

The Beauty of Biomimicry

For a peek into the future of industrial design, look no further than the ears of a fly or the brilliant colors of a hummingbird's wing.

by Diane Stresing

Maybe you laughed as you watched Peter Parker discover he'd developed a sixth sense, disproportionate strength, and web-shooting abilities of a (not-exactly-garden-variety) spider. Comic book heroes notwithstanding, scientists aren't laughing at the potential biomimicry holds for industrial, medical, and other applications.

The term biomimetics comes from the Greek "biomimesis," meaning to mimic life. "Biomimicry is what happens when you invite a biologist to the design table," said Janine Benyus, author of *Biomimicry: Innovation Inspired by Nature*. The allure for designers, from the aerospace industry to medical fields, lies in the efficiency, strength, and general compactness of natural designs. The orb-weaver spider, for example, makes silk that is five times stronger ounce for ounce than steel. Scientists would also do well to duplicate the manufacturing process. Spiders make the stuff without high heat, pressure, or toxic chemicals.

Generally, humans use high heat, high pressure, and chemical treatment to create artificial materials. Ironically, because of this very trait, we consider ourselves to be the most highly evolved of all creatures. But nature's "lowly" creatures often have a better way of doing things, and they typically "manufacture" in or near their own bodies.

Take for example the peacock, the blue jay, or hummingbird. All appear to be painted beauties. But "nowhere in the natural world will you find a coat of



The secrets of the butterfly's wing, shown in various details here, offer a road map to innovation for scientists seeking new ways to make the world a better place.

paint on things. Paint can be very toxic," Benyus said. So how do the birds appear so brilliant? It's trompe l'oeil, an optical illusion. Peacocks, jays, and many other birds are actually completely brown in color. They appear brightly colored thanks to light that refracts through layers of keratin (the same protein in your fingernail). The animals make many thin layers of the stuff, and as light travels through those layers, it refracts in various wavelengths, creating the illusion of, for example, teal, yellow, and aquamarine.

Imagine the same process creating your laptop case, in bright purple if you wish. You'd get permanent, never-fade color that's chip resistant, too. Imagine such a dip-coat on your car, or a plane. Anything now made of molded composites could be treated to peacock-inspired color. Scientists at Sandia National Laboratories are working on it now. Similarly, the body of your next car may be treated with a substance inspired by the toughening properties of antler bone.

A wide variety of biomimetic projects are in development, in testing, or in use now. One company, Iridigm (www.iridigm.com), uses naturally inspired technology to create laptop displays that you can read in sunlight. While it works using a microelectromechanical device, its function was inspired by natural iridescence.

According to Benyus, another commercially successful example of biomimetic design can be found underfoot in many office buildings. A design called

Entropy is the top seller at the \$1.3 billion carpet maker Interface (www.interfaceinc.com). One reason it quickly became a top seller: When you need a new piece, you snatch up a section and replace it—and no one can tell where old and new meet thanks to a random patterning inspired by a leafy forest floor. The company recycles used carpet pieces, Benyus said, and routinely considers natural systems in new product design.

A surprising variety of other projects are under way.

Health and Industry

Would you wear a hearing aid modeled after a fly? Not just any fly, mind you, but the *Ormia*, native to the southern United States and Central America. Unlike the common housefly, *Ormia* has real ears, and the mechanical design of those ears is superior to human ears in several ways.

Ron Miles, professor in the Department of Mechanical Engineering at the State University of New York (SUNY) at Binghamton (www.me.binghamton.edu), said the *Ormia*'s design could resolve the chief complaint about hearing aids, that they are poorly designed to pick up directional noise. Since most speech occurs in front of a listener, hearing aids that could filter out extraneous noise and pick up sounds in line with speech patterns are of great interest to the medical world. The same line of research is being used to develop vibration dampers for magnetic data storage systems, and in early detection of joints fatigue. SUNY researchers have also studied how other animals communicate using vibration.

Miles, who has degrees in electrical and mechanical engineering, began his professional life doing acoustics work in the aerospace industry. A few years later, he hooked up with Ron Hoy and Daniel Robert, both biologists at Cornell University, and then, things got rather buggy. In addition to flies, Miles has shared his office with jumping spiders, katydids, crickets, and fish. His colleagues identify the species that have potentially useful nervous and biological systems, and Miles handles the measurement and analysis needed to create models to attempt to mimic unusual natural systems. "I can do the mechanics," he said, and "they help me out with the anatomy."

The cross-disciplinary nature of the SUNY research group is a key to its success. According to a 2000 report by NASA, advances in the field of biomimicry will come from teams in which scientists with a broad range of specialties work together.

What happens inside a biomimetic research lab? Consider a study of treehoppers. Miles, working with R. Coccoft of the University of Missouri, studied the vibrational communication between male and female insects, which resemble rose thorns, communicate with each other through vibrations. He "listened" as the male, sitting on a branch or twig, vibrated a "song" (which humans "hear" using a vibration sensor). When the female sitting on the same branch likes the song, Miles said, she calls out to him, effectively saying, "Come up and see me some time."

"He's got to know which way to go," Miles said. Finding

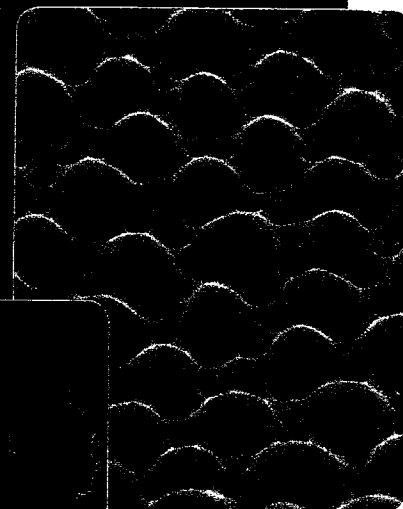
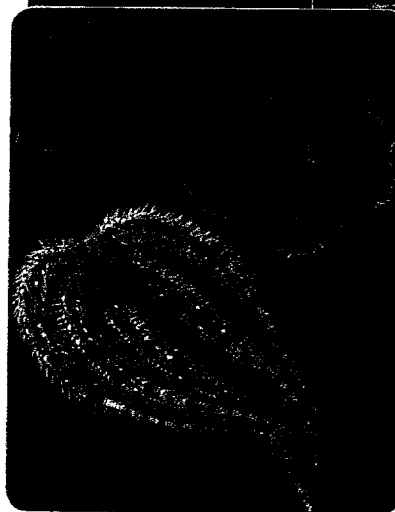
A Biometric Star Is Born

When you already hold more than 2,500 patents in optical technology, where do you look for inspiration? You might as well search the deep blue sea. That's where scientists at Lucent Technologies' Bell Labs (www.bell-labs.com) found the brittlestar. Related to the starfish, the marine invertebrate sports five long, thin, flexible legs on its disk-shaped body. Researchers have learned that all brittlestars are not created equal: there are light-indifferent species, and light-sensing varieties. Today, light-sensing brittlestars are getting the lion's share of attention, because they make a surprisingly efficient calcite crystal that acts as both armor and as an optical micro lens.

Biophysicist Joanna Aizenberg began studying brittlestars when she was a graduate student. She now conducts her research at Lucent Technologies' Bell Labs headquarters in Murray Hill, NJ. The brittlestar is a fairly common marine animal, but it was Aizenberg's studies that first showed how unusual their skeleton is, said Bell Labs spokesperson Saswato Das. Aizenberg figured out that it acted as a giant compound eye. On closer examination, it turned out to be composed of thousands of perfect microlenses. Nature has come up with a really neat design.

Explaining what physicists refer to as a "thick lens," which is different from the thin lens common in eyeglasses, Das said, "Think of looking through a glass of water; that's a thick lens. You'll have distortion, caused by aberration. There are ways to correct aberration, but nature's design is better."

Das describes this as a long-term research project, saying he may not see products on the market with brittlestar lenses for several years. But eventually "they could be used everywhere micro lenses are used," Das said. The most immediate use, he said, might be in lithography, using photo-resist techniques to etch tiny chips for computers. The better the lens, the better the potential for sharp connections between the tiny lines on the chip.



Brittlestars are anything but, thanks to their calcite crystal armor.

out how the male senses the female response, and which way to go to find her, could be very helpful in marine and aviation systems. "This kind of thing could help identify where a troublesome vibration is coming from on a submarine or a plane," he said. It could also be developed into a simple

seismic detector, one that's compact enough for ground troops to carry. They could use it to determine which direction the (enemy) tanks are moving, and how close they are.

But how do insects sense vibrations? Miles' office, a 1,400-square-foot lab, is equipped to find out. Among more traditional measurement devices, the lab includes three laser vibrometers (ranging in cost from about \$50,000 to \$200,000 each) and vibration-isolation tables. The non-contacting laser vibrometers are especially useful, for example, when Miles is measuring the vibration of a fly's eardrum or a spider's leg.

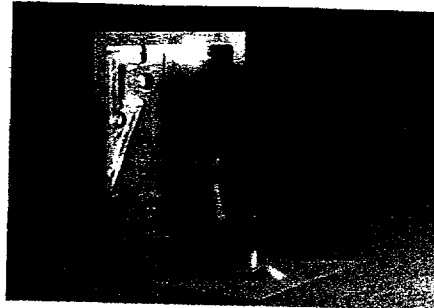
Miles' studies of crickets, katydids, and flies focus primarily on finding potential models for improved human hearing aids. His studies of fish may help the Navy. Although sound travels much faster in water than in air, fish can determine the acoustic pattern and the direction from which a sound originates, Miles said. Such data holds rather obvious promise for developers of marine navigation systems.

Meanwhile, at the Beckman Institute at the University of Illinois (www.beckman.uiuc.com), Scott White and other researchers are creating autonomic materials systems. Systems that mimic the body's processes, from regulating temperature to healing broken parts, can be built into new materials. The project that's been driving White for seven years is a composite material that heals itself.

Funded in large part by the U.S. Air Force, White said the self-healing polymer was "inspired by the body's mechanism for healing itself—skin is an excellent example. When [skin] is cut, it triggers a cascade of chemicals that tell the body, 'heal me here.'"

To create the self-healing composite (similar to that which is used to make airplane bodies), a catalyst is ground into a fine powder and mixed into an epoxy resin. A liquid healing agent is then encapsulated in a polymeric shell and mixed into the resin. When cracks occur, the capsules also crack, "spilling" the chemically active liquid, which is drawn to the cracks. When the catalyst comes into contact with the liquid, it triggers a reaction and bonds the cracks closed. Certainly, this has potential in the aerospace industry.

Years—and many clinical trials—from now, the compound may also be safe for use in artificial bone and joint replacement. Today's artificial joints tend to degrade over time, lasting about ten years. A biocompatible self-healing polymer could mean that your next knee replacement would



Researchers at the University of Illinois are attempting to create self-healing polymers that mirror the body's own resilience.

be your last knee replacement. Alas, the best catalyst White has used to date (he calls it "perfect," as it is both highly stable and highly reactive) cannot be used inside your body. Still, White anticipates a day, not long from now, when a biocompatible catalyst will make the self-healing polymer available for knees, hips, and other joints.

It's a short stretch from artificial joints to artificial muscles. Natural muscles are essentially bundles of long, thin cells called muscle fibers. Each one is thinner than a single human hair. Each fiber is made of thousands of thinner threads, or fibrils, and each of those is made of proteins that sense electrical signals from the brain and spinal cord. Those neuro signals are what make muscles contract and expand.

MuscleSheet, created by Biomimetic Products (www.biomimetic.com), is a soft, electroactive composite material that can be mechanically bent by applying low-voltage charges. How much it bends depends on the frequency of the applied voltage and the thickness of the sheet. Because it is ionic, MuscleSheet needs to be wet to work. Not coincidentally, it is being used in propulsion fins for surface and underwater vehicles in autonomous swimming structures, biomedical endoscopic devices, and actuators in space applications. Biomimetic Products founder Mehran Mojarrad began work on MuscleSheet and similar products as part of his graduate research.

Mojarrad founded Biomimetic Products in 1995 with a design philosophy that he said "was inspired by biological systems. The idea was, 'How can we replace or replicate biological muscles?' All biological muscles are polymers that occur naturally. These [polymers in MuscleSheet] are special polymers, consisting of ionic chains of molecules."

Mojarrad is working to reduce the risk of biorejectivity. In the future, he'd like to see MuscleSheet used to successfully replace damaged human muscle. Mojarrad said it will take "about a decade and moderate private and federal funding" to reach the point where human muscle replacements are common and don't carry the risk of rejection. In the meantime, he said, "The biggest growth (for this product) will be in commercial uses, especially remote control toys." Other areas in which this product will be used include biomedical sensing and environments unsafe for human access such as space.

Another man-made muscle is already in use in industrial

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applications. Designed by Festo (www.festo-usa.com), the Fluidic Muscle is a pneumatic actuator that offers several unique attributes not found in conventional pneumatic cylinders. Festo's muscles, like their natural counterparts, perform with smooth motions, and provide their greatest force at the beginning of a stroke, which increases acceleration.

To compete with pneumatic cylinders, the Fluidic Muscle provides about ten times more force at the beginning of a stroke, which increases acceleration efficiency. To increase overall efficiency, they work in the beginning of the stroke. The Fluidic Muscle also works in about one third of the space required for conventional pneumatic cylinders, said company spokesperson Allan Poxon, although, like natural muscle, Festo's device widens radically when in use. While the Fluidic Muscle was designed for mechanical applications, it clearly took a page out of the anatomy book.

From War Games to Fun and Games

A submarine that swims like a shark and is made of something akin to dolphin skin sounds like a good design concept, doesn't it? As early as 1960, scientists (and governments worldwide) were investigating natural fluid-dynamic systems to make better war machines.

Today, some people wonder if the U.S.—or another—government is using ultraminiature airplanes, indistinguishable from honeybees, as reconnaissance vehicles. There's no proof, although such speculations have found their way into aerospace industry circles. Understandably, much early-stage research and many projects are not ballyhooed by the government agencies involved in the work. However, unclassified documents and even stories in the popular press describe many projects in brief.

Last year, the U.S. Navy introduced a biomimetic lobster designed to detect mines. Some welcome news: The Navy-made lobster is taxpayer friendly, with an estimated cost of less than \$1,000 each.

In general, military research projects focus on biomimetic sonar (like that of bats and marine mammals) for navigation systems, on marine propulsion techniques, natural cooling systems, anti-fouling coatings, and adhesive properties in natural organisms, like slugs.

Meanwhile, the beauty of natural systems has impressed

designers at commercial sporting goods manufacturers. Nike (www.niketown.com) advertises new soccer shoes made of a material like kangaroo skin, only better—it's not from a kangaroo, and it's actually stronger. Rawlings' (www.rawlings.com) Vise softball glove is designed to keep a catcher's fingers close together, as they are in a natural, barehanded catch. The result is a stronger grab and reduced risk of injury. Then there's Ornitech (members.tripod.com/ornitech), the Warwick, NY-based business started by two high school kids. They sell make-your-own kite kits for kites that flap their wings just like dragonflies and swallows. While the founders are still in their teens, their business is three years old.

Flying machines based on flapping wings are called Ornithopters. Nathan Chronister, president of The Ornithopter Society (ornithopter.org), said man has learned much about the process since da Vinci's first ornithoptie sketches, but we've yet to master flapping flight. One nifty trick we'd like to duplicate: Birds make mid-flight adjustments to deal with wind currents. Yet, Chronister admits, "It's hard to reach (a bird's) level of efficiency." Ornithopters today use more power than the same size bird.

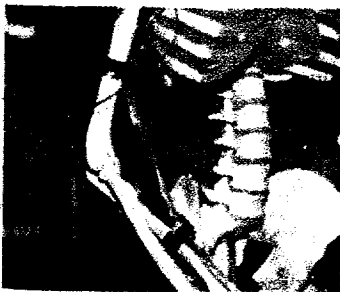
The Ornithopter Society itself doesn't sponsor research, but many of its members are serious about unlocking the secrets of winged flight through their own research programs. Former member Paul McCready, founder of AeroVironment (www.aerovironment.com), has worked closely with NASA and other government agencies to develop viable Unmanned Air Vehicles, or UAVs. One model, the Pathfinder Plus, is solar powered and has a wingspan of more than 100 feet. It set an altitude record of 80,000 feet.

Birds, in fact, have a whole flock of researchers following them. Not just to mimic flapping flight, but also to understand and use some of their navigational and language learning abilities. We've yet to crack bird migration systems, for example. Every autumn, summer songbirds leave northern climes for winter perches far south. Migration paths can span 3,000 miles or more.

Making the trip even more difficult, most songbirds make their migratory flights at night. How do they navigate? Studies by Cornell University in the 1960s suggested that birds used the stars for guidance. But more recently, scientists observing bird migrations by radar have noted large oriented flights on even overcast nights, when the birds could not have used the

stars for guidance. Researchers with their eyes on the skies continue to study migration patterns for clues to the secrets of bird navigation.

Speech studies with birds as subject are also in the works. In May, Duke University neurobiologist Erich Jarvis received the prestigious Waterman Award, and \$500,000



Biomimetic Products' MuscleSheet could be coming soon to a toy near you. It may one day be used to replace damaged human muscle.

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43

Leeching: A Modern Twist on Old Medicine

If you look through old anatomy books and medical journals, you'll find leeches touted for many uses. In fact, leeches still offer viable treatment options. Creating a new, improved leech is the goal of scientists Gregory Hartig, who heads the project, Nadine Connor, and Michael Conforti, all at the University of Wisconsin, Madison.

Conforti, who conducts most of his research at the Veterans hospital, said the trio's mechanical leech is designed to do what natural leeches do, only better—at least from the doctor's and patient's viewpoint. What does a live leech do? Looking for a meal, it makes an incision and begins to deconstruct tissue. At the same time, it secretes an anti-coagulant and, researchers think, a sort of anesthetic, too.

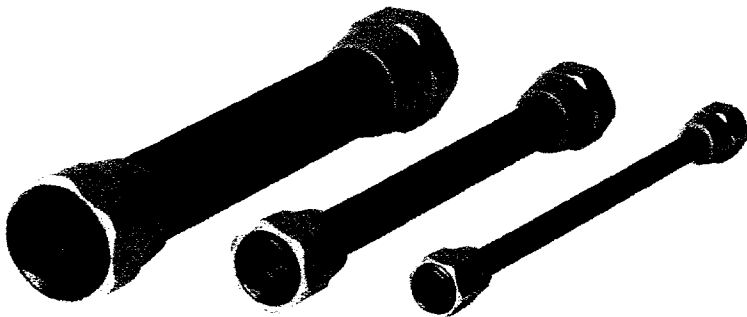
As creepy as leech therapy may seem, it has terrific benefits for post-operative patients. The three researchers have developed a prototype mechanical leech that may be better behaved and cheaper than nature's original design. "A (live) leech may cost \$5 to \$7, plus shipping," said Conforti. "If you throw on a leech or two every hour, it adds up." Once a live leech has done its job, it is removed from the patient and then killed in alcohol. A mechanical replacement would probably be a once-a-day sort of application, with the device's head sitting on the patient's skin while tubing handled the in- and outflow of fluids.

Plus, the mechanical leech Conforti, Connor, and Hartig designed does an even better job at getting under the patient's skin. "A real leech seems to stay superficial, while the mechanical leech goes a little deeper and is able to tap into some larger blood vessels in the deeper layers of the skin. We go into the dermis, and even under."

in research funds, from the National Science Foundation (NSF). Although only three bird orders (hummingbirds, songbirds, and parrots) are known to be capable of vocal learning, Jarvia is studying their brain structures as they relate to language learning in the human brain.

Biomimetics—Will it Compute? And, What's the Catch?

What in nature could make your laptop lighter and your palm more powerful? Photosynthesis, in a battery cell. In a nutshell, here's how it works: Leaves take sunlight and



They may look like dumbbells, but these cylinders are actually man-made muscles that provide smooth, lifelike movements.

"crack" water molecules into oxygen and hydrogen, using the hydrogen energy (something humans have experimented with, you may remember) to produce sugars and starches. Naturally, such batteries create fewer problems in landfills compared to their lithium counterparts.

When the digital world isn't fast enough, Benyus said, perhaps we should consider natural computing. "Exploring how nature computes leads to true molecular electronics." The next generation of computing may be biological. A cell is just like a computer, Benyus said. "As molecules jigsaw together in cells, they set off a cascade of reactions that pass along a message."

When you think of computing in the simple sense of "signals plus meaning equals actuation," and consider what happens in your body when a fire alarm goes off, you'll see her point. Faster than any man-made parallel computing system, adrenaline signals your stomach to stop digesting, tells your lungs to grab some air, your heart to beat faster, and your muscles to prepare to take flight. "Shape-based computing and massive parallelism" are available to us when we use nature as a guide, Benyus said.

As more money and research focuses on mimicking nature's designs, is there a danger we'll lose the collective brainpower of some of our top scientists, who might otherwise come up with truly new (better than nature) designs?

While that's theoretically possible, it's not likely. It's more likely that we will come up with better ways to wage war, Benyus said. "We mimicked dolphin skin and put it on a submarine to deliver weapons faster." She's quick to point out another concern with biomimetic research. "There's a real danger, I think, in looking at nature for our ethics. I don't think the natural world is a place to look for our morals. Who are you going to imitate? A lion? A bear?"

We could benefit from countless natural designs. Or we could use them to create faster ways of killing each other or of depleting resources, Benyus said. "We could hook into the power of the sun, and have unlimited energy," she said with both hope and irony. What we do with that energy then, for better and/or for worse, is up to us. "If we focus on creating conditions conducive to life, biomimicry might earn our species a longer stay on the planet," Benyus said. "Imagine real distributed manufacturing using abundant local merchants and life friendly processes. Nature doesn't have a central energy manufacturing plant; each leaf gathers its own energy to make what it needs. All the while, every cell in that leaf is processing feedback from its environment. That's what makes ecosystems run smoothly: sunlight and information."

As research continues in biomimetic, nanotechnology, molecular computing, artificial life, and other scientific and medical fields, more arguments will arise in courtrooms, funding meetings, and boardrooms. In hindsight, the dilemmas posed by cloning, stem cell research, and remote medical care may be considered the easy scientific debates of this century.