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Biomimetics

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Biomimetics: Design by Nature

What has fins like a whale, skin like a lizard, and eyes like a moth? The future of engineering.

By Tom Mueller

One cloudless midsummer day in February, Andrew Parker, an evolutionary biologist, knelt in the baking red sand of the Australian outback just south of Alice Springs and eased the right hind leg of a thorny devil into a dish of water. The maneuver was not as risky as it sounds: Though covered with sharp spines, the lizard stood only about an inch high at the shoulder, and it looked up at Parker apprehensively, like a baby dinosaur that had lost its mother. It seemed too cute for its harsh surroundings, home to an alarmingly high percentage of the world's most venomous snakes, including the inland taipan, which can kill a hundred people with an ounce of its venom, and the desert death adder, whose name pretty well says it all. Fierce too is the landscape itself, where the wind hissing through the mulga trees feels like a blow dryer on max, and the sun seems three times its size in temperate climes. Constant reminders that here, in the driest part of the world's driest inhabited continent, you'd better have a good plan for where your next drink is coming from.

This the thorny devil knows, with an elegance and certainty that fascinated Parker beyond all thought of snakebite or sunstroke. "Look, look!" he exclaimed. "Its back is completely drenched!" Sure enough, after 30 seconds, water from the dish had wicked up the lizard's leg and was glistening all over its prickly hide. In a few seconds more the water reached its mouth, and the lizard began to smack its jaws with evident satisfaction. It was, in essence, drinking through its foot. Given more time, the thorny devil can perform this same conjuring trick on a patch of damp sand—a vital competitive advantage in the desert. Parker had come here to discover precisely how it does this, not from purely biological interest, but with a concrete purpose in mind: to make a thorny-devil-inspired device that will help people collect lifesaving water in the desert.

A slender English academic with wavy, honey-blond hair beneath a wide-brimmed sun hat, Parker busied himself with eyedroppers, misters, and various colored powders, the better to understand the thorny devil's water-collecting alchemy. Now and then he made soft, bell-like, English-academic sounds of surprise and delight. "The water's spreading out incredibly fast!" he said, as drops from his eyedropper fell onto the lizard's back and vanished, like magic. "Its skin is far more hydrophobic than I thought. There may well be hidden capillaries, channeling the water into the mouth." After completing his last experiment, we gathered up his equipment and walked back to our Land Cruiser. The lizard watched us leave with a faint look of bereavement. "Seeing the devil in its natural environment was crucial to understanding the nature of its adaptations—the texture of the sand, the amount of shade, the quality of the light," Parker said as we drove back to camp. "We've done the macro work. Now I'm ready to look at the microstructure of its skin."

A research fellow at the Natural History Museum in London and at the University of Sydney, Parker is a leading proponent of biomimetics—applying designs from nature to solve problems in engineering, materials science, medicine, and other fields. He has investigated iridescence in butterflies and beetles and antireflective coatings in moth eyes—studies that have led to brighter screens for cellular phones and an anticounterfeiting technique so secret he can't say which company is behind it. He is working with Procter & Gamble and Yves Saint Laurent to make cosmetics that mimic the natural sheen of diatoms, and with the British Ministry of Defense to emulate their water-repellent properties. He even draws inspiration from nature's past: On the eye of a 45-million-year-old fly trapped in amber he saw in a museum in Warsaw, Poland, he noticed microscopic corrugations that reduced light reflection. They are now being built into solar panels.

Parker's work is only a small part of an increasingly vigorous, global biomimetics movement. Engineers in Bath, England, and West Chester, Pennsylvania, are pondering the bumps on the leading edges of humpback whale flukes to learn how to make airplane wings for more agile flight. In Berlin, Germany, the fingerlike primary feathers of raptors are inspiring engineers to develop wings that change shape aloft to reduce drag and increase fuel efficiency. Architects in Zimbabwe are studying how termites regulate temperature, humidity, and airflow in their mounds in order to build more comfortable buildings, while Japanese medical researchers are reducing the pain of an injection by using hypodermic needles edged with tiny serrations, like those on a mosquito's proboscis, minimizing nerve stimulation.

"Biomimetics brings in a whole different set of tools and ideas you wouldn't otherwise have," says materials scientist Michael Rubner of MIT, where biomimetics has entered the curriculum. "It's now built into our group culture."

Shortly after our trip to the Australian desert, I met up with Andrew Parker again, in London, to watch the next phase of his research into the thorny devil. Walking from the Natural History Museum's entrance to his laboratory on the sixth floor, we traversed warehouse-size halls filled with preserved organisms of the most exuberant variety. In one room were waist-high alcohol jars of grimacing sea otters, pythons, spiny echidnas, and wallabies, and one 65-foot-long case containing a giant squid. Other rooms held displays of gaudy hummingbirds, over-the-top toucans and majestic bowerbirds, and shelf after shelf filled with beetles as bright as gemstones: emerald-green scarabs, sapphire-blue *Cyphogastras*, and opalescent weevils.

To Parker this was not a mere collection of specimens, but "a treasure-trove of brilliant design." Every species, even those that have gone extinct, is a success story, optimized by millions of years of natural selection. Why not learn from what evolution has wrought? As we walked, Parker explained how the metallic sheen and dazzling colors of tropical birds and beetles derive not from pigments, but from optical features: neatly spaced microstructures that reflect specific wavelengths of light. Such structural color, fade-proof and more brilliant than pigment, is of great interest to people who manufacture paint, cosmetics, and those little holograms on credit cards. Toucan bills are a model of lightweight strength (they can crack nuts, yet are light enough not to seriously impede the bird's flight), while hedgehog spines and porcupine quills are marvels of structural economy and resilience. Spider silk is five times stronger by weight and vastly more ductile than high-grade steel. Insects offer an embarrassment of design riches. Glowworms produce a cool light with almost zero energy loss (a normal incandescent bulb wastes 98 percent of its energy as heat), and bombardier beetles have a high-efficiency combustion chamber in their posterior that shoots boiling-hot chemicals at would-be predators. The *Melanophila* beetle, which lays its eggs in freshly burned wood, has evolved a structure that can detect the precise infrared radiation produced by a forest fire, allowing it to sense a blaze a hundred kilometers away. This talent is currently being explored by the United States Air Force.

"I could look through here and find 50 biomimetics projects in half an hour," Parker said. "I try not to walk here in the evening, because I end up getting carried away and working until midnight."

In one such late-night creative burst eight years ago, Parker decided to investigate the water-gathering skills of a desert beetle by building an enormous sand dune in his laboratory. This tenebrionid beetle flourishes in the Namib Desert in southwestern Africa, one of the world's hottest, driest environments. The beetle drinks by harvesting morning fogs, facing into the wind and hoisting its behind, where hydrophilic bumps capture the fog and cause it to coalesce into larger droplets, which then roll down the waxy, hydrophobic troughs between the bumps, reaching the beetle's mouth. Parker imported several dozen beetles from Namibia, which promptly scampered all over the lab when he opened the box, but eventually settled contentedly on the dune. There, using a hair dryer and various misters and spray bottles, Parker simulated the conditions in the Namib Desert well enough to understand the beetle's mechanism. He then replicated it on a microscope slide, using tiny glass beads for the bumps and wax for the troughs.

For all nature's sophistication, many of its clever devices are made from simple materials like keratin, calcium carbonate, and silica, which nature manipulates into structures of fantastic complexity, strength, and toughness. The abalone, for example, makes its shell out of calcium carbonate, the same stuff as soft chalk. Yet by coaxing this material into walls of staggered, nanoscale bricks through a subtle play of proteins, it creates an armor as tough as Kevlar —3,000 times harder than chalk. Understanding the microscale and nanoscale structures responsible for a living material's exceptional properties is critical to re-creating it synthetically. So today Andrew Parker had arranged to view the skin of a thorny devil museum specimen under a scanning electron microscope, hoping to find the hidden structures that allow it to absorb and channel water so effectively.

With a microscopist at the helm, we soared over the surface of the thorny devil's skin like a deep-space probe orbiting a distant planet, dipping down now and then at Parker's request to explore some curious feature of the terrain. There seemed to be little of interest in the Matterhornlike macrostructure of an individual thorn, though Parker speculated that it might wick away heat from the lizard's body or perhaps help capture the morning dew. Halfway down the thorn, however, he noticed a series of nodules set in rows, which seemed to grade down to a larger water-collection structure. Finally we dove into a crevasse at the base of the thorn and encountered a honeycomb-like field of indentations, each 25 microns across.

"Ah-ha!" Parker exclaimed, like Sherlock Holmes alighting upon a clue. "This is clearly a superhydrophobic surface for channeling water between the scales." A subsequent examination of the thorny devil's skin with an instrument called a micro-CT scanner confirmed his theory, revealing tiny capillaries between the scales evidently designed to guide water toward the lizard's mouth. "I think we've pretty well cracked the thorny devil structure," he said. "We're ready to make a prototype."

Enter the engineers. As the next phase in his quest to create a water-collection device inspired by the lizard, Parker sent his observations and experimental results to Michael Rubner and his MIT colleague Robert Cohen, a chemical engineer with whom he has worked on several biomimetics projects in the past. Rubner and Cohen are neatly groomed gentlemen who speak in clipped phrases and look frequently at their watches. While Parker likes to explain his work via a stroll through a botanic garden or by pulling out drawerfuls of bright beetles in a museum, they are more likely to draw a tidy graph of force over time, or flip through a PowerPoint presentation on their laptop. But a pooling of biological insight and engineering pragmatism is vital to success in biomimetics, and in the case of Parker, Cohen, and Rubner, it has led to several promising applications inspired by the Namib beetle and other insects. Using a robotic arm that, in a predetermined sequence, dips slides into a series of nanoparticle suspensions and other exotic ingredients, they have assembled materials layer by layer that have the same special properties as the organisms. Soon they hope to apply the method to create a synthetic surface inspired by thorny devil skin.

Though impressed by biological structures, Cohen and Rubner consider nature merely a starting point for innovation. "You don't have to reproduce a lizard skin to make a watercollection device, or a moth eye to make an antireflective coating," Cohen says. "The natural structure provides a clue to what is useful in a mechanism. But maybe you can do it better." Lessons from the thorny devil may enhance the water-collection technology they have developed based on the microstructure of the Namib beetle, which they're working to make into water-harvesting materials, graffiti-proof paints, and self-decontaminating surfaces for kitchens and hospitals. Or the work may take them in entirely new directions. Ultimately they consider a biomimetics project a success only if it has the potential to make a useful tool for people. "Looking at pretty structures in nature is not sufficient," says Cohen. "What I want to know is, Can we actually transform these structures into an embodiment with true utility in the real world?"

Which, of course, is the tricky bit. Potentially one of the most useful embodiments of natural design is the bio-inspired robot, which could be deployed in places where people would be too conspicuous, bored to tears, or killed. But such robots are notoriously difficult to build. Ronald Fearing, a professor of electrical engineering at the University of California, Berkeley, has taken on one of the biggest challenges of all: to create a miniature robotic fly that is swift, small, and maneuverable enough for use in surveillance or search-and-rescue operations.

If a blowfly had buzzed into Fearing's office when we first sat down on a warm March afternoon, the windows flung wide to the garden-like Berkeley campus, I would have swatted it away without a second thought. By the time Fearing finished explaining why he had chosen it as the model for his miniature aircraft, I would have fallen on bended knee in admiration. With wings beating 150 times per second, it hovers, soars, and dives with uncanny agility. From straight-line flight it can turn 90 degrees in under 50 milliseconds —a maneuver that would rip the Stealth fighter to shreds.

The key to making his micromechanical flying insect (MFI) work, Fearing said, isn't to attempt to copy the fly, but to isolate the structures crucial to its feats of flying, while keeping a sharp eye out for simpler—and perhaps better—ways to perform its highly complex operations. "The fly's wing is driven by 20 muscles, some of which only fire every fifth wing beat, and all you can do is wonder, What on Earth just happened there?" says Fearing. "Some things are just too mysterious and complicated to be able to replicate."

After CalTech neurobiologist Michael Dickinson used foot-long plastic wings flapping in two tons of mineral oil to demonstrate how the fly's U-shaped beat kept it aloft, Fearing whittled the complexity of the wing joint down to something he could manufacture. What he came up with resembles a tiny automobile differential; though lacking the fly's mystical 20-muscle poetry, it can still bang out U-shaped beats at high speed. To drive the wing, he needed piezoelectric actuators, which at high frequencies can generate more power than fly muscle can. Yet when he asked machinists to manufacture a ten-milligram actuator, he got blank stares. "People told me, 'Holy cow! I can do a ten -gram actuator,' which was bigger than our whole fly."

So Fearing made his own, one of which he held up with tweezers for me to see, a gossamer wand some 11 millimeters long and not much thicker than a cat's whisker. Fearing has been forced to manufacture many of the other minute components of his fly in the same way, using a micromachining laser and a rapid prototyping system that allows him to design his minuscule parts in a computer, automatically cut and cure them overnight, and assemble them by hand the next day under a microscope.

With the microlaser he cuts the fly's wings out of a two-micron polyester sheet so delicate that it crumples if you breathe on it and must be reinforced with carbon-fiber spars. The wings on his current model flap at 275 times per second—faster than the insect's own wings—and make the blowfly's signature buzz. "Carbon fiber outperforms fly chitin," he said, with a trace of self-satisfaction. He pointed out a protective plastic box on the lab bench, which contained the fly-bot itself, a delicate, origami-like framework of black carbon-fiber struts and hairlike wires that, not surprisingly, looks nothing like a real fly. A month later it achieved liftoff in a controlled flight on a boom. Fearing expects the fly-bot to hover in two or three years, and eventually to bank and dive with flylike virtuosity.

To find a biomimetic bot already up and running—or at least ambling—one need only cross the bay to Palo Alto. Ever since the fifth century B.C., when Aristotle marveled at how a gecko "can run up and down a tree in any way, even with the head downward," people have wondered how the lizard manages its gravity-defying locomotion. Two years ago Stanford University roboticist Mark Cutkosky set out to solve this age-old conundrum, with a gecko-inspired climber that he christened Stickybot.

In reality, gecko feet aren't sticky—they're dry and smooth to the touch—and owe their remarkable adhesion to some two billion spatula-tipped filaments per square centimeter on their toe pads, each filament only a hundred nanometers thick. These filaments are so small, in fact, that they interact at the molecular level with the surface on which the gecko walks, tapping into the low-level van der Waals forces generated by molecules' fleeting positive and negative charges, which pull any two adjacent objects together. To make the toe pads for Stickybot, Cutkosky and doctoral student Sangbae Kim, the robot's lead designer, produced a urethane fabric with tiny bristles that end in 30-micrometer points. Though not as flexible or adherent as the gecko itself, they hold the 500-gram robot on a vertical surface.

But adhesion, Cutkosky found, is only part of the gecko's game. In order to move swiftly—and geckos can scamper up a vertical surface at one meter per second—its feet must also unstick effortlessly and instantly. To understand how the lizard does this, Cutkosky sought the aid of biologists Bob Full, an expert in animal locomotion, and Kellar Autumn, probably the world's foremost authority on gecko adhesion. Through painstaking anatomical studies, force tests on individual gecko hairlets, and slow-motion analysis of lizards running on vertical treadmills, Full and Autumn discovered that gecko adhesion is highly directional: Its toes stick only when dragged downward, and they release when the direction of pull is reversed.

With this in mind, Cutkosky endowed his robot with seven-segmented toes that drag and release just like the lizard's, and a gecko-like stride that snugs it to the wall. He also crafted Stickybot's legs and feet with a process he calls shape deposition manufacturing (SDM), which combines a range of metals, polymers, and fabrics to create the same smooth gradation from stiff to flexible that is present in the lizard's limbs and absent in most man-made materials. SDM also allows him to embed actuators, sensors, and other specialized structures that make Stickybot climb better. Then he noticed in a paper on gecko anatomy that the lizard had branching tendons to distribute its weight evenly across the entire surface of its toes. Eureka. "When I saw that, I thought, Wow, that's great!" He subsequently embedded a branching polyester cloth "tendon" in his robot's limbs to distribute its load in the same way.

Stickybot now walks up vertical surfaces of glass, plastic, and glazed ceramic tile, though it will be some time before it can keep up with a gecko. For the moment it can walk only on smooth surfaces, at a mere four centimeters per second, a fraction of the speed of its biological role model. The dry adhesive on Stickybot's toes isn't self-cleaning like the lizard's either, so it rapidly clogs with dirt. "There are a lot of things about the gecko that we simply had to ignore," Cutkosky says. Still, a number of real-world applications are in the offing. The Department of Defense's Defense Advanced Research Projects Agency (DARPA), which funds the project, has it in mind for surveillance: an automaton that could slink up a building and perch there for hours or days, monitoring the terrain below. Cutkosky hypothesizes a range of civilian uses. "I'm trying to get robots to go places where they've never gone before," he told me. "I would like to see Stickybot have a real-world function, whether it's a toy or another application. Sure, it would be great if it eventually has a lifesaving or humanitarian role...."

His voice trailed off, in a wistful, almost apologetic tone I had heard undercutting the optimism of several other biomimeticists. For all their differences in background, temperament, and ultimate aims, most practitioners conclude their enthusiastic discourses on their bio-inspired invention with a few halfhearted theories on how it may someday make its way into the real world. Often it sounds like wishful thinking.

For all the power of the biomimetics paradigm, and the brilliant people who practice it, bio-inspiration has led to surprisingly few mass-produced products and arguably only one household word—Velcro, which was invented in 1948 by Swiss chemist George de Mestral, by copying the way cockleburs clung to his dog's coat. In addition to Cutkosky's lab, five other high-powered research teams are currently trying to mimic gecko adhesion, and so far none has come close to matching the lizard's strong, directional, self-cleaning grip. Likewise, scientists have yet to meaningfully re-create the abalone nanostructure that accounts for the strength of its shell, and several well-funded biotech companies have gone bankrupt trying to make artificial spider silk. Why?

Some biomimeticists blame industry, whose short-term expectations about how soon a project should be completed and become profitable clash with the time-consuming nature of biomimetics research. Others lament the difficulty in coordinating joint work among diverse academic and industrial disciplines, which is required to understand natural structures and mimic what they do. But the main reason biomimetics hasn't yet come of age is that from an engineering standpoint, nature is famously, fabulously, wantonly complex. Evolution doesn't "design" a fly's wing or a lizard's foot by working toward a final goal, as an engineer would—it blindly cobbles together myriad random experiments over thousands of generations, resulting in wonderfully inelegant organisms whose goal is to stay alive long enough to produce the next generation and launch the next round of random experiments. To make the abalone's shell so hard, 15 different proteins perform a carefully choreographed dance that several teams of top scientists have yet to comprehend. The power of spider silk lies not just in the cocktail of proteins that it is composed of, but in the mysteries of the creature's spinnerets, where 600 spinning nozzles weave seven different kinds of silk into highly resilient configurations.

The multilayered character of much natural engineering makes it particularly difficult to penetrate and pluck apart. The gecko's feet work so well not just because of their billions of tiny nanohairs, but also because those hairs grow on larger hairs, which in turn grow on toe ridges that are part of bigger toe pads, and so on up to the centimeter scale, creating a seven-part hierarchy that maximizes the lizard's cling to all climbing surfaces. For the present, people cannot hope to reproduce such intricate nanopuzzles. Nature, however, assembles them effortlessly, molecule by molecule, following the recipe for complexity encoded in DNA. As engineer Mark Cutkosky says, "The price that we pay for complexity at small scales is vastly higher than the price nature pays."

Nonetheless the gap with nature is gradually closing. Researchers are using electron- and atomic-force microscopes, microtomography, and high-speed computers to peer ever deeper into nature's microscale and nanoscale secrets, and a growing array of advanced materials to mimic them more accurately than ever before. And even before biomimetics matures into a commercial industry, it has itself developed into a powerful new tool for understanding life. Berkeley animal locomotion expert Bob Full uses what he learns to build running, climbing, and crawling robots—and they in turn have taught him certain fundamental rules of animal movement. He has discovered, for example, that every land animal, from centipedes to kangaroos to humans, has precisely the same springiness in its legs and generates the same relative energy when it runs. Kellar Autumn, the gecko-adhesion specialist and a former student of Full's, regularly borrows bits of Cutkosky's Stickybot to compare them with the animal's natural structures and to test central assumptions about gecko biology that cannot be learned from the geckos themselves.

"It's no problem to apply a 0.2 Newton preload to a patch of gecko adhesive and drag it in a distal direction at one micron per second," Autumn says. "But try asking a gecko to do the same thing with its foot. It'll probably just bite you."

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Biomimicry helps to create technologies that you use in your daily life. Read this article to learn more about getting inspired by nature or animals.Â Believe it or not, engineers turn to nature to tackle some of the worldâ€™s biggest challenges. Biomimicry is the future. By Donovan Alexander. Nov 28, 2018. Source:1,2. Engineers can and have learned a lot from nature. Scientists and engineers alike are on the hunt to tackle some of the issues the currently plague the world. It seems the process of Biomimicry could have a lot of those answers. Understanding Biomimicry. What is Biomimicry you ask? Biomimicry is an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies. Biomimetics - Designed by Nature. Home. Clips. Main content. This programme is not currently available on BBC iPlayer. Biomimetics - Designed by Nature. Fran Scott takes a unique look into some of the latest biomimetics technology and talks to some of the pioneers working on ways to interpret nature's biological mechanisms. 29 minutes. Last on. Biomimetics is a peer-reviewed, open access journal of biomimicry and bionics, published quarterly online by MDPI. The European Network of Bioadhesion (ENBA) is affiliated to Biomimetics. Open Accessâ€" free for readers, with article processing charges (APC) paid by authors or their institutions. High visibility: indexed within Scopus, ESCI (Web of Science), PubMed, PMC, CAPlus / SciFinder, and many other databases.Â The design of the human ear is one of natureâ€™s engineering marvels. This paper examines the merit of ear design using axiomatic design principles. The ear is the organ of both hearing and balance. A sensitive ear can hear frequencies ranging from 20 [...] Read more. The design of the human ear is one of natureâ€™s engineering marvels. Biomimetics or biomimicry is the emulation of the models, systems, and elements of nature for the purpose of solving complex human problems. The terms "biomimetics" and "biomimicry" are derived from Ancient Greek: Î²Î¯Î¿Ï, (bios), life, and Î¼Î¯Î¼Î·ÏƒÎ¹Ï, (mÄ«mÄ“sis), imitation, from Î¼Î¹Î¼Îµá¿–ÏƒÎ¸Î±Î¹ (mÄ«meisthai), to imitate, from Î¼á¿–Î¼Î¿Ï, (mimos), actor. A closely related field is bionics.