

SECOND NATURE

MORE AND MORE, INNOVATIVE SCIENTISTS ARE TURNING TO THE
NATURAL WORLD FOR INSPIRATION . . . AND DESIGN SOLUTIONS

BY JIM ROBBINS

A

FTER DONNING WHITE

Tyvek suits and slipping
plastic booties over our

shoes, Jeffrey Turner and I enter a cavernous metal building on a farm outside Montreal. Having never seen a genetically modified animal before, I don't know quite what to expect. The goats I see immediately disarm me with their intensely curious doe eyes. One buckskin-colored nanny with long, floppy ears rears up on her hind legs, begging for a scratch. I'm under strict orders, however, not to touch her or any of the others because I might inadvertently pass along germs that could make them sick. That would not be good—these animals represent more than \$20 million in research. In a feat of technical wizardry, biotechnicians have inserted genetically modified fertilized eggs into the

goats' wombs. Their offspring will carry a silk-producing gene from a golden orb weaver spider in their genetic libraries. Turner expects that milk from these goats will contain the essence of spider webs. Move over, Spider-Man.

Turner, a molecular biologist and the president and CEO of Nexia Biotechnologies, Inc., is betting his career and a great deal of money that these animals will make history. While they may never be as famous as Dolly, the sheep cloned by Ian Wilmut of the Roslin Institute in Scotland, they could prove far more lucrative. Pound for pound, the gossamer silk threads created by orb weaver spiders are five times stronger than steel. One day spider silk might be found in everything from air bags, fishing line and non-tear sports jerseys to ophthalmic sutures and artificial tendons.

The quest to harvest spider silk is one of the latest and most promising experiments in biomimicry, a burgeoning field in which scientists and designers alike mine nature for solutions to all sorts of problems. Says Janine Benyus, a science writer who popularized the term biomimicry in her 1997 book of the same name: "Unlike the Industrial Revolution, the Biomimicry Revolution introduces an era based not on what we can *extract* from nature, but on what we can *learn* from her." Biomimicry has the potential to make products cheaper, better, more efficient and ecologically friendlier.

Human engineers, of course, have always looked to nature for inspiration. "Human ingenuity may make various inventions," Leonardo da Vinci wrote in the 16th century, "but it will never devise any inventions more beautiful, nor more simple, nor more to the purpose than Nature does; because in her inventions nothing is wanting and nothing is superfluous." Witness the multifrequency echolocation system of the bat, which enables it to navigate in pitch darkness at breakneck speeds, or the remarkable stamina of the arctic tern, which migrates 22,000 miles a year.

The most significant biomimicry breakthroughs have come not from merely copying nature, however, but from learning the principles and mechanics behind natural systems and then applying them to human needs. In fact, direct copying of biological organisms can lead to poor, or even disastrous, engineering designs. Consider all the failed attempts humans made to fly by building contraptions with flapping wings. The Wright brothers found success not by replicating the motions of a bird but by discerning the subtleties of lift and stability in the action of a bird's wing and translating them to a fixed-winged craft. "My observations of the flight of buzzards," wrote Wilbur Wright to engineer Octave Chanute in 1900, "lead me to believe that they regain their lateral balance, when partly overturned by a gust of wind, by a torsion of the tips of their wings." Says Robert J. Full, a biologist at the University of

California at Berkeley, "This is biological inspiration, not direct copying from nature. I can't fly across the country on a bird—planes are pretty good."

Likewise, inspired by a shrubby tree found in Texas, entrepreneur Michael Kelly filed a patent for barbed wire in 1868. He had observed that farmers would install thorny plants to contain their animals in areas where wood for fencing was in short supply. But the plants took a long time to grow and weren't portable. So Kelly decided to give "fences of wire a character approximating . . . that of a thorn-hedge," mimicking the barbs on the Osage orange tree. Like the Wright airplane, it was not strict emulation: the angle of the thorns was not the same, and the wire was more vine than tree branch. But it worked. (Today, more than 100,000 tons of barbed wire are sold in the United States alone each year.)

So, too, the mandibles of the larvae of a wood-boring beetle became the model for the teeth of one modern chain saw design. And, in perhaps the most well-known example of biomimicry, Swiss engineer George de Mestral, in the early 1940s, drew inspiration from the annoying cockleburs that stuck tenaciously to his hiking pants and to the hair of his dog, to come up with the Velcro fastener, a product in which one surface, consisting of many small hooks, secures to another covered with loops. It became commercially feasible when engineers designed machines that could shape nylon into masses of small, flexible hooks that do not lose their shape.

More recently, in 1995, Ray Anderson, president of Interface, one of the world's largest commercial carpet companies, turned to David Oakey Designs, a textile design company near Atlanta that now specializes in biomimicry, to create carpeting that would be more environmentally friendly. Prompted by Anderson's interest in biomimicry, Oakey asked his designers a series of provocative questions: "Can you [color] it without dye, but with refraction, like the feather of a bird? Can you make it like a snakeskin, where instead of taking out the whole carpet you take a sliver off the top and replace [just] that?"

Answering questions such as these led Oakey and Interface to develop Entropy, a carpet that mimics the randomness of the forest floor with small sections, or tiles, each composed of different shades of color. Because color matching is no longer a problem, only a worn or damaged section needs replacement.

STILL, MUCH OF THE NATURAL WORLD has been inaccessible to scientists because its mechanics are so complex and take place on such a small scale. It's one thing to apply the lessons of a thorny bush, another to understand how a hawk's biological clock tells it to fly south for the winter.

“There is no assembly plant so delicate, versatile and adaptive as the cell,” writes Philip Ball, a consulting editor for the British science journal *Nature*. But as we press more confidently into the inner workings of DNA and the proteins that control so many of the processes of the human body, our ability to reap new harvests from the natural world will grow significantly. Promising new commercial and military technologies—in aerospace materials, smart sensors and robotics—have applications far beyond what we see in nature.

Researchers at the University of California at Berkeley and Stanford University, for example, have focused on the small hairs on the antennules of the spiny lobster, which are sensitive to smells in shallow, turbulent waters. Using lasers, dye and high-speed video, they discovered that the small hairs trap part of an “odor plume” in the water. A rapid flick of the antennule by the lobster clears the hairs and captures a new set of data. Thus, a series of quick flicks gives a lobster useful information about the odors in the water around it, even as the water—and odors—speed by. The researchers are studying how the lobster determines the location of the odor source. “The lobster had millions of years to learn how to accomplish an exceedingly difficult task with relative efficiency,” says researcher John Crimaldi, now at the University of Colorado. Keith Ward, chair of the Office of Naval Research’s Biomolecular and Biosystems Science and Technology Group, says he expects the research to lead to sensors that the Navy can use to locate and identify unexploded ordnance and chemical weapons in shallow marine waters.

While lobsters may provide clues to building smell sensors, a parasitic fly is a source of inspiration for designing better hearing aids. At first sight, the *Ormia* fly appears quite unremarkable, a yellowish housefly that deposits its larvae on the bodies of living crickets. Researchers at the State University of New York at Binghamton and Cornell University have discovered, however, that the fly locates crickets by tracking their chirping sounds, using the equivalent of directional microphones. The fly’s hearing organ is so effective that it could provide a model for making tiny hearing aids with improved directional capabilities.

Then there’s the gecko, the lizard capable of bounding across walls and ceilings with speed and confidence. Berkeley’s Robert Full studies the microscopic hairs on the gecko’s toes, which adhere to surfaces through molecular interactions known as van der Waals forces. Although these individual attractions are weak, the combined adhesion of the billion split ends on the feet of a single gecko could theoretically support a 60-pound weight. Full believes that this effect can be harnessed to create an adhesive tape that could be used again and again. Similarly, scientists

are studying the mussel, which uses proteins to make a glue so effective that it bonds the bivalve to rocks, even in cold seawater. Such a glue could be used for everything from surgical adhesives to ship repair.

One biomimicry product to come to market recently is Lotusan, a silicone-based paint inspired by the lotus plant. Although the plant grows in mucky swamps around the world, its leaves remain clean and dry—dirt and water simply do not stick to them. The German manufacturer of Lotusan claims that the house paint will repel dirt like the lotus and needs only a light washing with water. The microscopic surfaces of both the dried paint and the lotus leaf resemble jagged mountainous terrain, which repel dirty water because the contact area is reduced.

BUT THERE MAY BE NO BETTER EXAMPLE OF NATURE’S elegance and efficiency than the silk in a spider’s web. In his cubbyhole office at the University of Wyoming in Laramie, molecular biologist Randy Lewis displays a computerized anatomical drawing of the golden orb weaver spider. Each of six separate sets of glands in the spider’s abdomen produces a different protein solution, or dope, which the spider forces through spinnerets to produce six kinds of silk: one for wrapping eggs; another to secure prey; three for building a web; and, strongest of all, dragline silk, which a spider uses to hang from a ceiling or branch and for the structure of its web. “Dragline silk is the strongest material ever made by an animal,” says Lewis, a leading expert on spider genes. In theory, a braided spider silk rope the diameter of a pencil could stop a fighter jet landing on an aircraft carrier. And it is as elastic as nylon. The combination of strength and elasticity allows it to withstand an impact five times more powerful than can Kevlar, the synthetic fiber used in bulletproof vests.

But harvesting spider silk is not a job for Little Miss Muffet. “Everyone has tried to farm spiders,” says Nexia’s Turner, “but no one has been successful.” Put spiders together and they end up eating one another. In 1998, Turner learned that Lewis and others had isolated the genes for spider silk. Aware that researchers had used the lactation system of goats to produce medicines, he wondered why a goat couldn’t also make spider silk in its milk. After all, the gland that produces silk in a spider is similar to that which produces milk in a goat. “So I called up Randy to help us with the golden orb weaver genes,” Turner recalls.

Nexia technicians began by removing hundreds of fertilized eggs from several dozen goats. The researchers then inserted spider silk genes into the fertilized eggs and returned them to the goats. As the first of the resulting females become mothers themselves this summer, Nexia technicians will skim and concentrate their milk, which at

this stage will look like maple syrup. Up to this point, Nexia will not have done anything so revolutionary. “Mimicking what the spider does is the hard part,” says Turner. In its spinnerets, a spider somehow turns the liquid dope into silk of a perfect consistency—not too wet or brittle but strong and super elastic.

Turner volunteers only the barest details about how Nexia and its collaborator, the U.S. Army Soldier Biological Chemical Command in Natick, Massachusetts, force the spider dope through a syringelike apparatus to create long monofilament fibers that can be braided or woven. In preliminary tests of silk produced by isolated cells in the lab, Nexia has created silk with many properties comparable to natural spider silk. But, Turner admits, it has only 30 percent of the natural fiber’s strength. Still, he is optimistic that he can make the fiber stronger, and he says he will patent the process in the next several years.

SUCH FUNDAMENTAL TINKERING IS NOT WITHOUT CONTROVERSY, of course. “There’s this simpleminded notion that you’re dealing with Lego blocks and if you pull one out and put it somewhere else, you know exactly what you are doing,” says Ruth Hubbard, a professor emerita of biology at Harvard and a founder of the Council for Responsible Genetics. “But it’s unpredictable, and it’s naive to think you can predict exactly what will happen. I always ask ‘Why are we doing this?’ If there’s a good reason for doing it, and it’s done carefully, it’s OK. If it’s just another way of making money, I don’t think it’s worth taking the chances.”

But there’s more than one way to skin a cat—or mimic spider silk. David Kaplan, a professor of chemical and biological engineering at Tufts who has studied biological silk for years, has high hopes for braided silkworm silk. While it is not as strong as spiders’, he says, it can be used in biomedical materials relatively quickly and is commercially available in large quantities.

In his Tufts laboratory, Kaplan shows me a large, shallow metal box, called a winding tray, that looks something like the inside of a grand piano and holds a dozen tiny electrical motors. Taut four-foot-long fibers, each composed of ten strands of silkworm silk, are affixed to the motors at each end of the tray. A computer programs each motor to wind fibers with a different number of twists per inch, giving each fiber a different strength and elasticity. “You can get whatever properties you need if you bundle it and cable it the right way,” Kaplan says.

He believes that human tissue will grow around the fibers to create new ligaments. Though he is concentrating on making an artificial alternative to the anterior cruciate ligament, the knee tissue that is a problem for many athletes, “in theory it could be used for any tendon or liga-

ment, as well as other tissues,” he says. Human trials are between one and three years away.

Society may decide to embrace genetic engineering or it may reject it as too dangerous. But in either case, the natural world will continue to inspire designers, scientists and other innovators. As I stood in the hallway of the kid nursery at Nexia’s farm and came to grips with the idea that frolicking goats like these might someday produce the raw material of bulletproof vests, the possibilities of biomimicry seemed limitless. As scientists peer more deeply into nature for inspiration, who knows what products will emerge to change the course of our lives. 

Jim Robbins, who lives in Helena, Montana, wrote A Symphony in the Brain: The Evolution of the New Brain Wave Biofeedback.

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