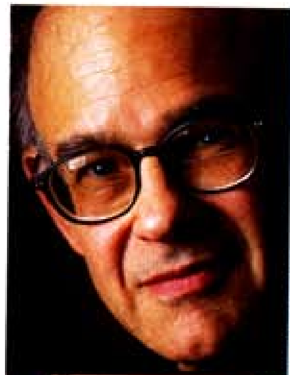
Koehl Ph.D. '76, a professor of integrative biology at the University of California at Berkeley, hoped her mechanical lobster could offer up information about how the real animal's olfactory system functions. To find out, she and several colleagues met at Stanford University's Environmental Fluid Mechanics Laboratory. There, an enormous tank simulated the flow of a turbulent ocean. Snappy reggae music played in the background as the researchers readied an experiment. They planned to release an odor, colored by fluorescent green dye, into the water with Rasta Lobsta. Then they would monitor how the smell found its way to a sensor mounted on the robot's antennae-like nose.

There was only one problem: The sensor refused to

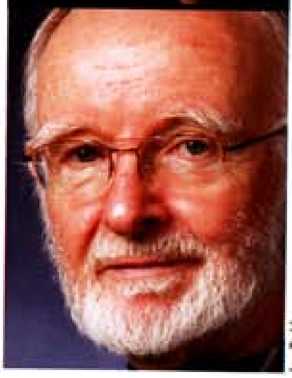
Sea Change

At Duke, Mimi Koehl Ph.D. '76 studied under renowned zoology professors Steven Vogel and Stephen Wainwright '53. While her dissertation included interesting revelations about sea anemones, it had an impact well beyond the study of *anthopleura*: causing her mentors to re-envision their field.

Until the 1970s, biologists who explored the way living organisms function tended to adhere to disciplinary boundaries similar to those established by mechanical engineers. Solid-mechanics specialists like Wainwright (pictured below right) studied the design of organisms, while Vogel (top) and other researchers in fluid mechanics studied the ways that these organisms interact with their environment.



Duke University Photography



Les Todd

But Koehl's dissertation project, which examined the way that particular species of anemones change shape in reaction to ocean wave forces, combined the two fields. Her thesis, Vogel recently wrote in the journal *Integrative and Comparative Biology*, "triggered the conversation that led [Wainwright and me] to give, in the following year, a course we called 'Biomechanics,' renamed ten years later 'Comparative Biomechanics.'"

Over the next three decades, they would co-teach the course twenty-six times, influencing the way that legions of zoology students understand organismal biology and shaping a new field of study that applies principles of engineering and physics to the study of animal movement.

The field has grown steadily, with Duke's zoology (now biology) department serving as an incubator early on. Three Ph.D. graduates have gone on to win prestigious MacArthur Fellowships: Koehl, a Wainwright student, in 1990; Barbara Block Ph.D. '86, a Knut Schmidt-Nielsen student, in 1996; and Thomas Daniel Ph.D. '82, a Vogel student, also in 1996.

Program graduates have gone on to populate top departments in the field, including those at Harvard University, the University of California at Berkeley, the University of Chicago, and the University of Washington (where Daniel is chair of biology).

Others have made an impact in related fields. Tierney Thys Ph.D. '98, a Wainwright student, studied fish biomechanics at Duke. She now produces documentaries on marine life as a research consultant with the Sea Studios Foundation in Monterey, California.

These offspring have even begun to produce star students of their own. Sönke Johnsen, an assistant professor of biology at Duke whose study of tiny, transparent sea creatures was featured on the cover of the November-December 2005 issue of *Duke Magazine*, studied under Wainwright protégé William Kier Ph.D. '83 at the University of North Carolina at Chapel Hill.

Though now overshadowed by molecular biology—in terms of faculty spots and grant money—at many universities, including Duke, the field of comparative biomechanics remains popular, Wainwright and Vogel say, in part because it is a young discipline and there is so much left to study.

Meanwhile, Wainwright and Vogel, both retired from teaching at Duke, continue to spread their knowledge to new generations, albeit in different ways.

Vogel is the author of a textbook on comparative biomechanics, co-editor of a teaching website on the topic, and a frequent speaker at academic conferences.

Wainwright has gone on to establish two nonprofits based in Durham. One, the Center for Inquiry-Based Learning, encourages middle- and high-school science teachers to "teach science as an interesting humanity instead of as a list of impossible words to memorize." At the second, SeeSaw Studio, he works with public high-school students to design and sell art.

—*Jacob Dagger*

work. After a week together, "we'd gotten almost no useful results," recalls Jeff Koseff, the Stanford engineering professor who hosted the gathering. At 10 o'clock on the last night, Koseff sent home his exhausted doctoral student and turned to Koehl.

"Mimi, what do you want to do?" he asked.

"Why don't we just do the best we can for the next three hours and take some data?" Koehl replied.

Until 1 a.m., Koehl, Koseff, and a technician improvised without the sensor. Shining a thin sheet of laser light into the tank to isolate where the odor hit the nose, they videotaped Rasta Lobsta as it flicked its antennules—small antennae clipped from a freshly dead seafood-market lobster—through the cloud of dye. By the night's end, Koehl felt energized again. Later, reviewing the video, she realized it was full of "beautiful data." Watching the motion of the dye after each antennule flick, she could reconstruct how the delectable odor of a rotten fish might reach a lobster's hairy nose.

For three decades, Koehl has worked in this nether zone between biology and engineering—a hybrid and relatively new field known as comparative biomechanics. In the process, she has helped solve some of the most basic mysteries of how living things interact with water and air. Besides lobsters, her subjects have included bull kelp, a seaweed that grows almost the length of a city block in a single summer, and *Microraptor gui*, a small feathered dinosaur whose fossilized remains were recently discovered in China.

She has studied how sea anemones survive hostile ocean waves; how the stubs on the sides of insects evolved into flightworthy wings; and how tiny sea-slug larvae tumbling through the water manage to land on the coral that provides their food. As with Rasta Lobsta, Koehl sometimes builds models of these organisms, complete with detachable body parts à la Mr. Potato Head. (Just for fun, she once designed hats and purses for some mechanical flying frogs.)

Along the way, Koehl has piled up accolades, including a $260,000 "genius" grant from the MacArthur Foundation in 1990. Three years ago, she was the subject of a book called *Nature's Machines* by Deborah Parks, part of a series on female scientists written for middle-school students. Colleagues say Koehl's success stems from her willingness to venture into unexplored territory—to cross traditional discipline lines, to study organisms others have overlooked, and to challenge assumptions about how natural systems operate.

"A lot of what she's done has been a matter of audacity," says Steven Vogel, a James B. Duke Professor Emeritus of biology and one of Koehl's early mentors at Duke. Her boldness "didn't develop right away," he says. "She certainly didn't have it when she started as a grad student." Growing up with a mother who tried to limit her homework time, fearing a studious girl wouldn't get dates, Koehl first needed to unlearn some childhood lessons before she could develop her scientific chops.

BACK THEN, SCIENCE WAS FOR BOYS. Koehl's father was a physicist. Her mother painted portraits. That was the social order in midcentury Silver Spring, Maryland, and Koehl was not encouraged to stray. She declared herself an art major when she began her undergraduate studies at Gettysburg College in Pennsylvania. From her parents' perspective, "it was expected that girls would do art," she says.

In the studio, Koehl found herself drawn to sea shells, bone textures, and plant surfaces. She painted and drew both literal and abstract images. But when she took her first biology class, mere representation suddenly seemed insufficient. "What I realized was that what scientists do is understand how nature works," she says. "That seemed much more exciting and satisfying than simply appreciating the forms." She switched majors at Gettysburg, then in 1970 joined Duke's graduate zoology program.

When Koehl announced her plans to become a scientist, "her family wasn't the least bit of help," Vogel says. "Going to graduate school was ducking out of her responsibility to get married and produce another generation." Once, when her parents visited Duke, the family went out for a meal with Koehl's academic adviser, Stephen Wainwright '53. Wainwright, now a James B. Duke Professor Emeritus of biology, still recalls the drive to Chapel Hill: "Mama's

Getty Images

Ideas take flight: Koehl tinkers with *Microraptor gui* dinosaur model, above; photo of fossil, left.

sitting in the back seat. She says, 'Dr. Wainwright, don't you think it is totally wrong for young women to be studying to be scientists?' It was so unexpected, because there wasn't any lead-up to it, that I had to pull over and stop."

Wainwright, who has a reputation for launching Duke students into successful careers, provided the antidote to Koehl's upbringing. As with other students, he required her to take a British-style tutorial and write five research papers, which he critiqued rigorously. Pushed to excel, Koehl started to discover her own intellectual heft.

ington, she rigged her electronic equipment to measure the water flow at the bottom of the channel where the anemones lived. She was puzzled when the meter registered hardly any flow at all.

"When it's raining and the waves are crashing and there's a lot of salt in the air, your electronics often suffer," she says. She rechecked her equipment before realizing the readings were correct: The animals had flattened themselves into inch-high disks and hidden in the slower-moving "boundary layer" below the turbulent waves. As a result of this behavior, she says, "these sea

mal's design can affect both the forces it encounters and the way it reacts to those forces.

Koehl was working at the border of two established disciplines: solid mechanics (the design of organisms), which was Wainwright's specialty, and fluid mechanics (how those organisms interact with the surrounding air and water), which was Vogel's.

"Putting the two together, she got a system to tell her things that no one had ever even asked before," Vogel says. Her research "really gave you the picture of how the anemone was making it in the world that you didn't get from either field separately."

Low tide: Green sea anemones like those studied by Koehl and ochre sea stars in Clallam Bay, Washington State; *anthopleura xanthogrammica*, below.

George Grall

anemones are living in a microhabitat that's much more protected than what you would think if you just stood on the shore and watched the waves crash."

"Wainwright kicked her when she needed it and told her she was as good as anyone in the world," says Vogel.

Wainwright also introduced Koehl to comparative biomechanics, a then-emerging field that uses engineering principles to understand living organisms. The thought of studying the literal structure of life appealed to her. For her dissertation, Koehl explored how giant green sea anemones, whose squishy bodies she compares to water balloons, manage to withstand the violent waves of the Pacific coast.

Working on rocky Tatoosh Island, Wash-

What's more, she learned, the anemones huddle together. "If you think about yourself standing in the surf with a bunch of friends around you, you realize that maybe you're protected from some of that really rapid flow," she explains. The discovery provided a lesson that still informs Koehl's research: If you want to understand how a creature survives, you have to view the world as that creature does.

Following up, Koehl analyzed two anemone species whose different body shapes allow them to thrive in different habitats. The resulting paper showed how an ani-

KOEHL DID A POSTDOCTORAL FELLOWSHIP at the University of Washington's Friday Harbor Laboratories, then taught at Brown University. In 1979, she joined the Berkeley faculty and turned her attention to new questions, including one that had long vexed evolutionary biologists, and still does: How did insects develop wings that enable them to fly? The evolution from winglessness to working wings presumably entails intermediate generations with stubby wings that are too short for flight. Why would nature select for useless stubs over no wings at all?

But what if the short wings served another purpose? Could they have worked as parachutes or steering rudders even if they were inadequate for flight? Could they have served as tiny solar panels? What if they made an insect sexier? These competing hypotheses had been the subject of a lively debate among scientists.

To explore this question, Koehl teamed up with Joel Kingsolver '75, another Wainwright protégé who was now a postdoctoral fellow in her lab. Kingsolver, who had studied wings as solar collectors, knew about the debate. "There were a lot of ideas that had been proposed, but people hadn't really done anything quantitative with it," he says.

The Duke alumni decided to go the Mr. Potato Head route, building epoxy models of insect fossils, each with detachable wings. (Kingsolver, now a biology professor at the University of North Carolina at Chapel Hill, says he loved brainstorming with Koehl about these models. Once, he recalls, they were talking about how to build an aquatic insect. "Mimi said, 'Oh! You need something that soaks up water, holds it well, and wicks out to the edges. How about tampons?' ")

Adding and removing wings of different sizes, Koehl and Kingsolver tested their insects in a wind tunnel and under a heat lamp—a series of experiments that evolutionary theorist Stephen Jay Gould later called "elaborate and elegant." As they reviewed the data, the duo came to detect an evolutionary two-step. As long as insect bodies were small, their proportionately small wings were useless for flight, but they had another function: The longer the wing—up to a point—the better it absorbed the sun's heat and therefore helped regulate the insect's body temperature.

Could insects' wings have worked as parachutes or steering rudders? Could they have served as tiny solar panels? What if they made an insect sexier?

If evolution eventually produced larger insect bodies—the fossil record is unclear—the wing sizes would likely have kept pace. Beyond a certain length, though, the insect gained no more advantage in terms of thermoregulation. That's where Part 2 of the two-step kicks in: About the same time, Koehl hypothesizes, the wings were finally long enough to support flight. Thus, a body part that began with one function evolved to take on an additional function without changing shape. Whether such "functional shifts" were possible had been a hot debate in Charles Darwin's time, and Koehl and Kingsolver were weighing in more than a century later.

Koehl emphasizes that her conclusions are not definitive. "Without a time machine, we can never know whether that occurred," she says. Instead, what made the research extraordinary was the suggestion that simply by growing, a body part can take on a whole new use. "Nobody's ever thought about how size change could lead to a novel function," she says. "One of the questions you worry about a lot in evolutionary biology is, Where does novelty come from? And we're saying, 'Here's a really simple mechanism for generating novelty that nobody's really talked about before. So you ought to think about it.' "

JUST AS THE EPOXY INSECTS HELPED KOEHL EXAMINE THE FUNDAMENTALS OF FLIGHT, Rasta Lobsta helped her study the basics of smell. Intuition might tell us that odor molecules move in clouds, which are most concentrated at the source and disperse as they move away. But when Koehl and her colleagues shined their laser through the robotic lobster's tank, they saw another pattern entirely. The odor plume moved in filaments—long stripes that remained distinct from the surrounding water.

The Caribbean spiny lobster sniffs by flicking its antennules in two distinct motions. During a rapid downstroke, Koehl saw in her video, the lobster gathers a new sample of odor stripes in the sensory hairs of its antennules, and also sweeps away the scent molecules from its last sniff. A slower upstroke traps the smell long enough, presumably, for the animal to process what it's smelling. Through it all, the shape of the odor remains intact. Before the experiment, "nobody knew what would happen when an antennule interacted with the filament structure," Koehl says. "Would it get all mushed up? Would it be preserved? What we saw is that all those stripes of odor get preserved." Scientists still need to figure out what the lobster does with all that information once it reaches the animal's brain.

Koehl and Koseff, the Stanford engineer, published their findings in the journal *Science* in 2001. For Koehl, this was just the beginning. She is now studying the noses of other crustaceans like crabs and manta shrimp. "We'd like to study enough different kinds of animals to tease out what the basic design principles are for making a hairy nose that will catch odors in the ocean," she says. "If you make toothbrushy ones like crabs have, what are they good at? If you make comblike ones like manta shrimp have, what are they good at? Or do they all work equally well?"

But Koehl's worklife is not all sniffers all the time. One of her latest curiosities is *Microraptor gui*, the feathered dinosaur, which scientists say evolved long after early birds veered away from the dinosaur family tree. The discovery of the thirty-inch-long, four-winged animal by Chinese scientists in 2003 has given fodder to researchers debating the origins of bird flight.

"One school of thought is that these little guys were running away from the predator, and they're flapping their arms and their feathers, and they take off," Koehl says. "And then the other idea is that they were sitting up in the tree or on a cliff, and they jumped off, and they could glide if they had feathers. What I thought would be a fun project to do with teams of undergraduates would be to build models of these dinosaurs"—with feathers that can be placed in different positions or removed entirely—"and put them in the wind tunnel and basically do what Joel [Kingsolver] and I did for insects." After all, she says, "What kid doesn't like dinosaurs?"

Koehl hasn't reached any definitive conclusions from her research yet. But when she does—well, rack up another victory for Mr. Potato Head.

Yeoman is a freelance writer whose work appears in On Earth, AARP The Magazine, *and* O, The Oprah Magazine.

Peek in Koehl's lab; watch an animated cartoon explaining her work on sea anemones: www.dukemagazine.duke.edu