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INDUSTRIAL MANAGEMENT & TECHNOLOGY

Learning at Mother Nature's Knee

Designs fine-tuned by billions of years of evolution inspire 21st-century inventions through the science of biomimicry.

By John Greenwald

Natural selection has been at work for eons, creating designs that outperform anything humans have yet devised: abalone shells tougher than the hardest ceramic, spider silk stronger than steel, a sea creature called a brittle star that can focus light ten times more sharply than the finest man-made lens. Today researchers are studying such forms in hopes of hatching new products and technologies. The work is advancing at companies as varied as Lucent Technologies and Nike, which this year retained a biologist to advise its shoe and clothing designers, and at centers like the new Biodesign Institute at Arizona State University, which plans to build nearly $350 million of laboratory and conference facilities over the next few years.

It is all part of an emerging science known as biomimicry that studies nature's models and imitates and adapts them for human use. Some of biomimicry's first fruits can already be found in such disparate applications as fabrics and house paints that emulate the uncanny ability of lotus leaves to repel dirt and water, carpets styled after the randomness of stones and leaves on forest floors, and superefficient fans and rotors.

The gap between natural inspiration and profitable invention sometimes remains hard to bridge. Three years ago a Canadian company called Nexia Biotechnologies generated headlines when it spliced spider genes into goats and created what it called the world's first man-made spider silk from the animals' milk. It named the product BioSteel. But the company couldn't economically mass-produce the fibers, and it quietly scuttled the project this year. Another goat-inspired product, Nike's Goat-Tek, a late-1990s trail shoe with a sole modeled on a mountain goat's hoof, never bounded off store shelves and was discontinued. Some researchers remain skeptical. Asks Rustum Roy, professor emeritus of materials science at Pennsylvania State University: "Biomimicry may produce something useful in very tiny areas, but what else are we going to apply it to? Not to highways or steel mills."

The speculative nature of many biomimicry projects means that they require big investments that can come only from government agencies, universities, and major corporations. At Lucent's Bell Laboratories, researcher Joanna Aizenberg has spent three years studying the brittle star, a relative of sea urchins and starfish. The five arms of the brittle star bristle with thousands of microscopic crystalline lenses. Together they act like one big eye, enabling the hand-sized invertebrate to spot predators and find hiding places in the shallow Caribbean waters where it lives. The curved lenses, which look like tiny bumps when seen under an electron microscope, are virtually perfect optical instruments, better than anything current technology allows.

It' s not just the lenses that captivate Aizenberg and her colleagues. The tiny crystals are surrounded by pigment-bearing pores that adjust the amount of light the lenses let in. "We don't want to re-create the brittle-star eye but to replicate the structure of the lens and pores," she says. Among other applications, the replicated array could give rise to faster fiber-optic networks and be used to replace the expensive lithographic masks that etch microscopic circuits onto silicon chips. Aizenberg estimates that such applications could be "maybe five years away," while conceding that's only a rough guess.

Probing nature at the molecular level is a hallmark of recent biomimicry work. Past efforts were confined to the macro world: Velcro began as a gleam in the eye of a Swiss inventor who studied the tiny hooks on cocklebures that stuck to his dog's fur. "Today's discipline focuses on small-scale remaking of biological materials," says Ilhan Aksay, professor of chemical engineering at Princeton University and principal investigator for the three-year-old Biologically Inspired Materials Institute, a consortium of research institutions funded by NASA to conduct basic research into space-flight materials.

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Mounted on bookshelves in Aksay's office are two abalone shells that embody properties that could help future spacecraft withstand cosmic radiation, micrometeorite strikes, and other hazards of interplanetary travel. Abalone shells are light yet extraordinarily tough: 1,000 times more energy is required to break the shells than to fracture the toughest man-made ceramics. Once cracked, moreover, the shells can repair themselves—something no ceramic can do. The abalone's toughness derives from layers of tiny calcium-carbonate plates that make up the shiny mother-of-pearl interior of its shell. When struck, the layers glide over one another to absorb the shock. If cracks develop, the plates simply grow back together.

Inspired by this self-healing property, the Princeton researchers are using it as a model for structures that can be built in orbit. Similar principles could apply to military vehicles damaged in battle. Aksay holds up a prototype self-healing strut: a thin metal tube fitted with copper wire and filled with a solution of silica particles to serve as clotting agents. A break in the strut generates an electric field that causes the micron-sized particles to flow to and fill in the wound. Says Aksay: "We're looking at a five- to ten-year process to develop these materials."

No less remarkable than the abalone shell is spider's silk. It is light, flexible, five times stronger than steel on a pound-for-pound basis, and tougher than bullet-resistant Kevlar—yet spiders spin it without the high heat, crushing pressure, or toxic chemicals required to produce man-made materials. Scientists have long searched for a way to produce such high-tensile fiber for applications ranging from medical sutures to body armor.

Taking a different tack from the people who tried to make spider silk from goat's-milk, Oxford University professors David Knight and Fritz Vollrath have been moving toward a solution. Working with an Oxford-launched startup called Spinox and its German sister company Spin'tec Engineering, they are developing a system that mimics processes found inside spider glands. "We've produced beautiful, lustrous fibers," says Knight. Spin'tec wants to develop an "optimized and ruggedized" device for reeling out high-performance fiber within three years. Since the process is expensive, it will be used in biomedicine and other specialized applications. Future uses could range from fabrics for protective clothing to materials for airbags and seatbelts.

The spider's secret lies in how it spins its silk. Viscous, folded-up proteins are pulled from the gland by knobby appendages called spinnerets and emerge as glistening silk strands. The tough "dragline" silk for the spokelike frame of a web and the sticky "capture silk" for the cross-threads come from different glands. Since spiders are solitary predators and produce relatively little protein, the scientists use silkworms, whose silk has some 80% of the toughness of spider's thread. Knight envisions future applications like supertough sutures for sewing up nerves, something that doesn't exist today. Knight says Spin'tec hopes to hit the market with a suture within the next two years.

Spider webs' adhesiveness pales when compared with the feet of gecko lizards that can dart up walls, glide across ceilings, and hang by a single toe. The electrodynamic force that makes this possible is being exploited in robotics (see "Send in the Robots!" on fortune.com), but a far more wide-ranging application may lie in a new generation of smart adhesives. Since the billions of microscopic hairs on gecko feet stick to surfaces through molecular attractions rather than through gluelike bonds, they can be peeled off with little effort and come away dirt-free. This could lead to reusable self-cleaning tapes to anchor medical implants or dentures and give rise to other applications, from tire-traction-enhancing materials to fumble-free football gloves.

"This is the screw of the future," says Kellar Autumn, a biologist at Lewis and Clark College in Portland, Ore., and a leading gecko researcher. Cellphones, for instance, are assembled with screws but can shatter when dropped; if they break, they can't be put back together. However, if the pieces were held together by gecko tape, the phone could resist impact or even become more tightly bonded when dropped. Several years ago a student of Autumn's used patches of gecko hair to make a "gecko Band-Aid" that could be applied to the skin and lifted off as if it had never been attached. "The detachment force is nearly zero," says Autumn, despite the fact that "at a subatomic level, the gecko hair becomes one with your finger." Gecko-inspired tape is already being fabricated at the University of California at Berkeley and at other locations. The process involves replicating gecko hairs by subdividing synthetic materials into billions of strips. Autumn says a commercial product could be available "in a couple of years."

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Other sources of natural adhesives are also being investigated. At Northwestern University, biomedical engineer Phillip Messersmith is working with the Pacific blue mussel, a common bivalve that secretes a substance that bonds to objects under water—something few synthetic glues can do. He has not only developed a laboratory model of this adhesive but has also used it to fashion a two-sided compound that sticks to virtually anything with one side while repelling bacteria and other contaminants with the other. This could prove invaluable for medical and dental applications such as repairing complex bone fractures, preventing blood-clot formation on cardiovascular devices, anchoring implants, and guarding against tooth decay.

Why not just use blue-mussel adhesive itself? Too expensive, explains Messersmith: "You'd need an incredibly large number of mussels." His still-experimental biomimetic glue utilizes an amino acid called DOPA that is found at high concentration in mussel-adhesive protein; it adheres to wet surfaces and even to Teflon, a substance not even geckos can stick to.

One of the most striking and common patterns in nature is the spiral found in phenomena as varied as human embryos, nautilus shells, whirlpools, and galaxies. The shape has fascinated Jayden Harman since his childhood in western Australia, when he noticed it in swirls of kelp while snorkeling. "Seaweed is fragile, but it survives in storms by changing its shape to let the water go by," says Harman, founder and CEO of PAX Scientific, a San Rafael, Calif., designer of high-efficiency rotors and fans.

Unlike conventional fans that generate centrifugal forces, PAX Scientific's designs create centripetal flows that are pulled toward the center of the axis of rotation. This greatly reduces drag and generates energy savings. Founded in 1997, the company spent five years in R&D and now wants to license its technology. It launched commercialization efforts two years ago and is currently developing products with manufacturers in the automotive, industrial, and home-appliance fields. Some products could be in service as early as next year. Among the vast range of proposed applications are cooling fans for industrial, commercial, and consumer use, and mixers for blending paint and other products and for keeping municipal water systems fresh.

With sustainability a hot topic, researchers are drawing upon natural processes to synthesize biodegradable plastics. At Cornell University, biological chemist Geoffrey Coates and his colleagues have used a zinc-based catalyst to produce plastics from ordinary carbon dioxide and a liquid derived from orange peels. The result is a polymer—or plastic—that could replace the polystyrene used in food packaging, plastic utensils, and other products.

"We've got a very promising catalyst," says Coates, who notes that the world produces more than 150 million tons of plastics a year, nearly all of it nonbiodegradable and from energy-intensive processes that use petroleum-based feedstocks. Coates last year co-founded a company called Novomer to commercialize his process, which could roll out products within a year. "Either some other company comes along and licenses our catalyst or we develop the materials ourselves," he says.

Metabolix, a company that sprang out of MIT in 1992, is targeting the production of natural plastics in plants and microbes. Some soil bacteria store energy in the form of plastic rather than as carbohydrates or fats, and Metabolix is expanding on these models to produce natural plastics. It is working with Archer Daniels Midland to build a fermentation plant that will use microbes to convert sugars and vegetable oils into plastic, beginning in 2008.

In a second project, Metabolix teamed last March with Britain's BP to develop varieties of switchgrass—a prairie species on which buffalo once grazed—for extraction of commercial quantities of plastic; the leftover biomass could be used for fuel. Metabolix aims to have commercially viable, genetically engineered varieties of switchgrass in pilot fields in four or five years. "The plants would accumulate plastic in a benign manner," says CEO James Barber. "If you had these natural plastics in your hand, you couldn't tell the difference between them and the synthetic types in your cellphone housing, grocery bag, or food wrap."

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Of particular fascination to biomimics is the white lotus, a lily-like plant whose ability to keep clean in muddy waters makes it a symbol of purity in Asian religions. German botanists Wilhelm Barthlott and Christoph Neinhuis discovered the plant's secret in the 1970s, when they found that the smooth-looking surface of its leaves was really a bed of waxy microscopic bumps. Dirt perches on the frictionless nanoparticles and is easily washed off in a process the scientists dubbed the "lotus effect."

Among the companies that have recently exploited this effect is Swiss textile maker Schoeller, whose fabric is widely used in ski apparel and other sportswear. Schoeller's NanoSphere finish incorporates microscopic particles from which dirt, oil, and grease can be washed. Garments made of the fabric sell throughout Europe and are available in North America from Westcomb of Vancouver, B.C., and Beyond Fleece in Oregon.

To mimic the lotus-leaf surface, Schoeller coats fabric with modified silicon nanoparticles, explains CEO Hans-Jürgen Hübner. The toughest task is anchoring the particles to natural fabrics like cotton or wool whose fibers vary in thickness, unlike uniform synthetic fibers. The lotus effect is also featured in Lotusan exterior paints from Sto of Stühlingen, Germany, which calls its coatings the first to use the self-cleaning principle. Sold throughout Europe, the paints recently became available in North America.

Perhaps the ultimate biomimicry is computer software that mirrors evolution, nature's own method of design. Called genetic algorithms, or GAs, these programs replicate natural selection by creating myriad generations of possible solutions, nicknamed chromosomes. Testing the first generation of perhaps 10,000 chromosomes leads to the selection of a few best ones, which are replicated, spliced together, and mutated to create the next generation for testing. When repeated thousands of times, this process can solve problems ranging from factory production schedules to jet-engine design. The Space Technology 5 satellite that NASA plans to put in orbit next year will transmit data to Earth through an antenna created by testing some 20 million chromosomes.

"There's an analogy between GA and what's going on in business," observes David Goldberg, director of the Illinois Genetic Algorithms Laboratory at Urbana-Champaign. "Selection plus mutation is like the continual improvement of quality engineering," he says, "and selection plus recombination is like discontinuous change or the disruptive change of innovation."

For all its promise, biomimicry has only begun to explore its possibilities. Whether projects prove successful will depend on the ingenuity of scientists and the willingness of backers and investors to continue to support them. They had better be willing—billions of years of natural selection are a tough act to follow.

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