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Cover art

Woodland Night

pp. 2 - 3: *False Turkey-tails* | *Stereum ostrea* (L) Parchment fungi family (*Stereaceae*)

pp. 120 - 121: *Composed Polypores* | Lisa A. Frank | 2010

Design

Marjan Eggermont

Colin McDonald

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Monarch Cat

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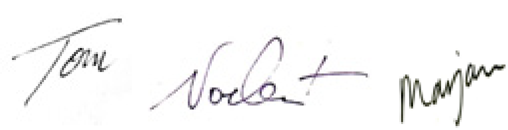
Translation

Translation is a very apt word in the business of bio-inspired design for it is a key step in any solution sequence. A designer or an engineer or a scientist will eventually have to translate something, whether it is an idea into a drawing, a set of specifications into a object, or a hypothesis into an experiment. It is rooted in the notion of "across" and those who work in our field cross boundaries routinely: from subject to subject, from discipline to discipline, from concept to concept, from theory to application, from scale to scale, from place to place, from species to species. Innovation itself might be approached formally in this way, by crossing boundaries in a comprehensive and divergent way, in order to conjure new ideas.

In this issue, the foremost popularizer of our field, Janine Benyus, tells us of the accomplishments and offerings of her organization, Biomimicry 3.8, and reflects on over a decade of promoting and organizing and enabling others to pursue this career. Along her path, translation has been a very important task, as she has first translated the work of scattered scientists for the general public, and then translated some of the lessons from nature to the professionals in the design and business fields. Brent Constantz, highlighted in our case study, has made a life's work of translating ideas from one discipline to another, first from geology to medicine, and then from the biomedical field to sustainable manufacturing and resource use. Interviewee Markus Beuhler's work involves translating natural protein arrays into new functional structures. Artist Lisa Frank translates biological ideas into her personal revelation and shares the experience of these ideas with the public.

There is another type of translation that we feel is needed in the still nascent bio-inspired design field, and that is a translation of best practices amongst ourselves. Ashok Goel and his fellow authors make an initial case for this kind of translation, the first step toward codification, in our WHICH section. The bio-design field is a wide one, growing rapidly and being done by people with many different backgrounds. For many, the work is currently a practice rather than a profession, and they are content to look to more traditional fields for their standards and career advancements. We feel that this will change as our field matures, and as it does, there is important work to be done to ensure that the same quality of professionalism is practiced.

The first step toward establishing those standards is a meeting of all the different stakeholders in this disparate field and a discussion of what is important, how it should be guaranteed, and who will do it. We call for an invitational international congress of bio-inspired practitioners, not to discuss academic work, but to discuss first a common language, some general agreement on what it means to practice, and a start on how to judge those practices. ×



Tom McKeag, Norbert Hoeller, and Marjan Eggermont

coral, westray, orkney

Photo: craigie3000_2011 | Flickr cc

Case Study

Making Paste: Biomedical Innovations Inspired by Coral

Tom McKeag

fall 2013 **Case Study** Making Paste

Author: Tom McKeag

Making Paste

The Problem (#1)

Dr. Brent Constantz was not really thinking of medical inventions the day he plopped down in his dad's study to watch a football game. He started to peruse some of his father's medical journals and came across an article on osteoporosis in the New England Journal of Medicine. He was particularly surprised by the statistics showing the costs of bone fractures to patients and hospitals.

With the world's highest health care cost, the United States hosts a trauma market where more than 6 million fractures occur every year, with nearly 1.4 million fractures in cancellous (spongy) bone treated surgically as noted by the National Osteoporosis Foundation. These incidences seemed likely to increase as the populous generation of baby boomers reached advanced age.

The current practices that orthopedic surgeons had for managing osteoporotic fractures appeared less than adequate, especially since most patients had poor quality bone in the first place that was not amenable to affixing the orthopedic pins, plates, and screws that would allow the patient to return to placing a routine load on the repaired bone. Patients were usually immobile for weeks due to marginal fracture fixation techniques. Because they were elderly, many were susceptible to extensive morbidity and eventual death, at a very high cost to society. Bone graft replacements at the time were solid blocks or granules used as defect fillers and were made of relatively brittle ceramics that could not provide structural stability to the reduced healing fracture.

Unlike his father, Constantz was not a medical doctor, but had been trained in marine biology and geology. Days later he was in the South Pacific studying corals when he put two ideas together. The results were two products and three companies that would add greatly to our ability to treat and heal patients suffering from bone fractures and blocked blood vessels.

Constantz was already an expert on biomineralization, having studied Caribbean coral reefs under a National Science Foundation Doctoral Dissertation Fellowship grant, supervised by Léo Laporte, an eclectic investigator and mentor, while at University of California Santa Cruz. He would later be a Fulbright scholar at the Weismann Institute under Drs. Stephen Weiner, and his mentor, Dr. Heinz Lowenstam, considered the father of the study of biomineralization. His dissertation had addressed three aspects of scleractinian, or stony, reef building corals: their structure and mechanical performance; their process of skeletal formation; and how they produced their skeletons.

The Inspiration

The animals that make up corals are anthozoans, a class of invertebrate within the phylum Cnidaria, which includes a diverse assortment of creatures like jellies, hydroids, and sea anem-

Biomineralization

A biomineral means a mineral produced by a living organism, but it also means that such a substance is likely to be combined in a composite with organic proteins like collagen or carbohydrates like chitin and be different itself in structure and composition than a mineral produced by inorganic chemistry. One of the remarkable aspects of biogenic minerals is the variety of intricate forms made of crystals; completely controlled by genetic information, faithfully replicated generation after generation, and often beyond our technical prowess to mimic.

Organisms from many different phyla have evolved to produce minerals since the end of the Precambrian Age, some 640 million years ago. Algae, diatoms, marine invertebrates and vertebrates like humans all have acquired the capacity to make minerals. To date, approximately 64 different minerals are known to have been produced by living organisms. The calcium bear-

The fossil coral Cladocora from the Pliocene of Cyprus
Photo: Mark A. Wilson, 2007 | Wikimedia Commons

ones. The stony corals make up the major modern taxa that form today's coral reefs, although at certain times in Earth's geologic history, reef formation was dominated by other types of coral, molluscs, and sponges. In this mostly marine and entirely carnivorous club you can either float or anchor yourself to a surface, and many do both within their lifespan. The corals have a symbiotic relationship with algae, which occupy their stomach lining giving the tissue its color and produce sugars in exchange for protection and the nutritious waste from the polyps.

When corals anchor themselves, they do so as attached polyps in large colonies, and they do it by forming calcium carbonate, or lime, from the constituents of seawater as a controlled calcium carbonate cement. The Great Barrier Reef along Australia's northeastern coast, for example, is a huge wave-resistant collection of these colonies, built on the 10,000-year-old ruins of their ancestors' exoskeletons. Charles Darwin's theory of reef and atoll formation, which preceded the Theory of Evolution and also stemmed from the Voyage of the Beagle, still remains the dominant explanation for these massive structures, the largest biological structures on Earth.

Each coral polyp within the colony will secrete an external skeleton of calcium carbonate in the form of the mineral aragonite from the calicoblastic ectodermis of its lower body to form a partitioned cup around the living creature. The cup is made up of upwardly radiating fiber bundles intergrown below the soft tissue. Both the hard mineral skeleton and the soft gastrovascular tissue of these corals will be joined, so that when the colony feeds at night by waving its tentacles in the water, everyone eats.

The Idea

While in the Tuamotu atoll of Rangiroa (the third largest atoll on Earth) Constantz had had time to reflect on what he had learned of osteoporosis, bone breakage and the challenges to immobilize these difficult to manage fractures. The creatures he was studying seemed to offer a process that might aid medical procedures. Why not mimic the way corals quickly produce skeletal minerals right inside the patient and patch up the bone fractures in place with this natural cement? The basic materials were similar; the process promised to be quicker and less invasive, and no one had thought of this before.

Making things using the coral technique was not exactly a new idea for him, but the application seemed a good fit. He knew that during the war in the Pacific, Allied crews had made good use of the cementing action of ground corals in building island roads and airstrips. Some of those airstrips are still in use today. Constantz thought he could harness this capacity more directly by what he had learned of the detailed chemistry of coral biomineralization, for he had made a key discovery: the Golgi bodies within the polyps' cells were forming seed crystals that could be used to reproduce the calcium carbonate cement structures of any specific coral species artificially in a test tube. It was then that he had a vision of seeding these crystals to initiate mineral formation in the form of a cement. Later he would see it as a method to hold an osteoporotic fracture while it healed and the patient was loading it, or even prevent such a fracture with a preventative injection of the mineralizing medium he'd invented.

ing minerals represent over 50% of these, with calcium carbonates being the most abundant and widespread. Phosphates make up a further 25%. In all cases the concentration of minerals is affecting the morphology of the organism and likely serving a successful function, typically in mechanical support, defense or feeding. For example, the spicules on an echinoderm like the sea star. Some functional structures are quite specialized, such as the concentration of minerals used as magnetic sensors in some magnetotactic bacteria.

This biogenic process is happening primarily at the cellular level. The methods used to make these minerals can be grouped into two main types based on the degree of control by the organism. The two types are biologically induced mineralization and biologically controlled mineralization. In the first, the organism induces the manufacture of crystalline material, but does not control the type or location. In the second, the organism does control these aspects

Scanning Electronic micrography of deproteinized trabecular bone - [100x magnification]

Photo: Sbertazzo, 2012 | Wikimedia Commons

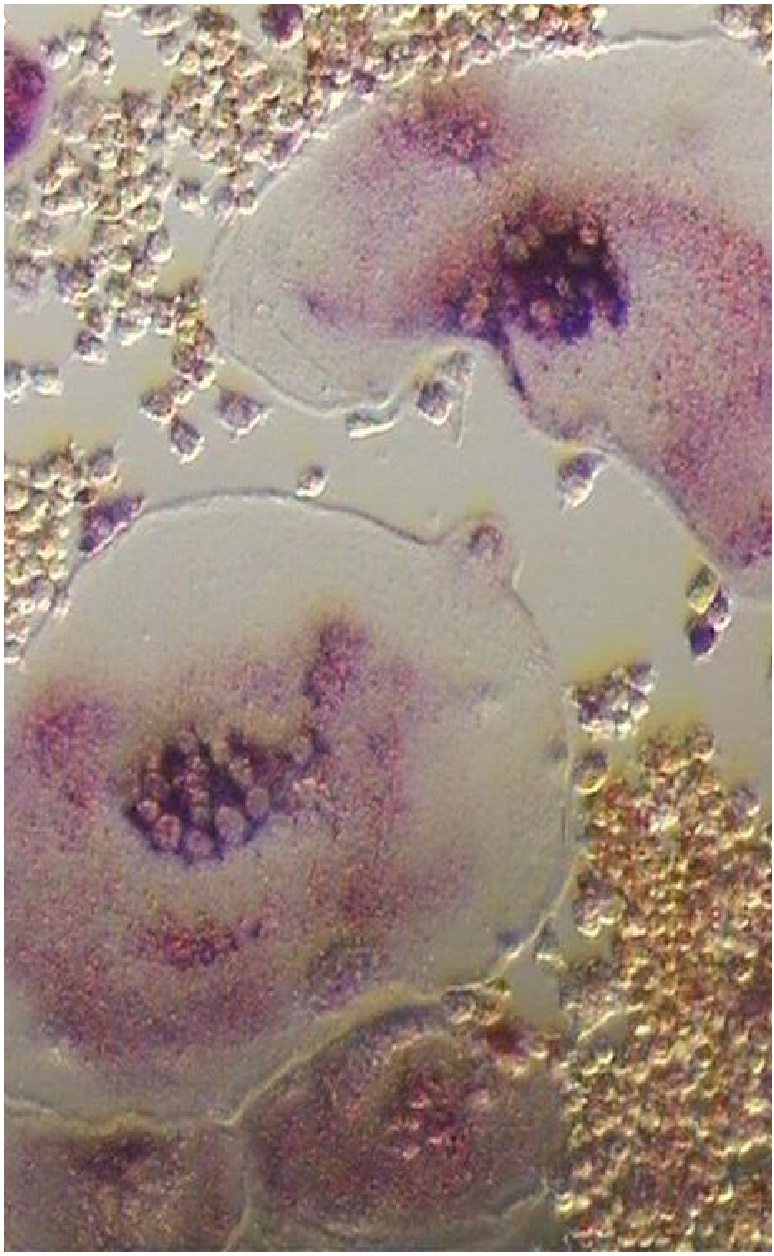
When the National Science Foundation grant which had funded his PhD research dried up, he gained a postdoc position at the U.S. Geological Survey with Dr. James O'Neil, a pioneer in carbon dioxide-water interactions, and founded his first company, Norian, in 1987. The name Norian itself suggests the interdisciplinary nature of the inventor and his idea. It is the name of a division of the upper Triassic geologic period distinguished by the presence of ammonites, ancient invertebrates with beautiful spiral shells. Stony coral reefs appeared in the mid Triassic and built reefs in a circumglobal seaway due to a different configuration of the continents.

The Results

The company's initial goal was to make analogs of seed crystals in order to form synthetic bone in situ as a standard orthopedic procedure for fracture fixation, especially osteoporotic fractures where the quality of the broken bone was compromised. If orthopedic surgeons could use the mineralizing cement to stabilize a reduced fracture and allow early loading, then they could avoid the prolonged postoperative immobilization after marginally successful, risky, painful and invasive procedures like rigid internal fixation with excessive metallic hardware. By 1995 the Norian team had performed animal and human trials of the procedure, and published "Skeletal Repair by in Situ Formation of the Mineral Phase of Bone" in the American Association for the Advancement of Science's journal, *Science*. It was the most cited journal article in Science that year and it showed how injecting a paste of monocalcium phosphate, tricalcium phosphate, calcium carbonate and a sodium phosphate solution into a damaged bone created a clinically effective cement, allowing patients at Massachusetts General Hospital to load their fracture earlier.

The new method was successful for initial bone repair, and was revolutionary as a load-bearing scaffold for new bone growth. Since bone growth and remodeling is regulated by mechanical stress, the new implant's ability to transmit mechanical stress from the surrounding bone facilitated its incorporation into the patient's normal skeleton during fracture healing. The material formed as the cement was dahllite. Dahllite is another name for carbonated hydroxyapatite, the most abundantly produced phosphate mineral in the natural world and is present in vertebrate bones and teeth, as well as in the shells of inarticulate brachiopods. It mimicked the lattice disorder and impurities found in the mineral phase of natural bone and, most importantly, the solubility of the natural material. This allowed the body's remodeling cells, osteoclasts, to tunnel through the material using carbonic acid, followed by other bone forming cells, osteoblasts, to spread its capillaries and reform Haversian systems within the cement implant, thus making the material alive with nutrients and cells. In effect, the injected calcium phosphate formed a composite with new natural bone. The injected paste hardened quickly and gained strength from the crystallization of the carbonated apatite contained. As this dahllite crystallized more and more, the compressive strength of the material increased, eventually achieving a final strength of around 55 MegaPascals (MPa), with a tensile strength of over 2 of nucleation, growth, morphology and location, usually quite precisely. Humans perform this when they form teeth and bones, as do mollusks and the scleractinian corals studied by Constantz.

In general, cells form the minerals within and then transport them through the cell to an outer surface. The transport methods may be passive diffusion through a membrane, active pumping or secretion with or without some containment vessel. Where the mineral ends up can also vary; it can be on the outer surface of the same cell, on another cell or group of cells. It may finally reside on an intricate matrix of proteins, polysaccharides or glycoproteins that have been secreted by epithelial tissue. The structures and compositions of these organic frameworks are genetically programmed to perform essential regulating and/or organizing functions that will result in the formation of composite biominerals, like you would see in



Osteoclast in cell culture

Photo: Cellpath, 2007 | Wikimedia Commons

MegaPascals (MPa). This was better than cancellous bone in compressive strength and comparable in tensile strength.

He is quick to cite the critical participation of Professor Dennis Cater, a biomechanical engineer at Stanford, and Dr. Harry Skinner of the University of California, San Francisco, starting in 2006, and in the early stages of introduction and adoption. Dr. Skinner was a reconstructive orthopedic surgeon and had been trained in ceramics so was familiar with the germane material properties. He was also the Chairman of the surgical device panel of the American College of Surgeons and was a professor in the department of orthopedic surgery at UCSF from 1978 until 1994 and UC Irvine from 1994 to 2007.

Spreading the use of this method still had its challenges since, as Constantz has put it, "the product is being manufactured by the client". He recalled one panicked call from Sweden in which an 88-year-old woman had been on the operating table for four hours and the cement had not set after they had applied it. "I explained to them how critical body temperature was to the setting, and, of course, this had been compromised after such a long time in a tourniquet."

"To introduce our bone cement, we set up training seminars for doctors, but we also did studies comparing the outcomes of patients who had had the traditional metal screw implant versus our synthetic bone cement. We didn't just look at recovery time, but looked at cost to the patient in time, money and opportunity. Our new method sometimes made the difference between someone returning to his old job, or keeping her mobility in old age. We called our metrics 'The New Standards of Care."

His first company, Norian, was acquired by Synthes of Davos, Switzerland in 1998, which divested itself of the company by court order to Kensey Nash Corporation in 2011. The two companies have a long-term supply agreement whereby Kensey Nash will manufacture the Norian products, and Synthes will exclusively distribute the products worldwide. Its product is called the Norian Skeletal Repair System (SRS).

The Problem (#2)

In 2002, Constantz and members of the former Norian team continued to make refinements to the initial product, and his cross-disciplinary capabilities again proved useful in solving a contradiction. They wanted to make the cement more injectable (less viscous), but diluting it would compromise its setting time and weaken its strength.

The Inspiration

A marine geological feature called the coastal anoxic ooze became an inspiration for the answer. Within its sedimentitious layer was an extremely slippery material that then set very very hard. This mineral material is made up of calcium/phosphate minerals and silica.

The Idea

In the marine phenomenon, calcium/phosphate minerals combined with silica in a composite matrix to cause the famously slippery effect.

According to Constantz, he typically starts with a problem and then labors to make a naturthe nacre of mollusks. There are a great variety of techniques.

Biomineralization is of great interest because of the lessons it can impart about material strength and durability, ease of manufacture, and self-organization. For example, the composite construction of mollusk shell has 3,000 times the fracture toughness of its primary constituent (95-99% by weight) calcium carbonate. Natural organisms can form these minerals relatively cheaply, in an aqueous environment, free of high pressure, heat or toxic substances. Finally, many of the techniques of nucleation and precipitation have potential applications in manufacturing at the nanoscale.

Spiny sea shell mollusk

Photo: enjoiskate8, 2012 | Flickr cc

Scuba Diving the Great Barrier Reef with “Crush” | Photo: University of Denver2008 | Flickr cc

al solution that will work, rather than seeking applications for an observed phenomenon. He believes, "...true innovations do not come as a result of changing higher applications, but by developing fundamental processes."

He credits his training under Jim Valentine, an evolutionist at the University of California Santa Barbara, for his approach. "More evolutionary training is needed for designers and inventors; it's here where you see what has worked and why."

He also believes that cross-training is essential to performing innovative work. Referring to the initial bone cement, "We found that many surgeons and other medical personnel did not understand how to solve some of these problems because they were not used to looking at a structure from an evolutionary (and therefore functional) perspective. For example, radiologists who were using our bone cement started to inject barium into it in order to track it and this was upsetting its performance; others would poke the cement to see if it had set, a natural thing to do, but this would weaken the ultimate structure. Until we could train them further, there wasn't this awareness of material functionality."

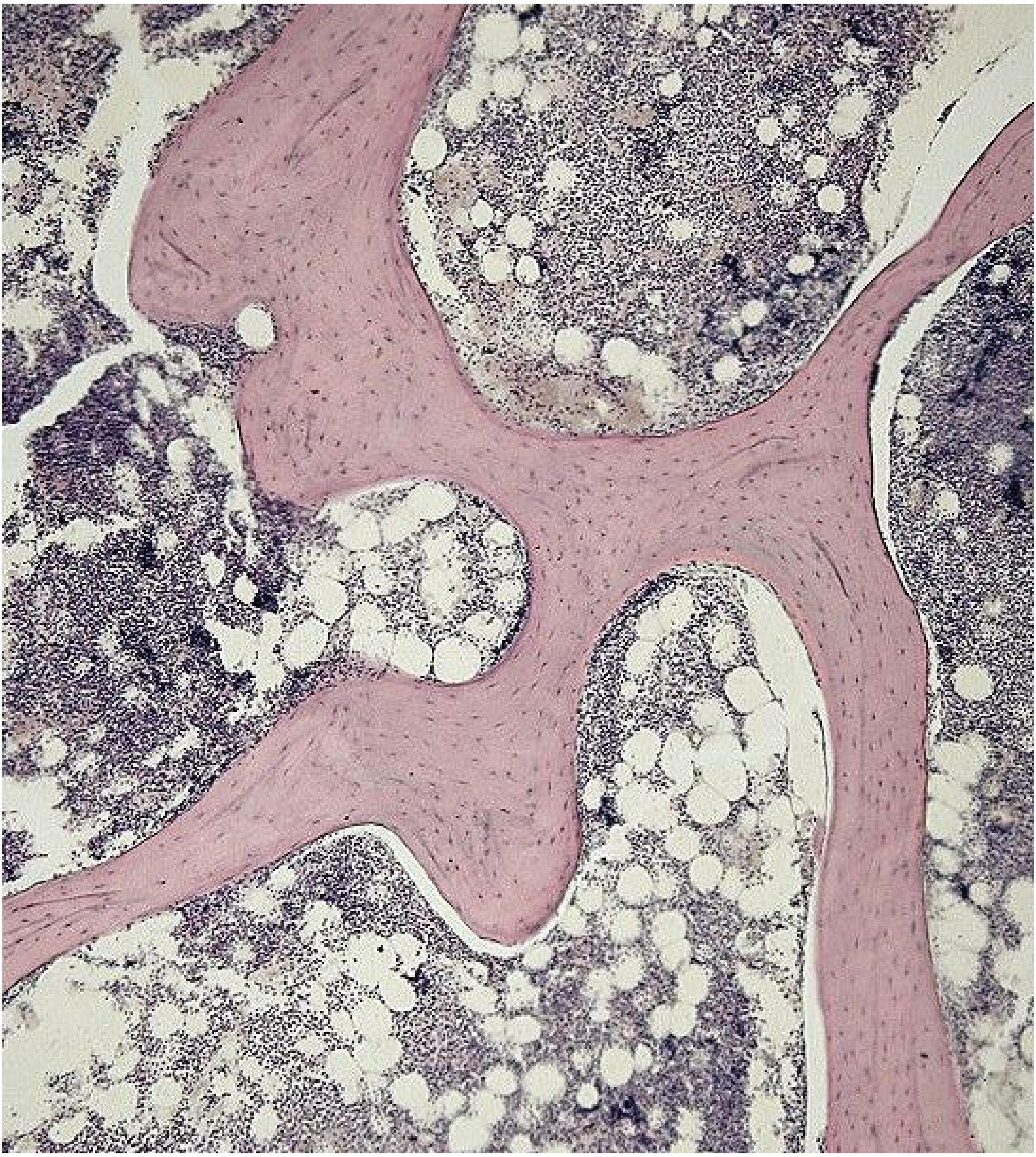
The Results

The team was able to integrate this chemistry into the formula for the cement, and this formed the basis for a new company, Skeletal Kinetics. Skeletal Kinetics LLC, develops, manufactures and markets SKaffold, a proprietary calcium phosphate bone void filler and autograft extender. The product is designed for use in regions of compromised cancellous bone resulting from trauma fractures. Cancellous (or spongy) bone occurs at the ends of long bones beneath joint surfaces, such as at the wrist, hip and knee. SKaffold can be either injected during surgery or applied by hand to voids in bone and sets in a matter of minutes and cures in 72 hours. It can be drilled soon after setting. Like the first generation of cement, its performance is very much time and temperature dependent, while it has improved tensile strength and handleability. The material is, of course, biocompatible and remodels via cell-mediated processes in a mechanical stress-directed fashion.

In August 2006, Skeletal Kinetics became part of the worldwide medical group of Colson Associates, Inc. Skeletal Kinetics maintains its headquarters, R&D and manufacturing facility in Cupertino, California (http://skeletalkinetics.com). Dr. Duran Yetkinler, its president, said that SKaffold has seen steady growth in specialized orthopedic surgery cases over the last 10 years.

The Problem (#3)

Upon selling Norian in 1998, Constantz returned to Stanford to teach, and within four days had formed a new company, Corazon Technologies, Inc. This time he teamed up with several Stanford colleagues among them Dr. Tom Fogarty, the inventor of the embolectomy catheter. The company was formed to address the problem of pathological calcification in the cardiovascular system. Here, there is a mineral buildup on the sides of the vascular vessel and this buildup reduces the normal flow of blood. In advanced cases this can lead to heart attacks, or in the case of diabetics, the loss of legs.



Light micrograph of cancellous bone showing its bony trabeculae (pink) and marrow tissue (grey).

Photo: Department of Histology, Jagiellonian University Medical College, 2006 | Wikimedia Commons

Coral Rocks

Photo: Joe Shlabotnik, 2007 | Flickr cc

The Idea

Three pieces of information were key to this next breakthrough idea: first, from his work developing the bone cement, Constantz had learned about the body's own dissolution of minerals in order to recycle and reform new structures. It typically uses a mild acid (carbonic acid) to dissolve the mineral phase of bone. Second, he then learned that the mineral phase of bone was an exact match chemically to the calcium collecting on blood vessels and causing the medical problems. Third, he learned that vascular material, such as forms the linings of blood vessels, was insoluble in acid. He reasoned, therefore, that the same treatment that the body used to rid itself of excess minerals in bone could be used to rid itself of calcification in its vascular vessels without harming the vessels themselves.

The Results

Corazon Technologies, Inc., was incorporated in 1999, with Constantz serving as President and CEO. The company was able to develop a process in which mild acid is injected into vascular vessels in order to dissolve and flush out the offending calcification. First tested successfully on rabbits, the procedure went through clinical trials in a mere five years.

Corazon Technologies, Inc. operated as a medical device company until it was acquired by the Cordis Corporation of Johnson and Johnson (http://www.cordis.com). It offered devices to remove calcification in coronary and peripheral arteries, kidney and urethral stones, covered surgical and percutaneous aortic heart valves repair, and preparation treatment for percutaneous valve replacement. The procedure offered an alternate to risky and painful bypass operations and traumatic amputations.

Some Common Elements for Product Development

The development of these successful products shared several common threads:

First, the conceptual ideas were based on a detailed knowledge of the process of biomineralization. This knowledge was the result of intensive and primary study of one particular organism, corals, but general conclusions were also induced.

Second, this study had been, from the first, interdisciplinary in scope and awareness because the study of biomineralization requires it. Subsequent product development followed that tradition.

Third, the translation of natural processes to technical applications did not jump scales to any great degree, but focused on the mimicking of molecular chemistry within new environments containing the thermodynamic forces necessary for the biomineralization to take place.

Fourth, great care was taken to ensure that the mimicked process was able to fit the new environment. This included further manipulation of the basic chemical process, study of reactions and rigorous testing of results.

Brent Constantz has gone on to found three more companies since his development of these biomedical innovations: the Calera Corporation, a carbon capture and cement manufacturing company; DeepWater Desal, LLC, a deepwater desalination company; and Blue Planet, a second generation biomimetic carbon capture company that converts carbon dioxide into cement and other building materials. Like his previous work, these organizations have been based on a fundamental knowledge of both biological and geological phenomena, and a clever awareness of how that might be made useful. ×

Salt mounds in Salar de Uyuni, Bolivia

Photo: Luca Galuzzi (www.galuzzi.it), 2006 | Wikipedia Commons

Saguaro skeleton

Photo: cunningba, 2009 | Flickr cc

The Science of Seeing
Jewels of the Desert
Adelheid Fischer

Jewels of the Desert

Careful observation is vital to successful outcomes in biomimicry. It is so essential that future biomimetic enterprises will either succeed or fail depending upon the attention that we bring to them: individually as scientists, educators and practitioners and collectively in our organizations and institutions. As Frederick Franck points out in his book The Zen of Seeing*, there's looking and then there's seeing. It's good to know the difference. "We do a lot of looking: we look through lenses, telescopes, television tubes," he writes. "Our looking is perfected every day—but we see less and less. Never has it been more urgent to speak of seeing."*

Welcome to the third in a series of essays entitled "The Science of Seeing."

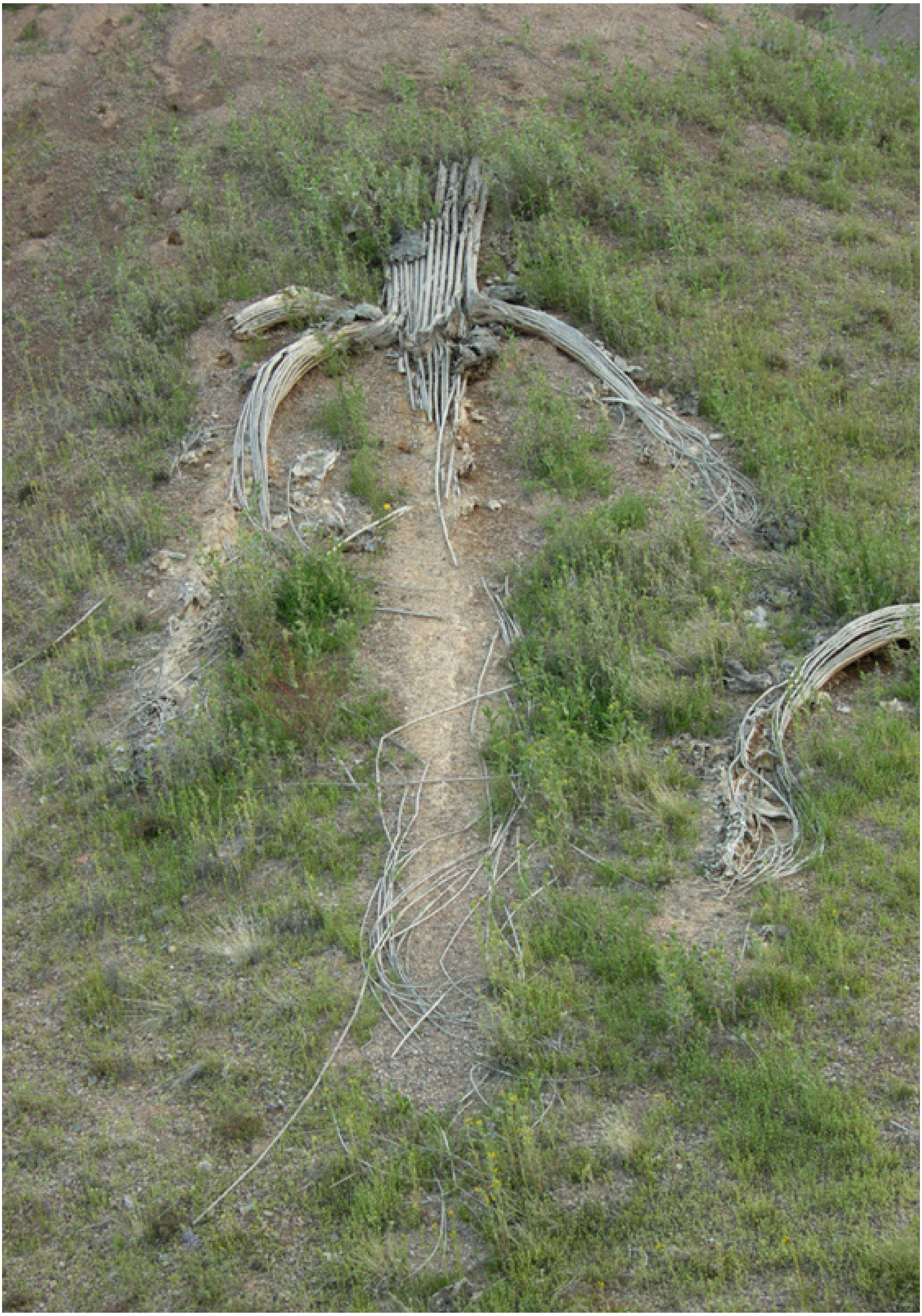
Laurence Garvie makes a left turn off a dirt road, crosses a line of railroad tracks and pulls over into a makeshift clearing in Saguaro National Monument. I reach instinctively for my hat, water bottle and sunglasses as we step out of his truck, blinking in the desert's hard white light one late morning in June. Although the site is less than two hours south of his office on the Tempe campus of Arizona State University, Garvie may as well be on another planet. As curator of the Center for Meteorite Studies at ASU, the world's largest university-based meteorite collection, he spends most of his working hours in a hushed, humidity-controlled room that is lined floor to ceiling with small drawers. They contain more than 30,000 extraterrestrial rock specimens that have hurtled to Earth from places as far away as the asteroid belt. An expert in electron microscopy, Garvie peers into their mineral structures for clues to the formation of the Solar System.

Garvie is as perfectly at ease in the desert heat as he is in cool, dim recesses of his ASU lab. In his spare time, the self-described desert rat can be found roaming the remote reaches of the Sonoran Desert—but not, as you might suspect, with his nose to the ground in search of meteorites. He studies the structure of cactus spines or listens to beetles rasping the woody hollows of a dead palo verde tree or picks through the charred remains of a mesquite after a rare wildfire. These are the kinds of goings-on in the desert that most people pass again and again with hardly a glance. For Garvie, however, they are every bit as intriguing as the mysterious mineral debris that rains down from outer space.

"Look at that spider," he points out as we trudge down a wash to the shade of a mesquite tree for lunch. "We haven't had rain in two months. How does it survive?"

To accompany Garvie on a walk in the desert is to witness what it means to care about a place, as defined by the deep meaning of the word's Old English root, *cearu*, which means to guard or watch, "to trouble oneself." Simply paying attention to the particulars of the world and taking

Saguaro dusty sunset | Photo courtesy of Laurence Garvie, 2013



Downed saguaro | Photo courtesy of Laurence Garvie, 2013

Saguaro ribs pumice | Photo courtesy of Laurence Garvie, 2013

the trouble to find out more about them have led Garvie to a whole grab bag of discoveries, many of which are new to science. On one desert outing in 1998, for example, he came across a small prehistoric potsherd covered by several different kinds of lichens. He took the specimen to his ASU colleagues, lichenologists Tom Nash and Matthias Schultz, who determined that one of them was the first known occurrence of that particular species in the U.S. On another trip, Garvie pocketed a sample of a large and lumpy black lichen that he discovered growing on an outcrop of limestone, a type of rock that is not commonly exposed in the Sonoran Desert. Nash and Schultz declared it to be a whole new species. A few years ago Garvie published a paper in a botanical journal, becoming the first to describe how, as saguaros age, the structure of their spine clusters changes dramatically, from formidable, downward-facing spikes when the cactuses are small to a more starburst-like pattern in their later years. “It’s not some great scientific discovery,” he observes. “For me, it was just a little puzzle that I’d seen for years.”

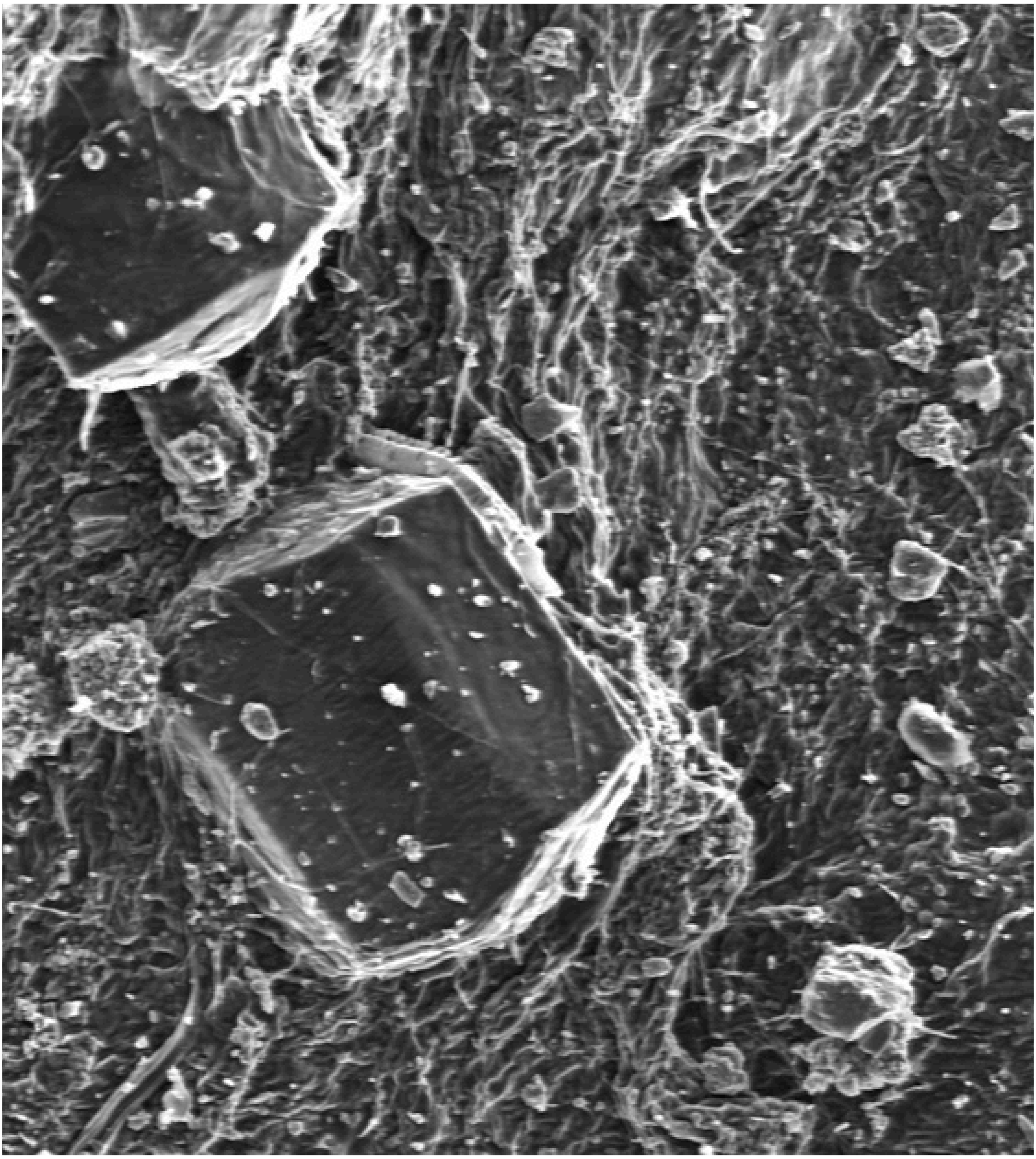
Arguably some of Garvie’s most exciting desert adventures have led him to explore the afterlife of saguaros, the towering sentinels of the desert that can grow to 60 feet or more and reach grand old ages of 200 years. As they near the end of their lives, these desert elders commonly are felled by a systemic disease in which fungi and bacteria attack the plant’s moist inner tissues. A telltale sign of infection is the weeping of a ripe-smelling black liquid from openings in the saguaro’s skin. Once the disease spreads, the plant turns into what Garvie calls a “fetid bag of goo” that can be easily downed by a strong wind.

Yet saguaros are as important to desert wildlife in death as they are in life. The towering cactuses are like gigantic sponges, their internal tissues saturated with up to 90 percent water. When they are toppled, they become an “organic moist soup that’s teeming with life,” he observes, adding that in the immediate aftermath of death, “the whole thing is moving, heaving with bugs, worms, and all sorts of microorganisms. It’s quite exciting.”

Scientists at the University of Arizona have conducted extensive postmortems of freshly toppled saguaros. In one cubic foot of a rotting saguaro, they catalogued 413 arthropods including beetles in both adult and larval stages, larval flies, pseudoscorpions, and mites. Some of them occur only in dead saguaros.

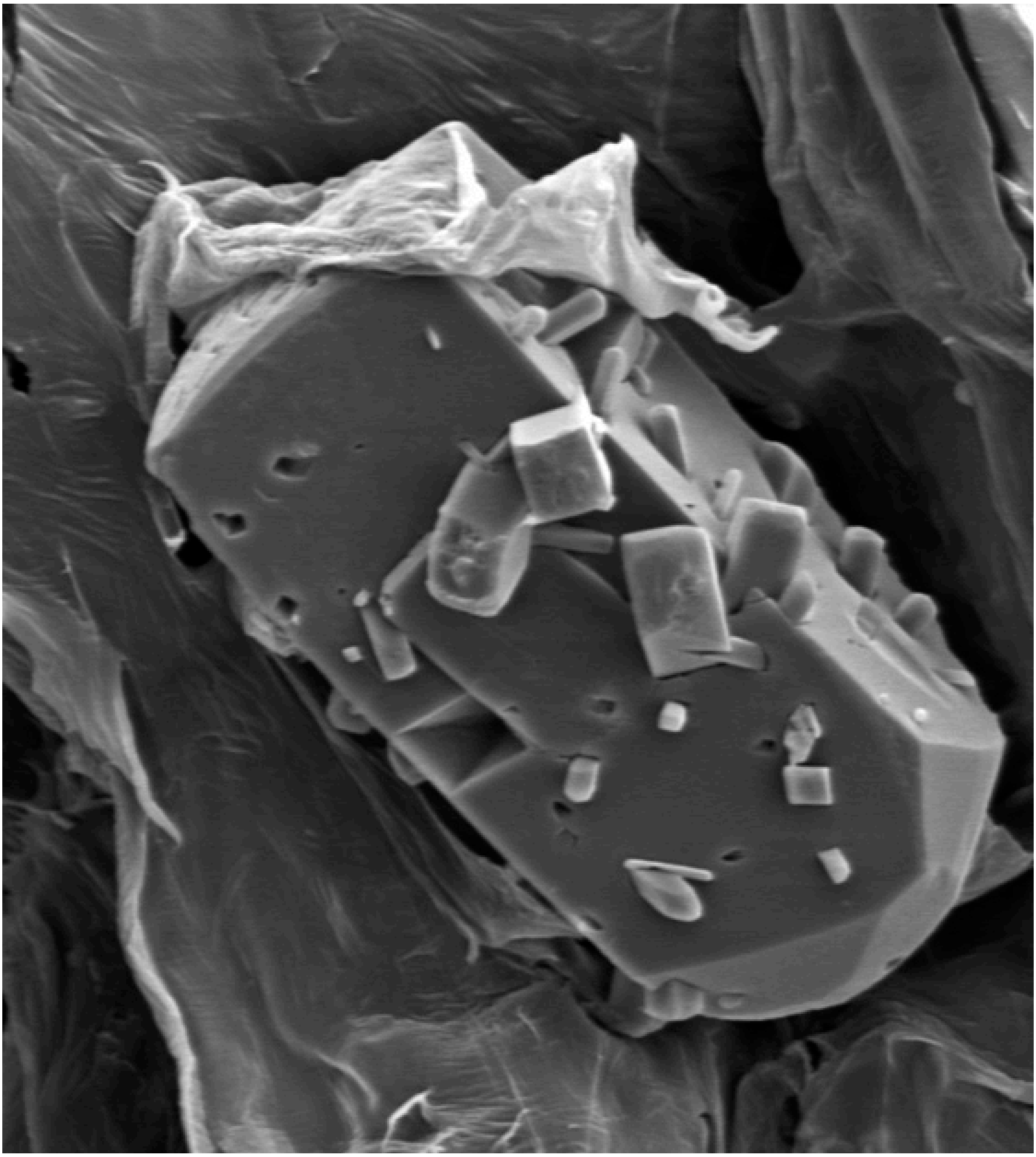
But when Garvie tore off a chunk of the rotting cactus, the mineralogist found more than biological treasures. “It was almost like a geode,” he explains. “The insides sparkled in the sun from all the new crystals that had formed.” But even more startling discoveries awaited Garvie when he took the glassy jewels back to his lab. The results were confounding. “I looked at my data and said, What on earth is this?” he recalls. His finds included rare, magnesium-bearing crystals with such exotic sounding names as lansfordite, glushinskite and nesquehonite (which has been located in mines and caves and is a common weathering product of Antarctic meteorites). Others rarely occurred in deserts. At least half a dozen additional crystals, he observes, were new to science.

These exotic crystals, however, form only when the saguaro’s putrefying pockets are moist, quickly disintegrating as conditions dry out.



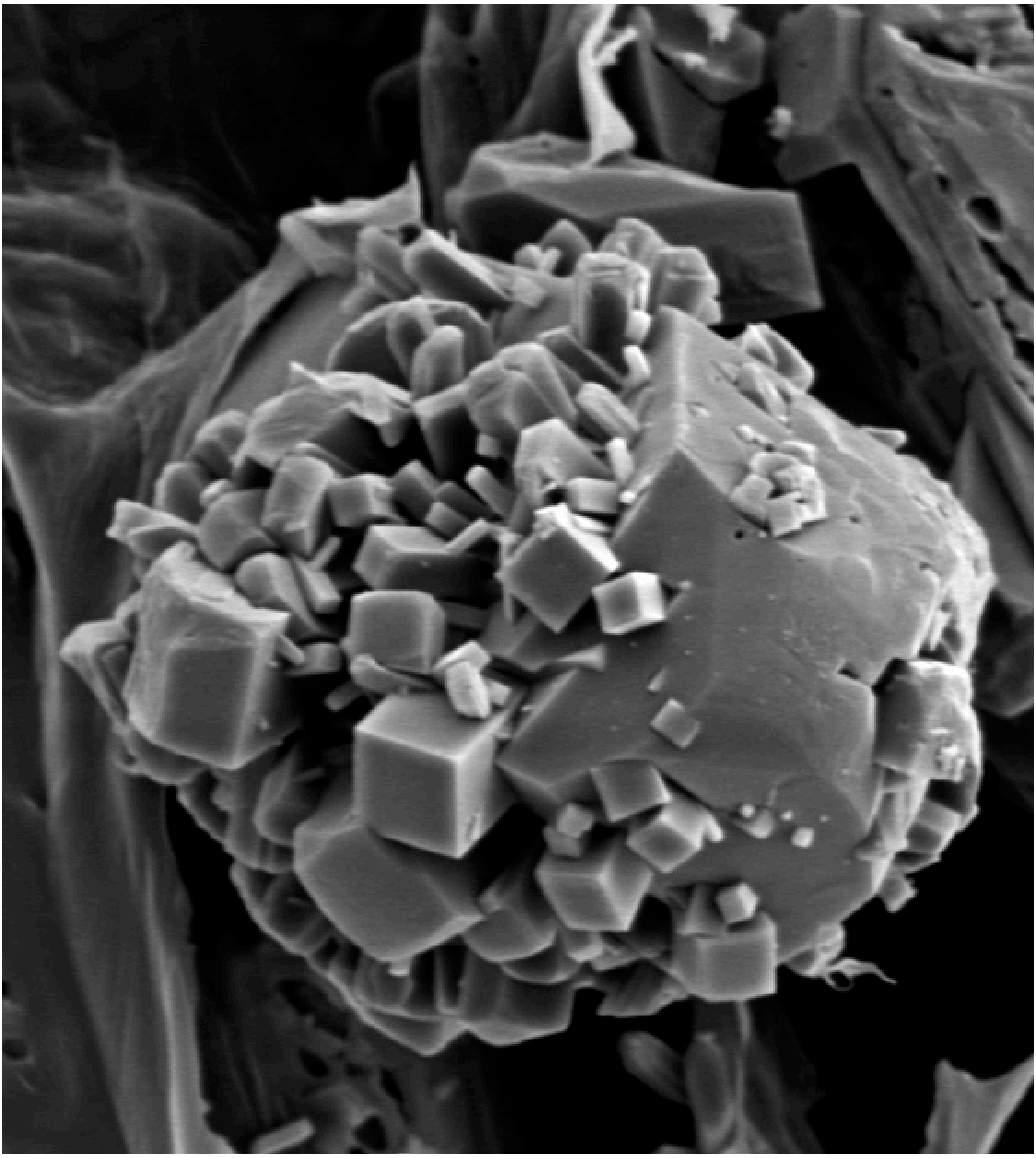
Glushinskite

Photo courtesy of Laurence Garvie, 2013



Calcium oxalate in saguaro

Photo courtesy of Laurence Garvie, 2013



Calcium oxalate in saguaro

Photo courtesy of Laurence Garvie, 2013

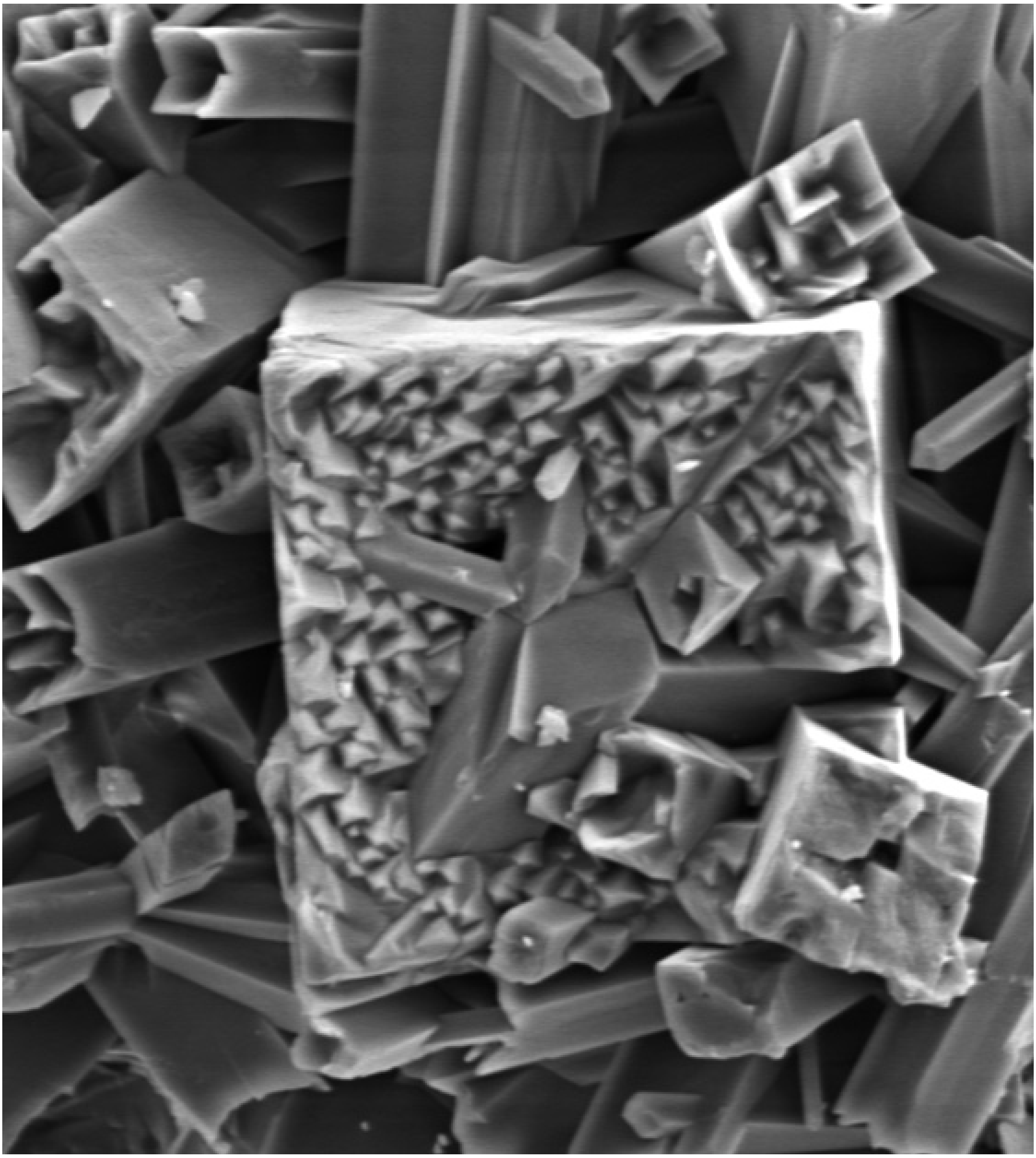
Other minerals—with equally strange and fascinating life stories—linger long after the plant's tissues have disappeared. As a newcomer to the Sonoran Desert in the 1990s, Garvie noticed chunks of a bone-colored material, as light and porous as pumice, heaped around the exposed wooden ribs of saguaro skeleton, the last of the plant's remains to decompose. "I remember collecting a piece after a year or so. It sat on my desk for another year. One day I had a few minutes and I subjected it to powder X-ray diffraction [a method geologists use to identify minerals]," Garvie recalls. Much to his surprise, the material was monohydrocalcite (also known as hydrated calcium carbonate). The last place Garvie expected to find this relatively rare mineral was on the surface of one of the hottest deserts in the world. Just what was it doing here?

Garvie launched a deep dive into the scientific literature and reconstructed the sequence by which this material came to rest in the desert. As it turns out, saguaros take up calcium—and lots of it—in groundwater. Excess calcium can be toxic so saguaros, like many other plants, safely sequester the mineral in their tissues in the form of insoluble calcium oxalate crystals. After most of the saguaro tissue has rotted away, these oxalate crystals remain as a kind of sand-like material. Even the calcium oxalates, however, don't last forever. In time, a specialized group of bacteria, known as oxalotrophic bacteria, which feed exclusively on oxalate crystals, begin to break them down. The final product? Chunks of monohydrocalcite, like the kind that launched Garvie's inquiry. Over time, the desert heat further transforms these chunks into calcite, a stable mineral that becomes mixed into the local soils.

When it comes to the rare, Soviet-era-sounding minerals that Garvie discovered in the hot rot of saguaro flesh, well, it's unlikely that companies will be filing mining claims any time soon. On the other hand, studying the transformation of calcium oxalate crystals into hydrated calcium carbonate may offer some interesting biomimetic insights. For example, scientists have studied the potential of forests to sop up the excess carbon in the atmosphere that leads to global warming. But these same trees release the stored carbon as carbon dioxide when they decompose. Saguaros and other cactuses, on the other hand, also take up CO_2 during their lifetimes but, as Garvie has shown, after they die, microbial helpers transform the carbon calcium oxalates into a stable, inert minerals that can't easily escape back into the atmosphere. Could mimicking this microbial process suggest another pathway for creating calcium carbonate for use in cement, an energy-intensive building materials? "It started with a scientific curiosity, and it's leading to some interesting research," Garvie says. "We really don't know where this research is going to go. Is it just fun research or is there a bigger story that will come out of it?"

A postscript.

This kind of scuff-your-boots, curiosity-driven research has resulted in a number of designs that now figure prominently on the list of biomimicry's Top 10 greatest hits. The Swiss engineer, Georges de Mestral, for example, stumbled (perhaps literally) across the idea of Velcro



Calcium oxalate in saguaro

Photo courtesy of Laurence Garvie, 2013

while walking his dog in the woods and wondering if the pesky burrs that hitchhiked a ride on his socks or became tangled his dog's fur could serve as a model for a new kind of attachment design.

These days, however, scientists can find themselves in a research Catch 22 that prevents the kind of free-form exploration which leads to startlingly original insights. This is an approach to discovery that the Spanish philosopher Jose Ortega y Gasset describes as "an attention that does not consist in riveting itself to the presumed but consists of precisely in not presuming anything and avoiding inattentiveness." Perhaps too many scientists in academia are pursuing money to support their labs rather than chasing their curiosity in the field. Trapped on the research-funding treadmill, they log long hours at their computer screens churning out more and more grant proposal pages about an ever-narrowing circle of expertise. It's a trend that worries Ahmed Zewail, the 1999 Nobel laureate in chemistry, who decried the thwarting of curiosity-driven research and warned that "to distract faculty members with the writing of extensive and numerous proposals or to turn them into managers is the beginning of the end. The modern enterprise of science has become so bloated and complex that the traditional models of funding must be re-examined."

Yet, as Garvie points out, "If you're someone who doesn't get a lot of grants, you're stuck. You can do nothing." Field observations may be free for the looking yet the follow-up research can be expensive. For example, the use of diffractometry to identify a crystal can cost hundreds of dollars per sample. Even if it's sitting idle in a university lab, sophisticated equipment, such as electron microscopes, are off limits to researchers unless they have the grant money to use them. "Every bit of analysis now requires money," he observes.

In this regard, universities could do well to follow the example of major companies, including 3M, Hewlett-Packard and Google, that have recognized the value of encouraging their employees to tinker, pursue hunches, to explore the great wide open, wherever it leads them, outside the boundaries of their committed areas of expertise--and on company time and in company laboratories. Early on in its history, Google instituted a practice known as Innovation Time Off which required its engineers to devote one hour to their own pet project for every four hours spent on an official company assignment. The idea was copycatted from a similar longtime program at 3M known as the "15 percent rule," through which 3M employee Art Fry most famously invented one of the company's most lucrative products: Post-It Notes.

Government agencies too could adopt practices to encourage more curiosity-driven research. Garvie suggests that grantors such as NASA diversify their long-term, big-buck funding portfolios with short-term, sudden-opportunity grants that would award more modest sums of money to researchers with errant but interesting ideas.

After all, he says, there is no shortage of fascinating leads to pursue in the world. "When I'm out in the Sonoran Desert," Garvie points out, "I'm always aware of the fact that there are probably all kinds of weird and wonderful things that I'm not recognizing. When I walk back to my car after each visit, I ask myself, What else can I see that's interesting or that I don't know about? I have found that the desert out there is just bursting with research opportunities. Every time I go out there I find something new." ×

Saguaro

Photo courtesy of Laurence Garvie, 2013

Painted Clouds | Montana

Photo: 5oulscape, 2012 | Flickr cc

Special feature
Janine Benyus in conversation with Megan Schuknecht
“Looking back, looking forward”

fall 2013

Special feature
"Looking back, looking forward"

Authors:
Janine Benyus and Megan Schuknecht

A Conversation with Janine Benyus, author of Biomimicry: Innovation Inspired by Nature, *and co-founder of Biomimicry 3.8*

MS for ZQ: Regarding how one goes about the business and process of bio-inspired design, within the last ten years how has the field of biomimicry changed, in your opinion. In other words, discuss any changes in the science, level of collaboration, rate of development, climate for investing, etc.

JB: I'll give you several things that I see have changed. Where and why biomimicry is undertaken, for example. When I wrote the book, it was mainly in academia. There weren't that many examples of biomimicry. It's still in academia, but it has also moved to corporations, design studios, architecture studios - the people who make our world are more likely than ever to ask "How would nature design our world?" and they have more access to tools like AskNature. The big change is that there is now a method to doing biomimicry in real time while you are designing.

The areas of inquiry are also expanding. Every year that goes by, another application area comes towards us. Economics and financial models are the latest. There's a book by Rafe Sagarin – *Learning from the Octopus*. Even national security advisors are asking biologists how to stay safe in a complex world, where we face terrorist threats and natural disasters.

There are great statistics on how biomimicry has changed. The number of research papers is doubling every 2-3 years, against a background rate of other scientific papers doubling every 13 years. Biomimetic products are doubling annually. You're starting to see, for instance, some financial projections about the impact of biomimicry, such as studies done by Point Loma

Octopus marginatus hiding between two shells
Photo: Nick Hobgood, 2006 | Wikimedia Commons

Nazarene University [*The Economic Impact of Biomimicry*]. The fact that it's landing on the pages of Forbes and the Harvard Business Review shows its growing acceptance. Investors are starting to see biomimicry as a good investment, regardless of the product category. Usually investments are grouped by product or sector – water purification, energy, etc. – but here you have people investing in biomimicry as a sector. Really biomimicry is an innovation approach. It's the first investment category based not on what you make but on where you took your inspiration from.

One of the big new things that has happened in 10 years, is that what began as a very fragmented group of researchers who didn't know about one another– in my book, none of them knew about each other – suddenly being able to self-identify as biomimics, and then the beginnings of a practice and an innovation practice in biomimicry starting. And people being trained at that, whether in university or through us, and beginning regional networks in their areas. Another big part of the story that I always talk about is the fact that this has done what nature does which is spread out and create networks of people who are increasingly becoming connected to one another. So we've become a network of networks and we're going global.

There's a methodology now, and tools to use, we have, for instance, students now being able to invent in this way during their schooling. And that also was just not happening. You had academics doing things like studying mussel glue and trying to figure out how to emulate it. But you did not have anyone in the design, engineering, or architecture schools trying out the biomimicry methodology as part of their educational curricula.

The other big thing is that biomimicry has been deepened by the use of "Life's Principles" (Biomimicry 3.8's problem-solving guidelines) in the innovation methodologies. We're not just looking to emulate a particular technology in the natural world but also looking at overall best practices in the natural world as a model. Nature's code of conduct was not consulted as much as nature's blueprints and recipes. I think that's a big change in the discipline since when I (first) wrote about it.

MS for ZQ: What are the major scientific, cultural, and environmental trends that you see shaping our world to come and how will they affect the way that we practice bio-inspired design?

JB: Scientifically, we're beginning to understand a little bit better how life works, how life has managed to work its miracles all these years. And that's simply because we have better instrumentation, better computer tools to do modeling and analysis, and just the nature of science, accumulating that knowledge over time. Every year that goes by, we're learning more and more. Culturally, I think that we are able to transmit that knowledge to each other as never before, so that actually increases the amount we are going to learn. And also the enabling technologies to emulate nature are really improving as well. So, just for instance, in the realm of how to manufacture using self-assembly, the way nature does – self-assembly science is really increasing in its ability to demonstrate self-assembly at a commercial level, that's new. But also 3-D printing and additive manufacturing instead of subtractive manufacturing – that's a huge enabling technology that allows us to do what nature does, which is build to shape. Self-assembly allows us to manufacture without heat, beat, and treat. Some of the things I talked about in the book, the enabling technologies, are starting to come to fruition.

Culturally, even more than 10 years ago, I think there's an understanding that no institution is going to be able to fully opt out of being an environmental citizen. I think more and more, as Amy Larkin has written so well in Environmental Debt, companies are beginning to find ways to create metrics that show their true impact in the environment because there's a realization that resources are not guaranteed. We are reaching peak everything, whether it's peak oil, peak soil, peak water. Peak clean air. I think there's a very strong understanding that we're starting to get up against the limits and in some cases have overshot. One of the things that is going to reverse it, or help us to squeeze through that bottleneck, is innovation, and that this time we better get innovation right. Culturally, more than ever, there's an opening to nature-inspired innovation because we're looking for models that work. We are living in a set of unintended consequences right now that are emergencies of our own making. So there's a receptivity to biomimicry because we realize that we can't take the risk of making it up as we go along anymore and we really need better models.

The other thing culturally that is happening is the move to localizing, and what I would call "distributed everything". We watched energy generation move from (being) very centralized, and now more and more people are doing distributed energy. They're starting to say how can we have our buildings do distributed wastewater treatment.

The biggest thing is really the local food movement around cities, and can we start to have locally produced food, and what does that look like. And that has come on very, very quickly, comparatively, the rise of local food. Local being the new organic, in other words. I'm looking for that sort of distributed meme to move into manufacturing next. I think the next thing is going to be local manufacturing. Manufacturing in your watershed. Things like additive manufacturing and commercial-scale 3-D manufacturing will allow for neighborhood manufacturing. Retail organizations, you know, instead of buying shoes at Famous Footwear, you'll walk in, there won't be shoes there, there'll be printers. I really do think we're going to be moving more and more towards that, that kind of thing. That's the cultural extension of this meme of distributed everything. I think we are understanding that our dependence on global partners really makes us less safe. Even in the energy sector, I think you're seeing people want to bring energy generation back here to the Unites States, for better or worse. And that's just a part of it. We talk about manufactured in the U.S.A., but I think soon we're going to be talking about manufactured in your county in the same way, not just your state but your county, in the same way we talk about food now.

Biomimicry has a part to play in that, because on a systems level locally produced and hopefully in a circular economy way – that's a biomimetic thing at the "Life's Principles" scale. But then also using local materials, "preferencing" local materials – and having manufacturing come back home – is really going to encourage us to figure out how do biomimetic manufacturing with local materials. And that's going to be a big opportunity for biomimicry.

MS for ZQ: What are the three most important tools that bio-inspired designers and problem solvers should have at their fingertips within the next five years? Why are they important? To what level have they been developed today?

JB: That's a great question. A good understanding of "Life's Principles". A really nuanced understanding of it, actually digging into "Life's Principles" and trying to work with them. I think that tool is a very important one. Number two, AskNature.org and the applications that will be built on AskNature. You can call this digital blueprints and software tools. We're hoping that people will build applications on top of the info in AskNature, which we hope to really broaden and have many, many more strategies in AskNature from which people can pull from and create applications. The most important thing from an IT standpoint is getting biomimicry into the tools that designers and engineers and architects use every day, which is their CAD/CAM programs. Say they want to create a truss structure – they're building a building – and they want to put a truss in that uses the minimal amount of material for a certain amount of strength. Hopefully, someday we'll get to the point where biologists biologists have learned enough about how nature creates lightweight structures, and we've been able to extract the design principles from those structures, and been able to put those design principles into either a downloadable 3-D model of a truss that has biomimetic intelligence inside it, and you download a bioinspired truss, or you are able to download a small algorithm or a software program that will create that truss for you to whatever size you want.

When we get to that point where designers who are using "Life's Principles" on a systems level and then they go to actually create technologies, they themselves do not have to read and digest the biological papers, but rather those papers have been summarized, synthesized – and the design principles have been translated into downloadable models or pieces of software that allow generative design to happen. When you get to that level, where biomimicry is actionable, because it's in the tool you use every day, that will be an enormous tool.

Then I think the third tool, I would have to say, is there is a way to continually learn from the natural world about the aspects that you are interested in in your work. That the scientific updates come to you easily. Let's call it the ability to do life-long learning in biomimicry. I am very struck by this new understanding that I have that biomimicry is not a download of a set of knowledge, but rather that it's a practice. And it's a practice that needs lifelong learning. And so I think a great tool would be a way to continually learn about the latest developments in how we're understanding what nature does, and how nature operates, from the technical all the way up to the systemic level. And that lifelong learning, I hope that we're somehow going to be able to develop that tool. I don't know. But I would love it if that kind of learning was available to people, almost like an iTunes of learning modules. That kind of thing, where it's very easy to access the latest, whether it's through coursework or a subscription to sort of a Lexus-

Cholla cactus skeleton

Photo: j.arsenault, 2007 | Flickr cc

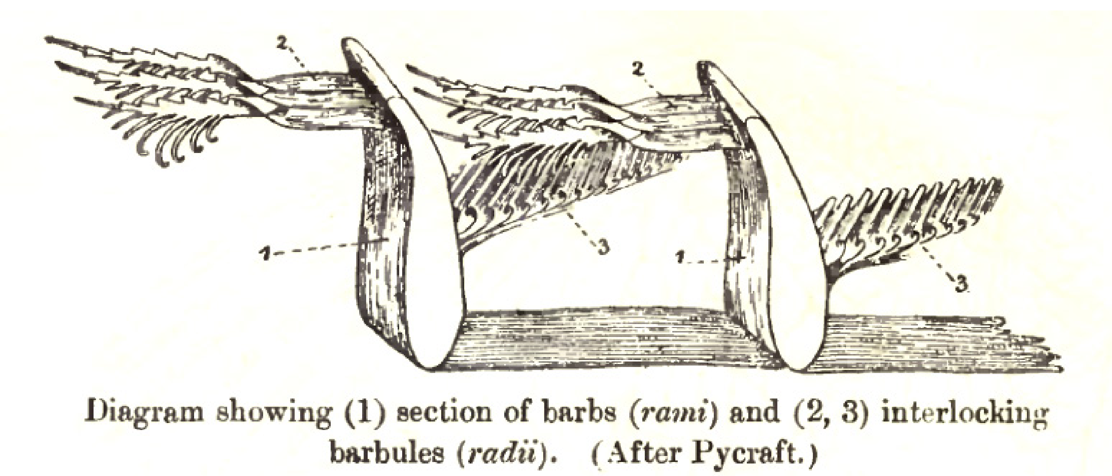
Nexus of biomimicry knowledge. That's essential. Otherwise our understanding of how nature works might stagnate while we know that the sciences are learning more every day. How do we keep up with those latest lessons?

MS for ZQ: You have done a lot of consulting to corporations over the years. Can you tell us what you consider your most successful problem-solving accomplishment and why? What role did nature play in this success? What was the specific challenge and how did you solve it? Why did you solve it that way?

JB: I thought one of the really creative projects, that had a huge impact actually, was the one where Interface asked us to rid them of one of their main environmental hazards, which was gluing their carpet tiles down. There were worker health issues, occupants had to vacate the premises when it was being put it because of the volatiles, but really the big thing was that the glues completely interfered with their main sustainability value proposition, which was to return the carpet tiles to the manufacturer for recycling. But they were glued down!

So we had this workshop in which we asked "How does nature adhere?" And we were looking at geckos, and flies, and all kinds of adhering and releasable organisms, and we realized that gravity played a part, especially when, for instance, the gecko was pushing its bristles down into a surface to get the connection with the van der Waals forces. Anyway, we were talking about gravity, and at the next table they were talking about "How does nature connect without fasteners?" They were working on a different problem. How do you get rid of things like zippers or other kinds of fasteners? And they were looking at bird feathers, and how the barbs and the barbules zip together, as a self-healing structure. And the two groups overheard each other and somebody stood up and said, "You know, if we connect the tiles to each other along the edges, like bird feathers, we'll essentially create a broadloom carpet and gravity will hold it down." And that turned into Tactiles, which was a way of attaching the carpet tiles to each other via a small coaster-like dot, a coaster-size dot, with a bit of releasable adhesive on both sides. And you connect the carpet tiles to each other, you lay them down, you create a broadloom, and indeed gravity holds it down.

This was able to reduce their environmental impact by 95% on all of their carpet tiles. It introduced an entirely new way to install carpet tiles.



Feather locking | W R Ogilvie Grant, 1921

Interestingly, it also paved the way for a brand new market, because it allowed the possibility that homeowners could install their own tiles. Out of that came the introduction of Flor, which is their residential area rug company, in which they are selling area rugs for under your dining room table and stuff and you can install them yourselves. You can have carpet tiles in the closet kind of thing and put down new carpets at new seasons, and all of this interesting stuff, and all of this because they were attaching the carpet tiles to each other instead of gluing them to the floor.

I love that story because of the environmental savings but also because it shows the creativity that can happen. Interestingly, they weren't able to figure out a way to put the carpet tile edges together, but they found something even simpler than that. This is the kind of brainstorming where you don't have to create a new thing, necessarily. I mean, Tactiles were new, but you don't have to go down to the molecular level and figure this out. Really, it was more of a conceptual idea.

The biggest win at Interface by far has not been the two products we've brought out, Entropy and Tactiles, but I think the bigger win is in how they think, and creating a company that runs more like a forest than a machine. That is a long-lasting thought process that we brought to them, and that we will continue to bring to them. I increasingly understand that "Life's Principles" as a design scoping, creating, and evaluating tool is as valuable, if not more valuable, than the individual technologies that we inspire. In terms of how nature was involved, we literally had nature's ideas at the design table. It was during a workshop with hands-on information and that was interesting to do.

MS for ZQ: Other than one of your own accomplishments, can you give an example of a bio-inspired product or service that most completely fits your criteria for success? Why do you choose this?

JB: A complete success would be a product or a service that, from its inception, is designed to fit "Life's Principles". It would be sourced from local materials, designed for return and disassembly, it would be capable of self-healing, of learning through feedback loops, it would be capable of adapting in real time and evolving from one generation to the next, it would be manufactured benignly, it would use very little energy in its making and in its use cycle, it would be completely without toxins, it would be able to be manufactured anywhere, it would be designed to be upcycled at the end of its life, and it would live in an ecosystem of products that reinforce each other, and those products would build prosperity for local communities and fertility and produce ecosystem services equal to local native systems and on and on and on.

Obviously that's a very high aspirational goal, and I think there are very few bio-inspired products and services that meet all the criteria, at this point. We are still in the transition to that. So instead, the way I'd like to answer this is to look at impact and what it shows about what biomimicry can do. I'm a big fan of things like the Caltech wind farm that uses already existing technology, these vertical axis wind turbines, but puts them in a cluster like a school of fish, so they can surf each other's wind vortices and produce ten times more wind power and use that

Schooling Banner fish

Photo: jon hanson, 2007 | Wikimedia Commons much less land. I find that really interesting, because again, it didn't require a new technology, just a new way of thinking inspired by the natural world. And obviously has a big impact, I think, in perhaps bringing wind farms closer to cities.

I also like, in terms of impact, Nova Laboratories and Biomatrica, two companies that are mimicking brine shrimp and tardigrades and other organisms that do anhydrobiosis, and they are able to make trehelose-coated vaccines, proteins, and other kinds of biologicals like blood samples. This is important because of the impact it has on people. This is a preservation system that needs no freezer. These are shelf-stable biologicals that are protected the way a tardigrade protects its cells when it dehydrates. Fifty percent of intended recipients don't receive their vaccines because of a break in refrigeration or in the cold chain. It eliminates that [problem] and so can save lives. But also, if you can imagine freezers in every hospital, every laboratory around the world, being unplugged, and being able to store things. It's incredibly important to think about this kind of preservation for foodstuff too. When I look at that stuff, when I look at the medical and possibly an agricultural impact, being able to remove spoilage from the food system, and remove toxic preservatives from other kinds of products, that's a really big impact, so I like that sort of thing.

I think another really important idea is the idea of taking life's optimization techniques and putting those into software. There's a product called OptiStruct, which is the software that is based on bones and how they reform. Essentially, it's a software program that is able to take material from where it is not needed and put it where it is needed along lines of stress. This kind of thing was used in the rib and wing assembly of Airbus airplanes, for instance and was able to lightweight that system by 40%. It's being used in GM and other car manufacturers. That's where we need to go, which is to take life's optimization ideas, whether it comes from the slime mold in order to create better transportation networks or it comes from ant colony optimization to create better logistics - routing of trucks as well as computer efficiencies.

These sorts of things, where we take life's ideas and begin to move them into algorithms basically and 3-D models that people can download and begin to use biology's ideas right in the designs that they are using every day. A big impact is going to happen when biological ideas that are now sitting in biological papers are synthesized and moved into biological blueprints, digital biological blueprints that can fit into tools inventors use every day, whether that's CAD/CAM programs that engineers use, whether its optimization programs that product designers use to lightweight their products or make them more efficient, even the build programs, the digital build files that will be used in 3-D printing. The ability to get nature's elegant and optimal solutions into those is going to be really, really important. So rather than tell you about one particular system, those are the things I'm thinking have quite a bit of impact.

The last one I'll mention will be in the realm of agriculture. There's a huge reboot of our understanding of how plants are able to defend themselves against pests, how they are able to resist drought conditions, how they are able to live in salty soils or overly wet conditions. All of those sorts of conditions are going to be with us with climate change, and it's going to be incredibly

Resurrection Plant, Rose of Jericho, *Anastatica hierochuntica*

Photo: hira zubairi, 2008 | Flickr cc

important to figure out how to put plants in conditions that allow them to be as resilient as they possibly can be. And I think what we're realizing is that plants don't do that alone. So I'm looking at revolutions in the field of microbial ecology of soils and how mycorrhizal fungi and helper bacteria allow plants to grow with less water, allow plants to protect themselves against pests with these helper groups. It's a large area to talk about, but it's this idea of using a community of helper organisms and creating conditions conducive to those organisms in turn helping a plant defend itself. For example, there's a nonprofit called Symbiogenics (founded) by Rusty Rodriguez, which is looking at fungus and inoculating seeds with helper fungus. Those agricultural models are going to be key. I think wisdom right now is coming from the rhizosphere. It's coming from soil communities and the more understand them, the better we'll be able to help our crops survive, help our crops adapt in a climate-change world.

In the realm of energy, I'm still very much looking for photons to fuel. I'm looking for artificial photosynthesis that doesn't stop with an electrical wire but rather splits water and takes CO_2 as a plant does to create fuels and to also create building materials, from CO_2, and a solar-driven process that allows that to happen. Those are the ones I think are really most impactful.

And one other, which would be anything in the realm of biomimetic membranes, because I think filtration is extremely important, not just for desalination but also for being able to separate out fine chemicals from organic waste streams, for instance. The biomimetic membranes to be able to pull what you want out of something else, to be able to chelate metals, for example, out of wastewater as organisms do, to be able to pull those things not only to remediate the water but also to collect the metals and other things you want. That ability to do selective filtration is going to be really important. Right now you have companies like Aquaporin doing that sort of thing, but that whole realm of biomimetic membranes is key.

MS for ZQ: In your opinion, where are the biomimicry research and development "hotspots" in the world, and why do you consider them to be so important? What places or people are worthy of watching?

JB: I have several kinds of answers to this question, because I think biomimicry is happening on many levels. When I wrote my book, I was looking at research labs around the world that were emulating the natural world and trying to come up with new inventions. And I'm still doing that. But where I think a lot of the most innovative things are going on is in our own community, in our own biomimetic networks. The regional networks of people that we're involved in with Biomimicry 3.8 and the Biomimicry Educators Network. These are the people who we have trained and who have now gone back to their home communities and are beginning to do all kinds of initiatives, locally, to take nature's wisdom into design of their home places and to start small biomimetic companies, and to train people in biomimicry locally. I think that's really something to watch.

I continue to look at the hotspots in research. When I look at the countries where it's happening, it's certainly happening here in the U.S., it seems to be a huge, very productive pipeline in

Baleen smile

Photo: Ryan Harvey, 2011 | Flickr cc

Germany, Sweden and the Scandinavian companies are also very serious about moving this research from the research labs into actual products, the U.K., Australia. China is doing an enormous amount of research right now, Japan always has been. In terms of Germany, I think what they've got going is the Biokon competence network which has produced a stream of products. This is a consortium of universities, biomimicry centers, economic development centers, and governmental help to pull these biomimetic products from research all the way through to adopted products. And they've done everything from EvoLogics dolphin-inspired modems to one that I love right now, which is actually being trialed on some Airbus planes – it's called Fraunhofer Institute – they've developed a technique to emboss structures of sharkskin onto aircraft paints, so this cool kind of stenciling, what they're doing anyway, but here's a stencil for your paint that will put the sharkskin on it. Those sorts of things are coming out of Germany all the time and I find that really interesting.

In terms of the centers, here in the U.S. I'm really watching the Wyss Center for Biologically Inspired Engineering (Harvard University). And almost most every week now they're coming out with something new. They do a lot in biomedical but they're very much focused on new materials like shrilk; it's based on the exoskeletons of insects and how they are laid up. Half the weight of aluminum but the strength of aluminum in a flexible plastic. And there is lots going on there because that center is about use-directed research, it's about creating useful products.

I'm also interested in what's happening at MIT, at the Mediated Materials Lab, Neri Oxman's lab, people like Marcus Buehler who are doing amazing things right now. I would also have to add that the clients that we work with, that biomimicry is beginning to take hold in corporate innovation labs as well. They are picking this up not just through us, but in many ways I'm starting to see them talking about companies like Airbus, and Qualcomm, large, large companies, GE, talking about their biomimicry projects. It's in our clientele for sure. Interestingly, it's in the corporations that are known for sustainability of course, but it's also not just in corporations known for innovation, which I think is a good sign, that it's seen as an innovation pathway, which makes it all the more important that the innovation not just be a mimicry of a particular technical aspect of the natural world, but that "Life's Principles" be applied in order to make that product not shallow biomimicry but a much deeper biomimicry.

The artificial photosynthesis folks, there continue to be more and more and more labs that are sharing that project. I'm starting to see things like that -- it's not really a particular place, but it's a consortium of places that are working on artificial photosynthesis. That continues to happen, it continues to happen in the world of materials as well, in which you can't really point to any one university or company, but rather these technologies, these holy grails in biomimicry, become strange attractors for a lot of different companies and universities to work on together.

Our biomimicry global conference made me feel like that was the center of the world in biomimetics at that moment. The educators, the practitioners, the clients, corporations, the academics – they were all in the room at once.

That's the sort of thing that made me feel like this discipline has come of age and that there's a center of gravity there developing. And there were teams of students from around the world who had been inventing biomimetically using both inspiration from AskNature and using "Life's Principles" in order to create new water technologies that the world needs, solving global challenges. And sitting there at the Harvard Club, watching teams from Mexico, and Egypt, and all over the world, I thought to myself, this is a hotspot of biomimicry right here in this room. The next generation of biomimics are the wellspring of sustainable solutions done not just in a shallow biomimetic way but with all of nature's wisdom lifting them. ×

We thank Janine Benyus for sharing her insights and Megan Schuknecht for coordinating and recording the conversation. Megan Schuknecht is the Biomimicry 3.8 Director of Design Challenges

Water striders using water surface tension when mating

Photo: Markus Gayda, 2005 | Wikimedia Commons

Gilled fungi with Rose of Sharon

Portfolio

Lisa A. Frank

Could you tell us about your background and how you got started in the field of art and photography?

When I was a young girl my father began a summer stock theatre in rural Illinois. For the years I lived at home I was able to participate in many phases of theatrical productions. I found that I particularly loved being around the people who were building and painting scenery. After getting an undergraduate degree in art and imagining my next years working in a restaurant I decided that I would instead move to NYC and learn to support myself as a professional scenic painter. After several years of internships I was accepted into the United Scenic Artists union. I began painting backdrops 3 stories high for the Metropolitan Opera, sets for Saturday Night Live skits and scrims for Broadway shows. Fast forward a few years and I was also gilding crosses and clock faces atop the highest churches in New York City. I painted *trompe l'oeil* murals at Saks Fifth Avenue and *faux bois* at Barney's.

As years went by I found myself working more quietly at a drafting table designing wallpaper and textiles rather than up on scaffolding. Now using pencils and watercolors as my tools it was becoming undeniably clear that I was struggling with a tremor that was affecting my ability to do hand rendered work. Soon I could no longer produce the clean, accurate work that my career as an artist was built on.

Luckily this was occurring at the transitional moment when computers were becoming a relevant design tool. I bought my first Mac (a very early model!) and took several digital imaging classes. Two more years after that, I bought a more powerful computer, a scanner and my first digital camera. I had acquired an entirely new set of skills.

During those few years of re-tooling, my favorite pastime was taking walks with my spirited young dog, a German Shorthaired Pointer named Caruso. In order to exhaust his irrepressible energy the walks became longer and the locations became wilder. I started to bring my camera with me to document what we would encounter. I began to bring home objects to scan and photograph. From suburbia where I was a thirty minute drive to natural areas, I moved to a house in the Catskills where I could walk out the door and find wildness all around.

This decision did not come as a surprise. During the summers when I was helping out at my father's theatre I was also going to scout camps where I developed a comfort and deep love for being in nature. Now, with a very good dog to follow, my shelf full of well worn field guides that I collected as a teenager, I began, once again, to explore, notice, collect, and identify. I felt like I had come home. With camera in hand and some woods to wander through, I rediscovered something essential.

What kind of techniques do you use for your work? Do you use any software?

These photographs are staged "scanographs" meaning that the entire image has been composed directly on the glass of a flatbed desktop scanner. The technique is fairly straightforward but a great deal of time is involved in placing and positioning the subjects. I have built a simple scaffolding over the glass from which I can

Pearl Oyster | *Pleurotis ostreatus*

suspend objects slightly off of the glass. I do this to promote a greater sense of depth and in some cases an illusion of gravity (the falling tulip petals in the Jack-in-the-Pulpit images are an example), and I sometimes suspend a 'backdrop' of patterns or texture over the entire composition.

My tools couldn't be more ordinary: clothespins, monofilament and chop sticks! I use a scanning software called SilverFast, and for image editing I use Photoshop and Aperture.

How has your art/style changed since you first started?

I have several different portfolios of work, all exploring themes related to environment, nature, pattern and place. There are a few references that bear mentioning.

The collection of scanographs was inspired by my interest in early botanical painting before the advent of photography. Created by botanists and artists alike such as Mark Catesby and Jakob Hoefnagel, these paintings blended myth and observation with varied levels of artistry. Working directly from nature, subjects seemed keenly observed but were often imaginatively interpreted.

As an observer and a witness, I am repeatedly stopped in my tracks to wonder, "How in the world did this happen?" Some of these scanographs are deliberately fanciful responses to that question. Staged as "Just So Stories" in the tradition of Rudyard Kipling's "How the Elephant Got His Trunk" they offer possible explanations for how a plant evolved.

"These, I, Singing in Spring Collect..." (Includes scanographs of jack-in-the-pulpits, skunk cabbages, and fiddleheads) | 100.5" x 40"

The Jack-in-the-Pulpit from this series is a truly peculiar plant. In spring, its purple and chartreuse striped hood is a bold and graphic design. This extraordinary hood is aroma-filled, attracting insects to begin the task of pollination. In late summer, the plant flowers again, this time with chunky green berries that change, in turn, to a jaw-dropping red in the autumn. Most incredibly, once mature, this plant is able to choose which sex to be the following year based on the amount of water and nutrients received during the previous summer. The real life cycle of this plant is so spectacularly odd, it seems just as plausible that the hood was created by the impact of falling purple tulip petals.

As the scanograph series developed, I began combining them with close-range photographs to construct large-scale, complex patterns. Densely ornamental, this work refers to the interior decoration documents of Britain's Aesthetic Movement of the late 19th century. The designer, William Morris, is particularly relevant for the ways his design work drew upon similarly themed subject matter, showing a love for all natural things and designing with an assurance gained from observing nature first hand. These photographs are presented in several different ways: as solitary repeating patterns, as standalone tapestry-like designs and as floor-to-ceiling "sections" that combine repeating patterns with elaborately constructed "trompe l'oeil" mouldings that include wainscoting, friezes, borders, swags and other architectural detailing.

My recent still life compositions are constructed almost entirely from unique individual photographs and rarely use two objects from the same image. They refer to the Dutch still life painting of the 17th–18th centuries. These Dutch artists painted from their imaginations with the help of life studies done throughout the year. They then reorganized the various components to create a world that could never exist in reality.

If deconstructed, my work too becomes a visual journal of separate studies. Flowers exist in a state of perfection that does not conform to time or season. Instead they break that bond between humans and nature, and coexist in a sovereign fantasy world. The "natural" is imposed on "nature". Although snakes, birds and insects all enter into the same artificial scene, it appears as if we have just happened upon them, catching them by surprise. The moment is then frozen and time is permanently suspended.

In 2011 I began working with computer scientists to transform my artwork into walk-about virtual reality environments. This unusual project was funded by the Wisconsin Institutes for Discovery, the Living Environments Laboratory, and the University of Wisconsin Design Gallery (all at the University of Wisconsin-Madison). Blurring the lines between art and technology, I created the exhibit, *<1>:"der"//pattern for a virtual environment*, a fifteen minute immersive experience that features six explorable environments that reference natural history dioramas as well as the experience of walking in the woods.

I am often asked how I reconcile my love for wilderness with the fact that I share some of those experiences using expensive visualization equipment. Since it is somewhat unusual, I would like to add additional information about the part of my work that involves advanced digital imaging.

My purpose with all of my artwork is to bring something to viewers that they wouldn't normally be able to experience. In my virtual reality work, the potential is compounded. Viewers can fly through an expansive landscape or land in a macro world, down in the dirt with mushrooms and electrified mycelia. They can discover themselves up in a nest cradled in the branches of a tree and go inside of an egg held therein. I have seen how this ability to access inaccessible or unusual spaces delights viewers: to change scale in our world, to have unexpected abilities, to live in the world differently can evoke wonder, and I think that's a powerful tool. It is my hope that I am fostering or reinforcing a connection to nature, particularly among children.

This reveals a rich paradox. Virtual reality is certainly not a natural space but there is clear potential to explore virtual environments as a path to better and deeper connections between people and nature. In fact, in some ways the novelty of a virtual reality experience can bring new focus and fresh attention to elements of our world that are unseen. In this anti-natural environment, an awareness can be boosted of what we have become immune to. Can this type of imaging be used to make observers more ecologically aware of what it means to be in the world, and – by extension – what the value is of protecting it? I think this is a very good question to continue asking myself. My thinking is this: we live in a world where technology evolves minute-to-minute, allowing us to process information in ever faster and more complex ways. As an artist who is interested in creating a connection between viewers and nature, I want to be realistic about what the terms are for the world we live in. I personally accept and celebrate my relationship to technology, but it co-exists with a realization that I need to balance it with walks in the woods where my senses and intellect are engaged differently. Nurturing a "hybrid mind" becomes my goal. This is a multi-tasking ability to experience both natural and virtual worlds. With my photography, I want to promote real-world experience but I will put digital technology and virtual experience to service to arrive at a related end. I hope that my photographic observations – even as they are translated via layer upon layer of digital manipulation – reflect an experience of the natural world that many crave but have no access to.

How does photography influence the way you see the world? Do you feel that you see things around you differently?

Bearing witness to haphazard wonders, the activity of taking pictures as I walk in the woods makes for a visual diary – it illuminates my position within the natural world while documenting changing evidence of the ordinary and the astonishing. The inter-relationships between all of nature's corresponding parts create the true "pattern" of my work. Season after season I trace nature's comforting repetition. The resulting subject matter for my photos changes with the calendar taking notice and making patterns of icicles one week and morels just a few weeks later. My artwork is connected to the "wildness" in nature even while it is taming it with formal patterning. All things are equal: I am as captivated by the full and magnificent bloom of autumn color as I am to the existential challenges implicit in its fade and decay. A personal, arbitrary, asymmetrical time chart is

Beginning work on the "Mushroom Diorama" with UW-Madison computer science graduate student, Nathan Mitchell

Exhibition title:*[1]: der //pattern for virtual reality*

First seen at the UW-Madison's Wisconsin Institutes for Discovery, December 2011

Photo: Leslie Frank Taylor, 2011

Attendees experiencing one of the virtual reality environments | Exhibition title: *[1]: der //pattern for virtual reality*

| First seen at the UW-Madison's Wisconsin Institutes for Discovery, December 2011 | Photo: Stephanie Nutt, 2013

formed that is deeply resonant for me and key to my understanding of what it means to be alive and of this world.

I choose to bring attention to discoveries that are not commonly seen or appreciated. Creating a context for connection, it is my purpose to draw the viewer into a local world as it hasn't been witnessed before - charged with wonder - rich, complex and changeable while being inclusive and accessible.

As an aside, I am not a particularly good birdwatcher because my eyes are always trained to the ground. I have over 10,000 photos of mushrooms as a result.

Who/what inspires you creatively? What do you feed on most?

Thoughtful exhibitions like "Hiding Places: Memory in the Arts" at the John Michael Kohler Arts Center here in Wisconsin. "Moonrise Kingdom" and "The Tree of Life". A new picture book. Walking in Muir Woods. The Metropolitan Opera production of "Satyagraha" by Philip Glass. A new camera lens. Rereading *Pilgrim at Tinker Creek*. The artwork produced by my friends and my students, and collaborating with unlikely partners.

What are you working on right now? Any exciting projects you want to tell us about?

One of my collaborative projects is a research study led by a team of scientists from the Beckman Institute at the University of Illinois Urbana-Champagne. I'm providing them with 3D videos that will be used in a fully immersive virtual reality environment. One simulates a walk in the woods, the other a walk in an urban environment. Using a treadmill we will be examining the effects of these virtual environments on different aspects of cognition including memory and attention, as well as the role of physical activity on the beneficial effects of exposure to nature. Finally, we'll be looking at the rehabilitative potential of a virtual nature environment, particularly for those suffering from PTSD.

What is the last book you enjoyed?

The Rediscovery of the Wild, edited by Peter H. Kahn, Jr., and Patricia H. Hasbach (2013, Massachusetts Institute of Technology, Cambridge, MA) This book explores the idea that we need contact with "wild" nature that is unmanaged, unencumbered and untamed by humans and unmediated by technological artifice.

On a lighter note, I enjoyed William Wegman's, *Hello Nature: How to Draw, Paint, Cook, and Find Your Way* (2012, Prestel USA). Although his dogs are thankfully still present, Wegman uses vintage Boy Scout manuals and field guides as source material for his new artwork. For me, it was a nostalgic reference to my first outdoor experiences at summer camp.

What are your favorite 3-5 websites, and why?

There are two photography-based websites that I'd like to mention. The Typologist: Collector of Collections" (http://thetypology.com/THE-TYPOLOGIST-BLOG) features curated photographs of object and photo typologies. Subjects vary from Duppi Hats from Uzbekistan to my own photograph of magnolia warbler taxidermy.

Despite its provocative name, http://cabinporn.com is truly "inspiration for your quiet place somewhere". The photographs thoroughly feed all of my escapist fantasies.

I have found the Museum of Modern Art's website to be a deep, exhaustive, and very handy resource: http://www.moma.org

I enjoy designboom for its interest in the future of architecture and design with specific attention on emerging talent: http://www.designboom.com

And my friends tell me I should confess to regularly visiting the Tom + Lorenzo: Fabulous & Opinionated site (http://www.tomandlorenzo.com) for its enjoyable banter about fashion design.

What's your favorite motto or quotation?

I refer to the New York Lottery every day: "You gotta be in it to win it." This is my lowbrow reference to a more thoughtful quote by Annie Dillard, "The answer must be, I think, that beauty and grace are performed whether or not we will or sense them. The least we can do is try to be there."

This provides me with a reminder: if I don't pull myself away from the computer, put the camera and dog into the Subaru and find some nature to be in I will miss the red-winged blackbird riding on the back of a sandhill crane and the line-up of eleven painted turtles on a log. ×

Blue Turkey Tail Fungi | *Trametes* versicolor

Digital Photograph | Lisa A. Frank | 2010

Morels and Fiddleheads | *Morchella esculenta*

Morels and Fiddleheads | ***Morchella esculenta***

Farmer's Market, Madison WI

Market Mushrooms with Snap Dragon

Jack-in-the-Pulpit's Berries with Two-coloured Bolete | *Arisaema triphyllum* / *Boletus* bicolor

Lactarius with Bellflowers (Peppery Milkcap) | *Lactarius piperatus / Campanula rapunculoides*

Fiddleheads

Fiddleheads

Russula in October

Russula

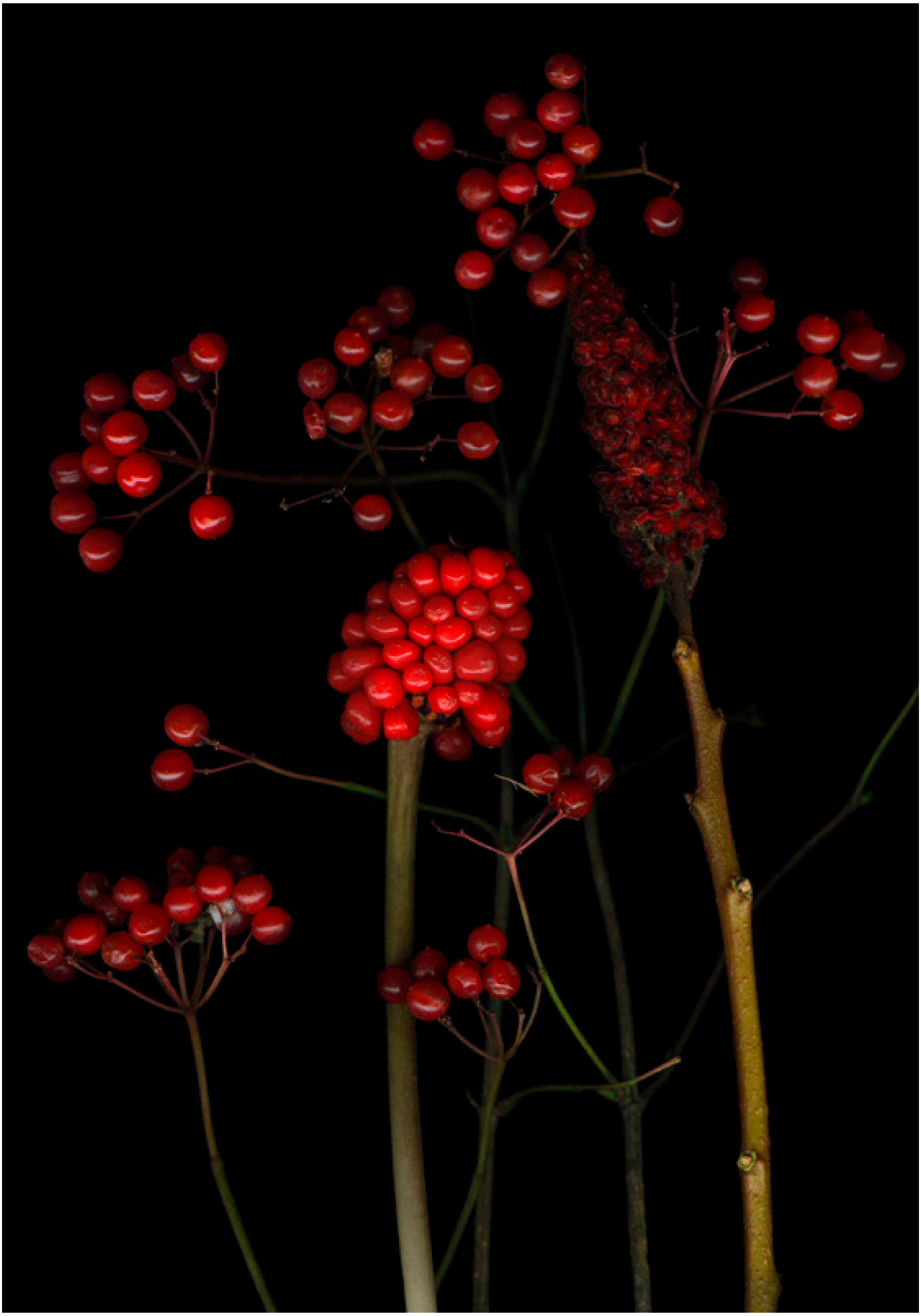
Secret Lives of the Jack-in-the-Pulpit | *Arisaema triphyllum*

Secret Lives of the Jack-in-the-Pulpits | *Arisaema triphyllum*

Bloodroot Diorama | *Sanguinaria canadensis*

Nested Skunk Cabbages | *Symplocarpus foetidus*

Smooth Sumac Fruit in Fall | *Rhus glabra*



Autumn Red Fruit

Trout Lily Diorama | *Erythronium americanum*

Yarrow with Creamy Wild Indigo | ***Achillea millefolium / Baptisia bracteata***

Decaying Leaves

Mushroom Diorama

Spiderwort and Prairie Smoke | *Tradescantia occidentalis / Geum triflorum*

Monarch caterpillar

Photo: sBegin, | Flickr cc

People *Interview with* Markus J. Buehler

Naturally occuring shells as biomaterials, and 3D printed bio-inspired composites. The image shows a manifestation of a hierarchical biological material rebuilt using engineering polymers, to achieve composites with greatly enhanced fracture toughness. It shows that simple building blocks can be used to create complex material functions, exploiting the design paradigm of structuring materials in complex geometric patterns. The different colors in the composite indicate regions of stiff and soft materials, respectively. | Photo courtesy of Markus J. Buehler and Graham Bratzel (MIT)

Interview

Markus J. Buehler

Markus J. Buehler is a Professor and the Head of the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology (MIT), where he directs the Laboratory for Atomistic and Molecular Mechanics (LAMM). Buehler is a leading scholar in the field of bio-inspired materials and founded the field of biomateriomics. He has published more than 200 articles on biological and bio-inspired materials, authored two monographs, and given several hundred invited, keynote and plenary talks. He is best known for his seminal contributions in multiscale modeling of hierarchical materials, and his work in linking experiment and computation towards the rational design of novel materials.

Buehler has received many awards for his research, including the TMS Hardy Award, the IEEE Holm Conference Mort Antler Lecture Award, the Materials Research Society Outstanding Young Investigator Award, the Society of Engineering Science Young Investigator Medal, the Thomas J.R. Hughes Young Investigator Award, the Sia Nemat-Nasser Medal, the Rossiter W. Raymond Memorial Award, the Stephen Brunauer Award, the Alfred Noble Prize, and the Leonardo da Vinci Award. He also received the National Science Foundation CAREER award, the United States Air Force Young Investigator Award, the Navy Young Investigator Award, and the DARPA Young Faculty Award, as well as the Presidential Early Career Award for Scientists and Engineers (PECASE). He was an invitee and plenary speaker at several National Academy of Engineering-Frontiers in Engineering Symposia. In 2010 he received the Harold E. Edgerton Faculty Achievement Award for exceptional distinction in teaching and in research or scholarship, the highest honor bestowed on young MIT faculty.

Buehler is dedicated to service to the academic community, and serves as a member of the editorial board of several international publications including: Roy. Soc. Interface, PLoS ONE, Int. J. Appl. MechJ. Mech. Beh. Biomed. Mat., J. of Engrg. Mech., and BioNanoScience (as Editor-in-Chief). He is the founding chair of the Biomechanics Committee at the Engineering Mechanics Institute of ASCE, a member of the U.S. National Committee on Biomechanics, and Co-Chair of the Nanoengineering in Biology in Medicine Steering Committee of ASME. He has participated in several K-12 educational programs and is committed to diversity at all levels.

http://web.mit.edu/mbuehler/www/

http://web.mit.edu/mbuehler/www/group/Markus_Buehler-biosketch.pdf

What are your impressions of the current state of biomimicry/bio-inspired design?

Biomimicry is in an exciting stage as we learn about the way nature designs and manufactures materials and structures at all scales, from the atomic to the macroscopic level. The field has moved from traditionally empirical approaches to more systematic methods, owing in part due to the emergence of mathematical models. For example, molecular modeling has paved the way to link the structure of molecules to the properties of a material or structure, which has enabled the rational design of materials inspired by nature. Moreover, the design of materials and other systems has been infused with creative approaches that have blurred the boundaries between art and science.

What do you see as the biggest challenges?

Bridging the scales in length and time remains a core challenge. This includes both understand-

Image of a mussel attached to a rock. The threads connecting the mussel to the rock are made from a protein material that features remarkable impact tolerance properties.
Photo courtesy of Zhao Qin (MIT)

ing the structural foundation to it and how to actually construct the kinds of structures we see in many natural systems, which are often complex hierarchical geometries. While engineers have traditionally created things by carving away materials – hence called subtractive manufacturing – nature typically uses additive manufacturing, and makes materials by assembling them molecule by molecule. New methods of manufacturing need to be developed that allow us to build the structures we observe in nature.

We know that the basic code of life is DNA, and that proteins and sugars and similar molecules are the universal building blocks of materials in the living world. However, how we connect molecules to generate materials, organs or organisms that work in a certain way remains a big challenge. For example, while we can make the proteins that make up a spider web in the lab, we have currently very limited ability to create a complex structure like a spider web or a cocoon in the lab.

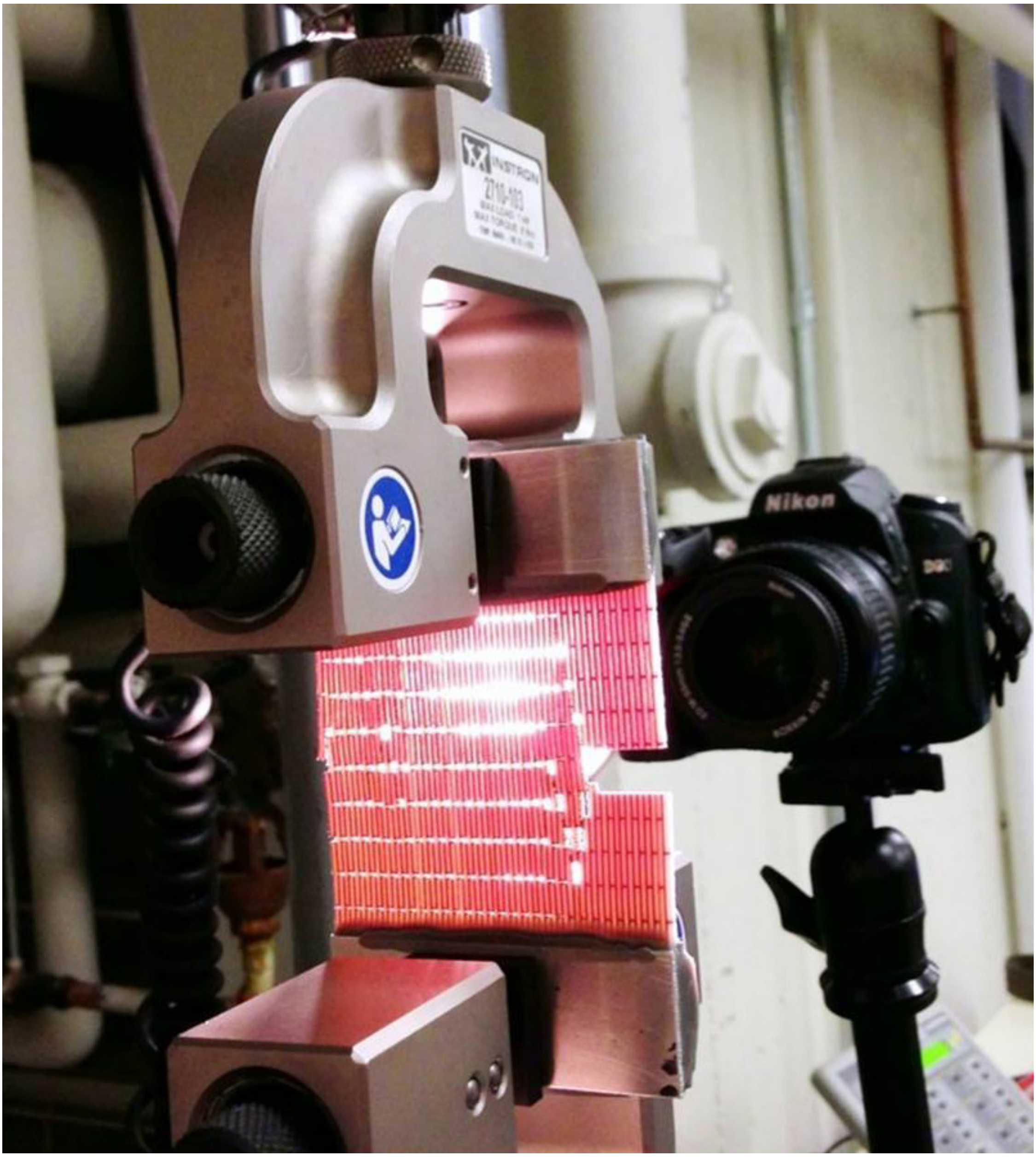
Many current efforts rely on existing organisms that are altered to produce certain materials, or that do that naturally, such as wood or materials extracted from plants. In the future, we want to find our own ways to produce complex function from simple chemical molecules, with similar elegance as what nature does, and harvesting matter that exists in abundance. What about taking silica from the sand at the beach, mixing it with proteins from soy beans, and building an airplane, all at room temperature and in an aqueous solution that does not involve any toxic chemicals? Turning the weakness of silica or glass into a strong material is impossible for engineers, but is achieved in nature in many sea animals such as diatoms or deep sea sponges.

What areas should we be focusing on to advance the field of biomimicry?

A more systematic, mathematics and modeling driven approach that relies on quantitative methods. Currently, there is a lot of ad-hoc and inspirational design happening, some very successful, but we want to apply the power of engineering and science to this field. While some advances have been made, more rigor is needed. This also raises the question of education, which should play a more prominent role. What about educating our undergraduate engineering students in new ways of thinking about materials, to consider the holistic balance of raw materials, energy, byproducts, and durability? These and other fields pose interesting challenges and give opportunities to lead new educational programs.

How have you developed your interest in biomimicry/bio-inspired design?

For many years I have been intrigued by the diversity of materials nature produces and uses – from wood, to bone, spider silk to organs or cells. Yet, these materials are made from some of the most basic chemicals known, at low energy and low temperature and in water. Engineers are far from replicating these processes and rely on much different methods. To make steel, we need a steel plant that relies on iron ore and substantive amounts of energy. Spiders produce silk threads at the strength of steel at low energy,



Experimental setup in which the 3D printed composite material is tested under extreme mechanical loading. This setup is used to extract strength and toughness and other mechanical properties of the material. Photo courtesy of Markus J. Buehler and Graham Bratzel (MIT)

A mussel attached to a rock, displaying the amazing strength of mussel threads and their adhesion pads. These materials do not only serve as adhesives under dry conditions, but also work extremely well under water. This is a remarkable feat. | Photo courtesy of Zhao Qin (MIT)

locally, and with simple protein building blocks. I am fascinated by identifying what these mechanisms are that turn simplicity to complexity in a way such that a material generated serves an array of complex functions.

What is your best definition of what we do?

I see the field of biomimicry as a nucleus to a much bigger step in our evolution of science and engineering, where we begin to understand and synthetically create materials and system with a level of complexity, in a controlled way and with the ease that we observe in nature.

By what criteria should we judge the work?

A critical measure is whether we can develop new products that have added value, to provide better function at lower cost with reduced environmental impact. The intrinsic added value of what we provide and innovate is critical.

What are you working on right now?

Much of our specific work deals with turning proteins into materials with diverse functions, and combining natural proteins like spider silk and elastin or collagen into new types of materials with a host of new functions. We rely on the use of big computers, advanced modeling and mathematical tools, and aim to achieve the rational design of materials for tailored functions. The simplicity of building blocks requires us to create complex hierarchical structures at multiple length-scales, which is an exciting frontier in materials science that involves multiple disciplines to work together effectively.

How did you get started in biomimicry/bio-inspired design?

It all started by asking simple questions – such as, addressing the challenge to replicate a simple protein like silk in a synthetic environment to create a thread or fiber that matches the natural ones. We quickly realized that this paradigm opens the door to many other materials that are constructed with similar principles.

Which work/image have you seen recently that really excited you?

Recent efforts to hierarchical structure materials at all scales, from molecules to the 3D printed architecture of a large-scale structure. Several groups have embarked on work at this interface, led by new insights from modeling, which provided substantial evidence for the powerful impact this multiscale approach can have.

What is your favorite biomimetic work of all time?

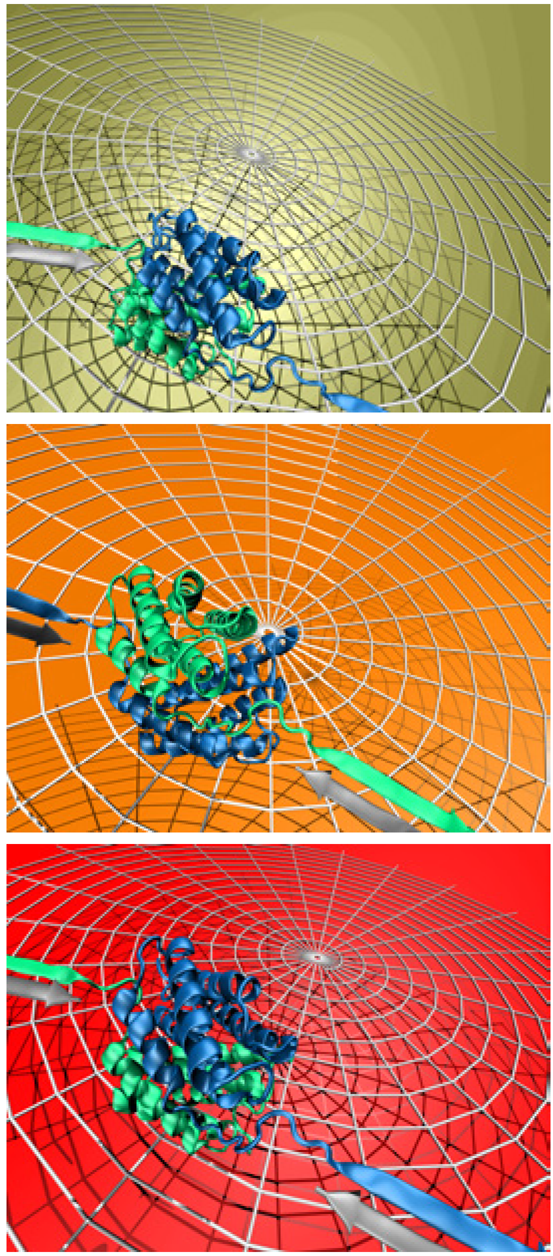
I see this very much as an evolution, which is currently in progress. I always found that adhesion inspired by geckos is an amazing topic with great practical relevance. But, I think the best is yet to be!

Who do you admire? Why...

There are many heroes in the world. I admire people with principles and perseverance, and those who sacrifice for others. Too often, we forgot to be thankful for the opportunities we have, and our own responsibility to contribute.

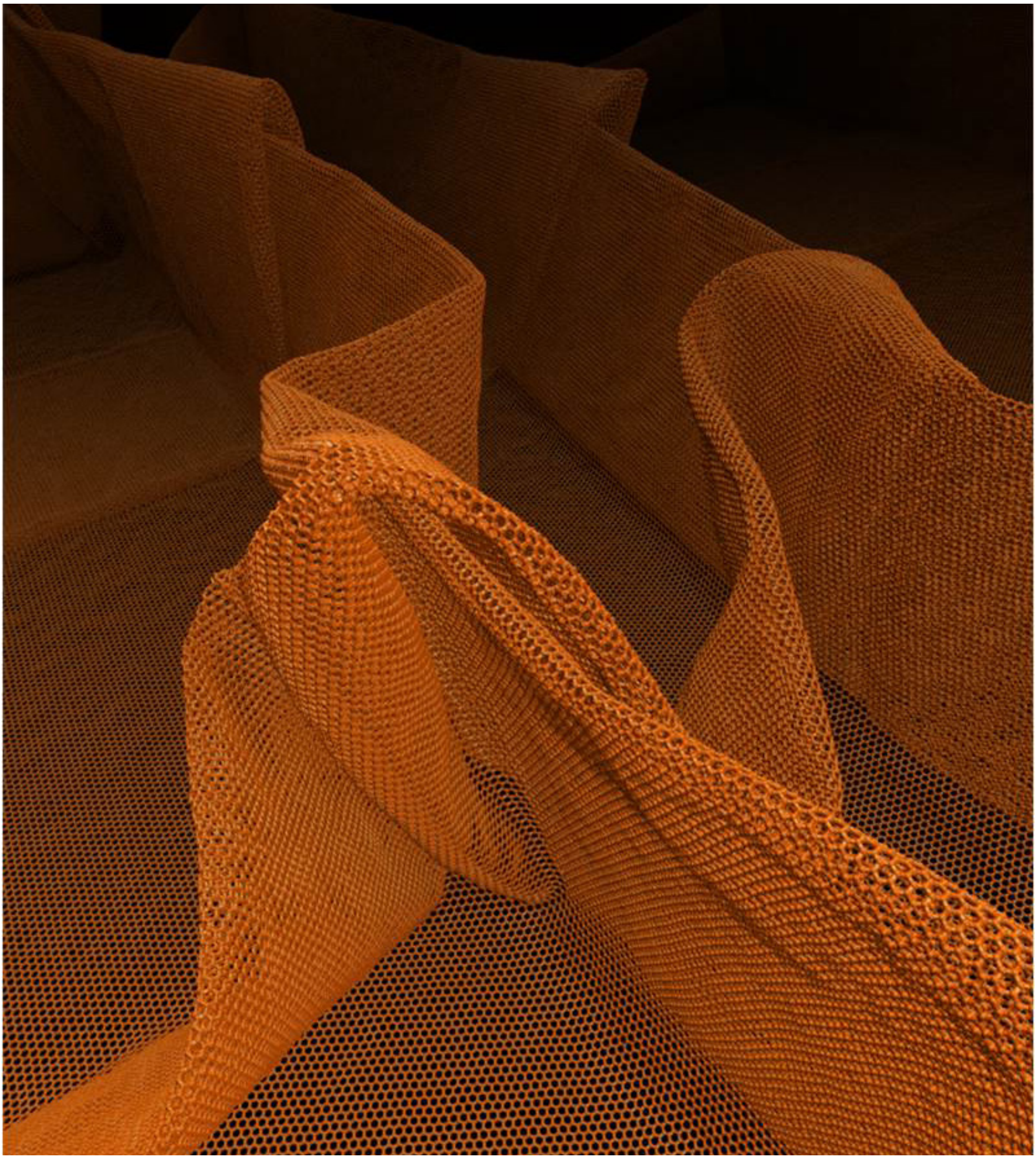
What is your idea of perfect happiness?

Spending time with my wife and kids, hiking in the woods or taking a long walk at the beach, on a sunny fall day in New England. And, watching the wonders of nature and the way materials are produced, used and break down under controlled conditions. I find much inspiration and ideas for new research by watching our environment. ×



Different visualizations of a spider web, showing the molecular structure of a key protein that controls the assembly of silk within the spider's spinning duct. A spider web is an intriguing structure that features designs at all scales - from the atoms to the web, and each of them contributing the enhancing the overall properties.

Images courtesy of Markus J. Buehler



Molecular structure of folded graphene. A synthetic material, graphene can be used effectively to construct complex hierarchical materials. Here, the material is used to mimic the nanostructure at the surface of superhydrophic materials as found in Lotus leaves.

Image courtesy of Markus J. Buehler and Seunghwa Ryu (MIT)


Ilaria Mazzoleni
Architecture Follows Nature
BIOMIMETIC PRINCIPLES FOR INNOVATIVE DESIGN
BIOMIMETICS SERIES
CRC Press

Book

Architecture Follows Nature: Biomimetic Principles for Innovative Design

Reviewed by Colleen Mahoney

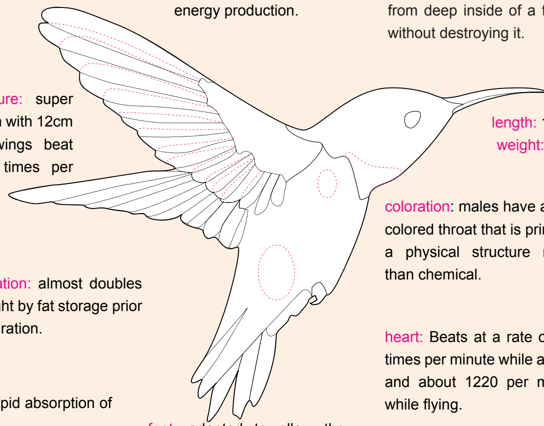
Architecture Follows Nature – Biomimetic Principles for Innovative Design

"If inspiration is taken from biology it is easier to understand nature's importance and to find meaningful design examples", states author Ilaria Mazzoleni in the introduction of her new book, Architecture Follows Nature - Biomimetic Principles for Innovative Design. Mazzoleni takes us on a journey specifically investigating animal skin in both a climatic and ecological context. Looking at animal coverings including fur, feathers, scales, exoskeletons, and shells, she guides the reader from natural inspirations to biomimetic case studies. This book has educational content for designers and architects wishing to look at biological inspiration for flexible and dynamic building envelope design. Mazzoleni asks, "How can architects and designers move beyond the formal imitation of nature to more sophisticated, nature-inspired, performance-based building design?" As a practicing commercial and residential architect, I am intrigued by the idea of dynamic building facades – and specifically using biomimicry in our effort to find solutions. Unfortunately, I did not find the inspiration I had hoped for in this book.

The book is organized into two parts. In Part I, Mazzoleni introduces design principles inspired by nature and biological concepts that inform architecture. I found Part I to be too academic and long for my liking, but I appreciate the effort to spread the meme. I was anxious to delve into the case studies that were to follow. Part II explores four sets of case studies with each investigating a particular function of skin: communication, thermoregulation, water balance, and protection. Each study begins by introducing the reader to a select animal and its skin functions, and then introduces theoretical "proto-architectural" projects. A rich combination of pictures and concept sketches help to communicate details about each animal, its habitat, and a description of its unique skin structure. After looking at the genius of skin we are introduced to conceptual design solutions which Professor Mazzoleni's students have explored. Some of the design solutions in this book have merit and architects may see possibilities for design and patterns for building skins, but some are just too far fetched, in my opinion. An example is the inflatable pods hovering: access to flowers without having to use a perch.

muscles: packed with mitochondria for cellular energy production.

beak: needle shape allows the bird to retrieve nectar from deep inside of a flower without destroying it.



body structure: super light skeleton with 12cm wingspan. wings beat up to 200 times per second.

length: 10 cm
weight: 3.2 g

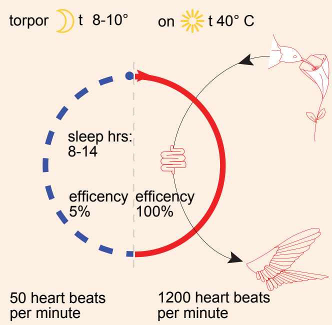
fat accumulation: almost doubles its body weight by fat storage prior to a long migration.

intestines: rapid absorption of glucose.

feet: adapted to allow the bird to secure itself to tree branches and other perches while sleeping.

coloration: males have a ruby colored throat that is primarily a physical structure rather than chemical.

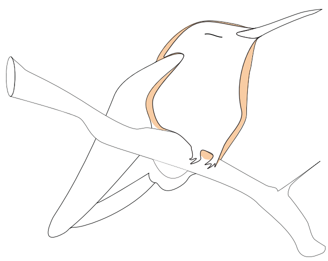
heart: Beats at a rate of 250 times per minute while at rest, and about 1220 per minute while flying.



habitat:

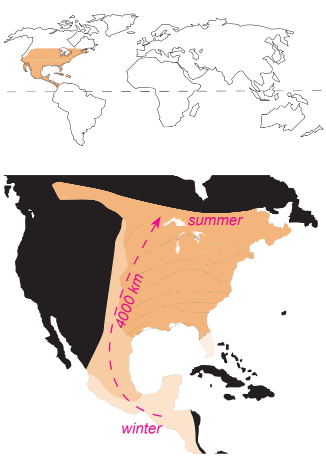
Neotropical migrant bird most commonly found in the Eastern U.S. and Southern Canada during the summer breeding season. Can be found wintering in Central America.

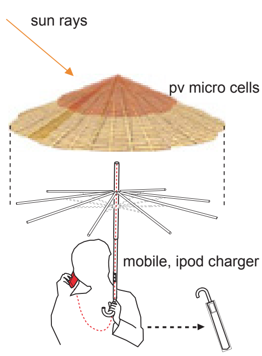
During spring these birds migrate north roughly following the 1.7°C isotherm (avg. nightly temp.). During autum many gather in the Southern U.S. in mid-September before flying across the Gulf.



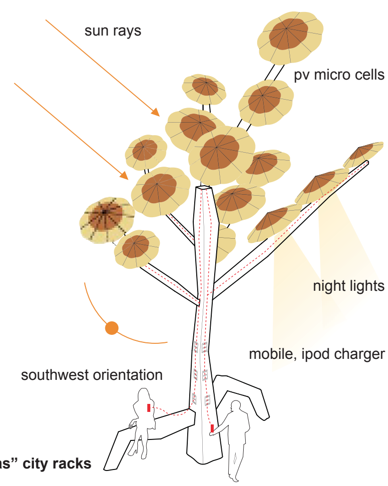
torpor:

The ability to undergo a short-term "hibernation" usually at night. This is characterized by a dramatic decrease in metabolic rate and results in a large drop in body temperature, respiration rate, heart rate, and most other body functions. Thus torpid animals can conserve significant amounts of energy over what they would have normally expended. Torpid animals appear to be in a deep trance and cannot easily be aroused.





"flower sun brellas"



"flower sun brellas" city racks

IM Studio MI/LA | principal: i.mazzoleni w/ j.chavez, biologist; design team: a. colli, s. proudian, r. molina

Image courtesy of im studio mi/la - ilaria mazzoleni

suspended under a Santa Monica pier concept. This is not a biomimetic design solution that I find inspiring or practical.

I am not sure where the voice of Shauna Price, Mazzoleni's biologist/co-author is in the case study solutions. "The architectural rendition of biology is simplified and selective as it draws from biological solutions to environmental challenges in nature and describes them in a language that traditionally pertains to architecture and design" states Mazzoleni. As I looked closely at each case study and its design solution I didn't find the clear integration or optimization of biological strategies. One of the case studies that explored skin as protection proposes the design of an emergency pavilion for post natural disaster or war zones. The proposed shelter would be packed into kits made of photovoltaic panels, flexible and translucent fabric, and a connecting umbrella-like structure. While the supporting structure "will maintain a rigid tactility through principles of tensegrity" the actual skin system is not clearly explained. My recent training has been in biomimicry as taught by the Biomimicry 3.8 organization in which several concepts called "Life's Principles" are outlined. The structure proposed by Mazzoleni does not appear to follow a couple of these principles. It does not propose the use of any materials that would be resourced locally, nor do any of the materials appear to be compostable (use of life-friendly chemistry).

In another case study, Mazzoleni and team chose the dense and insulating fur of the snow leopard to exemplify thermoregulation. The case study solution was designed for a mountainous site and proposed an inner geodesic structure that follows principles established by Buckminster Fuller plus an outer layer that can expand and contract. I found this design to have the beauty and elegance that we should expect in biomimetic solutions. Taking this idea further, the team might show the reader ideas for structural support - perhaps a fiber and matrix composite material?

The book gives a few good examples of design solutions that minimize the use of materials to get the job done. The proposed solutions don't seem to use construction methods that are locally attuned and the proposed materials do not demonstrate the efficient use of resources. I found myself asking with every design solution and its materials - does it use life-friendly chemistry? In the words of Janine Benyus, author of Biomimicry Innovation Inspired by Nature – "Will it fit in? Will it last? Is there a precedent for this in nature?" This book will challenge any architect or engineer to answer these questions. As we look to nature for solutions to design challenges, I think it is critical that the biological background is integrated into the proposed design. Structures should be faithfully coupled with function. As an architect, I would like to see more case studies that demonstrate the fit of form to function and set a high biomimetic benchmark.

How we revolutionize biomimetic design ideas that can be applied in the real world is the most vital challenge for the design profession today. This book is a good start for that conversation, and a good resource for the collaborators in biology and design.

Colleen Mahoney has been a practicing architect in the San Francisco Bay Area for over 25 years. She is enrolled in the current Biomimicry 3.8 Institute Specialist Certification program and has just returned from the cohort's second retreat in Marin County where she lives.

Architecture Follows Nature – Biomimetic Principles for Innovative Design

Author: Ilania Mazzoleni in collaboration with Shauna Price

2013 CRC Press

Hardback

Color and black and white plates

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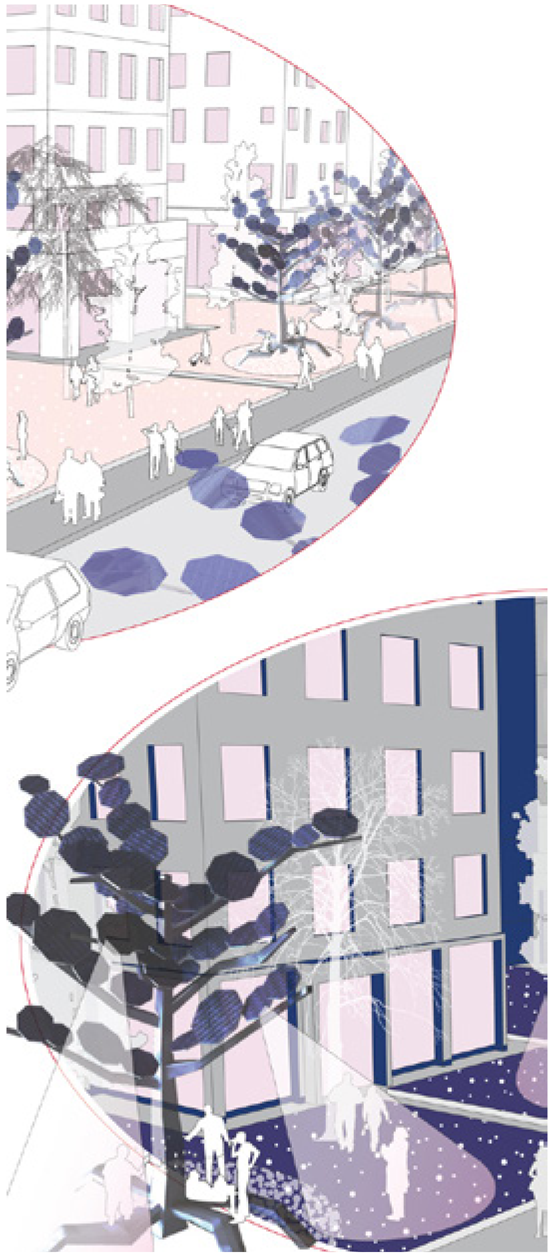

IM Studio MI/LA | principal: i.mazzoleni w/ j.chavez, biologist; design team: a. colli, s. proudian, r. molina

Image courtesy of im studio mi/la - ilaria mazzoleni

The Hague Beach

Photo: Kent Wang, 2005 | Flickr cc

World *Interview*
Biomimicry Netherlands

Saskia van den Muijsenberg is the co-founder of biomimicryNL, owner of nododo, and a Certified Biomimicry Professional with over 15 years of experience in marketing, change management and strategic innovation. With a variety of Fortune 500 companies (e.g. Lead GameChanger Innovation Workshop Program with Shell), Saskia catalyzes innovation by enabling others to explore life's design strategies to develop new ideas into real business opportunities.

Currenly, she is involved in a number of innovation projects. Saskia is also an instructor for Biomimicry 3.8's (8 month) European Biomimicry Specialist Program.

Born and raised on the coastal city of The Hague, the Netherlands, Saskia's love of nature was born on the beach, where you can find her especially on windy days.

How did you get started?

We, the three founders of biomimicryNL (Bas Sanders, Annette Schumer and Saskia van den Muijsenberg) didn't know each other before we started our not-for-profit organization. The linking pin between the three of us was Biomimicry 3.8. Each one of us learned about biomimicry through either Janine Benyus or Dayna Baumeister and expressed the wish to start something similar in the Netherlands and it was Dayna who introduced us to each other.

What is your mission statement?

Our mission is very similar to that of Biomimicry 3.8 (but with a regional focus): to train, equip, and connect biologists, engineers, educators, architects, designers, business leaders, and other innovators to sustainably emulate nature's 3.8 billion years of brilliant designs and strategies throughout the Netherlands.

Who is part of the group? How many members do you have? Are there different types of membership? Are you structured via a specific organizational model?

We are set up as a not-for-profit organization (social entrepreneur would describe our activities better but there's no such legal entity in NL yet). We have no people on the pay roll, but hire experts when and where needed, including ourselves. We essentially are a network organization, forming cooperative relationships as needed. We evaluate ourselves against the "Life's Principles" on a regular basis.

What other organizations are you linked to?

Biomimicry 3.8 and its regional biomimicry network alliance. We have strong relationships with Technical University Delft, Ministry of Economics, draaijer+partners (built environment), BELW Advies (ecological consultancy), Bionicacentrum Groningen, Biokon (Germany) and are currently building relations with MVO Nederland (CSR NL) and 'Het Groene Brein' (= 'The Green Brain', network of scientists for a sustainable and regenerative economy).

Untitled

Photo: Tim Zelle, 2008 | Flickr cc

Terschelling | Photo: marcoderksen2013 | Flickr cc

What initiatives are you working on? Can you highlight exciting Dutch research groups working in the area of bio-inspired design?

We signed a 'Green Deal' with some parties (private and public) along with our Ministry of Economics to develop a biomimicry knowledge infrastructure for the Netherlands, with the objective of initiating 50 biomimicry projects by 2020. We created a roadmap with a network of 100 people interested in biomimicry from government, industry, science, and education, focusing on 3 main areas:

1) promote nature-inspired innovation and R&D through projects such as bio-climatic buildings based on ecological performance standards; a life-friendly chemistry lab connecting scientists and business; a nutrients (phosphate) recycling project

2) embed biomimicry in education from K-12 to post university by influencing the Human Capital Agenda of various top industry sectors, training educators, etc.

3) connect relevant parties to each other and initiate new projects

What are your plans for the future?

The implementation of our biomimicry roadmap (until 2020) will keep us busy. Right now our network consists of mainly individuals interested in the topic of biomimicry. We want to further connect them and facilitate biomimicry projects. We try to link our work with other networks and get more people to 'plug in' biomimicry in their daily work. Bringing biomimicry into education is another big focus. Also, we're thinking how to best organize our 'consultancy' work (should it be a separate company etc.).

What inhibitors to success have you experienced?

Although everybody is interested in the field, it's hard to get businesses to really commit to biomimicry and start experimenting with it. I think for most businesses the vision is exciting but they are not sure how to start. Finding ways that bring them value right now while taking small steps to a more desirable future state is the key.

Another issue, especially for education, is that biomimicry is interdisciplinary and most institutions are not organized in that way. Breaking silos takes time. We also found that people think they should be able to practice biomimicry after a 3-day workshop. The truth is that doing 'deep' biomimicry is pretty hard and requires practice. Finally it is very hard to find financial support for 'awareness' activities, with which it all starts. It's also difficult to find funding for the first research phase, as there are no guarantees you will actually find something useful. Once you have proof of evidence and are ready to build prototypes it's much easier to raise funding.

How are you sustained financially?

We currently have an assignment from our Ministry of Economics and some funding to put towards additional fundraising, but we put a lot of free time and energy into it.

Untitled | Veluwe

Photo: BAMCorp, 2011 | Flickr cc

What is you geographical "reach" within The Netherlands, and where are your members, meeting places, project locations?

The Netherlands is small and we cover the whole country. Members are in every thinkable industry and all over the country.

What is the best thing that you've done within the last year? Ever?

Pffft, too difficult a question. I'm proud of how much we've achieved in a relatively short time. We got a lot of traction and found lots of people that want to bring it further. I'm also proud of how we work together. We started an organization without knowing each other at all, yet it worked really well because of shared vision, transparency of intentions and communication. We are also proud of the fact that biomimicry is now mentioned in our national nature conservation policy and is getting some traction within various innovation agendas. ×

Dutch Research:

TU Delft:

Biomechanical engineering / bio-inspired medical instruments (Minimally Invasive Surgery and Interventional Techniques, http://www.misit.nl) – Paul Breedveld, endoscope based on squid tentacles http://www.tudelft.nl/en/current/latest-news/article/detail/vici-voor-verdere-ontwikkeling-mechanische-inktvis-in-de-chirurgie/

University Utrecht:

Available Phd positions. There are many bio-inspired polymer and nanoscale energy conversion positions: http://www.nature.com/naturejobs/science/employer-directory/29533

Climate Design & Sustainability Onderzoeksgroep Green Building Innovation – Andy van der Dobbelsteen based on http://hetgroenebrein.nl/wetenschappers/andy-van-den-dobbelsteen/, van den Dobbelsteen is the "Chair Climate Design & Sustainability Research Green Building Innovation" at TU Delft

Biomimicry and Philosophy: Vincent Blok – exploring the ethics of biomimetic innovation through the analysis of the concept of one-to-one transferability

"The Ethics of Ecological Innovation. Biomimicry and Biomimesis as a new way of Thinking and Acting Ecologically" (V. Blok, B. Gremmen, S. van der Hout), paper presentation at the annual meeting of the Onderzoeksschool Wijsbegeerte (OZSW), November 15-16 2013, Rotterdam (The Netherlands)

Technical university Enschede:

MESA+ Institute for Nanotechnology

Development of cricket-inspired sensor (Crickethair) for imaging entire flow patterns. 'Non-resonant parametric amplification in biomimetic hair flow sensors: selective gain and tunable filtering' written by H. Droogendijk, C.M. Bruinink, R.G.P. Sanders and G.J.M. Krijnen will appear in *Applied Physics Letters* and has already been published online by the journal.

http://www.nanotech-now.com/news.cgi?story_id=47088

Technical University Eindhoven:

Adaptive building systems - Patrick Teuffel http://www.tue.nl/en/employee/ep/e/d/ep-uid/20127209/

Industrial Design Department: http://www.nextnature.net/ Koert van Mensvoort

University of Groningen:

Fluid mechanics and locomotion - Eize Stamhuis

http://bionik.fbsm.hs-bremen.de/pages_english/gi_staffmembers.html

Businesses:

O-foil, http://www.ofoil.nl/en/ (Bio-inspired wing propulsion for ships)

Groasis, http://www.groasis.com/en (Beat hunger and desertification inspired by nature)

Untitled

Photo: wester, 2011 | Flickr cc

Berlin

Photo: francescocarcano, 2012 | Flickr cc

World *Interview* Biomimicry Germany

How did you get started?

There were three parallel plots co-evolving the past years and it was not before 2012 that they converged:

As a biochemist and neuroscientist, Arndt Pechstein has been working in basic research since 2004. While he enjoyed working in this intellectually-stimulating, hypothesis-driven environment he also wanted to apply his fascination for technology, science, and biology as well as his knowledge and skills towards more tangible projects. In 2010 he eventually started to dive into novel creativity concepts, innovation methods, and biomimicry and eventually graduated as a Biomimicry Specialist in 2012.

In 2011 already, at a house party of a friend, Arndt met Gerard Webb, an architect and leading IT developer. When they started discussing about a resilient urban concept Gerard was working on, they immediately knew this will be a start of something lasting. As soon as Arndt introduced the concept of biomimicry, Gerard suddenly realized that this might solve some of the challenges he had been struggling with continuously. Arndt and Gerard met in regular terms from then on.

Eventually, in 2012, Prateep Beed became the third pioneer of Biomimicry Germany. Actually, Prateep and Arndt had known each other for quite some time given that they were both doing their PhDs within the same graduate school. Having started as an industrial engineer which sparked his interest in networks and the parallels in nature and technology, Prateep did his master in cognitive psychology before he specialized in neuroscience. His inter-disciplinary background and his desire to create innovative solutions that are sustainable he started studying biomimetic approaches. In 2012, Prateep and Arndt got in touch again via a discussion about biomimetic design.

In January 2013, Arndt, Prateep, and Gerard eventually organized the foundation of Biomimicry Germany e.V., a not-for-profit organization aiming at introducing biomimicry as an innovative, pro-active mind-set for a future society. Other members joined shortly after.

What is your mission statement?

Our mission is to successfully innovate and transform our society sustainably through a lateral problem-solving method that values and emulates biodiversity. Through strategic partnerships, educational programs, and research, we inspire and create well-adjusted solutions with zero-negative impact on the environment.

Who is part of the group? How many members do you have? Are there different types of membership? Are you structured via a specific organizational model?

We are a team of multi-disciplinary experts using biomimicry as a creativity and innovation tool to create sustainable, tangible designs, products, projects, and organization structures which are aligned with life's principles. The founders' team consists of:

> **Dr. Arndt Pechstein**: In 2012, having spent more than a decade in academic research, Arndt Pechstein decided to co-found Biomimicry Germany. Arndt received a PhD degree with honors in Biochemical Neuroscience from the Free University Berlin, specializing

Vertical Autumn

Photo: Passetti, 2011 | Flickr cc

Berlin, Botanischer Garten, 1.Mai 2005 | Photo: pansy burke, 2005 | Flickr cc


1.50
Gemessen am: 4.9.2004
1.00m
Gemessen am: 30.8.2004

in neuronal communication and holds a Diploma in Biochemistry & Biotechnology from the Martin-Luther University Halle. In 2010, he was awarded the Ernst-Reuter Award for outstanding research. At the Karolinska Institute in Stockholm, Sweden, he received the Wenner-Gren Post-Doctoral Fellowship Award and a Swedish Research Council Grant. In 2012, Arndt moved back to Berlin where he accepted a position at the Leibniz Institute for Molecular Pharmacology (FMP). In the same year, he graduated as Biomimicry Specialist at Biomimicry 3.8.

Arndt's strengths are an infectious enthusiasm and positivity combined with efficiency, discipline, perseverance and the desire to improve and innovate. He likes to challenge views and enjoys seeing the world through a critical lens. With many years in academic teaching and having worked as a personal coach for many years, Arndt is an experienced teacher and educator. He currently lives in Berlin and is a passionate traveler, outdoor enthusiast, climber, traceur, and cyclist.

Dr. Prateep Beed: His bachelor's degree in Industrial Engineering helped Prateep Beed to learn the basics of innovation & design. Soon he realized that machine design is far from humanized design since prototypes often lack the individualism required to cater to the needs of everyone yet at an individual level. He then pursued a master's degree in Cognitive Psychology & Neurosciences to better understand and relate to the human mind. Prateep went on to complete his PhD in 2010 in Neuroscience thematically focusing on spatial navigation & decision-making. In 2011, he was awarded the Tiburtius-Award for young investigators doing exceptional research.

Given the interdisciplinary academic background, Prateep started seeing the strength in combining his seemingly independent disciplines of study thereby shaping a new kind of thought process – design thinking. In 2012, this gave way to the co-founding of Biomimicry Germany. With his bivalent background in design and technology and his affinity to nature, Prateep is a very talented photographer. Prateep's strengths are positive, critical thinking combined with an extreme curiosity and the desire to actively shape a better world. He currently lives in Berlin and is a passionate musician.

Gerard Webb: In 2012, as an attempt to unite his expertise in architecture and genetic logic, Gerard Webb, decided to co-found Biomimicry Germany. As a Building Architect, Gerard started working on generative design systems and was amongst the first to create 3D visualization software decades ago. After having worked as an architect for 5 years, he spent 12 years as a software developer & architect writing genetic logic at banks and energy companies. During the past 4 years Gerard focused on architecture again. His particular interest lies in smart materials and organic structures being controlled using genetic logic that itself evolves.

Gerard has written a generative webgl based modeling software, and is now working on a novel 3D scanner and CNC systems. Currently, he is developing the next generation of web protocols together with the world's largest

IT corporations. Gerard's strengths are an almost infinite creativity combined with in-depth technological and analytical thinking. He lives in Berlin and Stockholm and loves being outside, especially going rock climbing.

Types of membership:

There are various types of members in our organization. We have regular active members that contribute on a regular basis and actively shape and plan the activities of the organization. Then there are interns and student affiliates that are peripherally associated and can become active members if desired; they may as well only be temporarily associated and become alumni afterwards. Third, there are institutional members (other NGOs, organizations, institutions). They too, as legal entities, can be members of the organization if there is an overlap in intention or joint projects. Fourth, we have corporate members comprising profitable bodies and companies with a fixed membership fee. Eventually, there are supporters and sponsors (both private and corporate) that financially contribute and support the organization's vision and actions. At some point there will be honorary members, too, individuals whose commitment were an exceptional example.

We are currently 10 active members from different fields and sectors. Our expertise encompasses biology, biochemistry/biotechnology, psychology, electrical engineering, IT, design, architecture, 3D printing, and bio-resource engineering. Besides, we have associated organizations and partners with whom we plan and execute joint projects.

Organization (Model):

Biomimicry Germany e.V. is a not-for-profit organization registered in Berlin, Germany. Our vision is to stimulate and create a resilient, adaptive, and thriving future inspired by nature´s best strategies. Pioneering this approach in Germany, we catalyze a paradigm shift towards sustainable living by solving the core human needs: food, shelter, energy, water, health, and education.

What other organizations are you linked to?

With Arndt being a fellow of the Biomimicry 3.8 institute, we are happy and proud to follow, extend, and further develop the footprints of B3.8, an organization that should be a role model for societal development.

We are establishing vital links with educational institutions, other not-for-profit organizations working towards similar objectives, centers of biodiversity and collaborating with companies offering manufacturing automation, architecture and product design.

Amongst our first partners is the Hasso Plattner Institute: School of Design Thinking (D.School), Potsdam, Germany. The D.School aims at bringing together students from diverse academic backgrounds to solve design challenges. Biomimicry Germany is happy to collaborate with the HPI School of Design Thinking adding an extra element to design thinking by introducing concepts of nature-inspired innovations. This is a step towards a strong symbiosis that can promote fruitful undertaking of projects by different organizations resolute at solving core needs


PITCHING
e.V.
MIMICRY
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and problems in our societies in a sustainable and resilient way.

Another important partner is Europe's leading 3D printing company with which we are currently planning joint projects, presentations and workshops. With 3D printing being extrapolated to become the third industrial revolution, a symbiosis between additive manufacturing and biomimicry seems vital to us, as many hardly foreseeable consequences may surface. To play an active role in shaping the development of that technology including the use of benign materials, putting it to the right use by drawing on the wide potential biomimicry offers while at the same time teaching and advertising the right mindset is amongst our top priorities.

What initiatives are you working on? Can you highlight exciting German research groups working in the area of bio-inspired design?

Resilient Berlin City

> This project is aimed at creating a regenerative city based on natural ecosystems. Integrating transport, energy and product streams with production, end-users and service providers Berlin may transform into a resilient city that is part of and not separate from its environment.

Berlin Open Office

> This crowd funding project is aimed at directly involving the residents of Berlin in shaping their immediate environment. We believe that people cherish and protect what they like and they are more apt to like and appreciate something if they (co)created it. If they understand that they are part of the same system. they will conserve it.

What are your plans for the future?

We have set ourselves some immediate and long-term goals to implement biomimicry in different sectors. One major focus is to introduce the concept and scope of Biomimicry to inspire people and businesses alike to tap upon this priceless source of sustainable innovation nature provides. Our intention is to link and integrate education, research, and implementation and to become a primary generator of thought leadership in nature-inspired innovation in Germany. In parallel we are involved in a children program teaching them role models, a first step into our intended direction of K-12 biomimicry education. Furthermore, we are working on a regenerative city model here in Berlin that would serve as a catalyst for a paradigm shift towards sustainable living. Meanwhile, we are forming a network with other European Biomimicry regional partners aiming at transnational projects and policy reforms. Following the example of B3.8, we plan to establish an innovation-for-conservation program to conserve the organism-habitat-ecosystem upon which innovations are based: replicable and adaptable for non-profits, cities, and companies.

What inhibitors to success have you experienced?

The main inhibitors to success are the mindset of people and a conservative attitude towards change. Successful designs have an open interpretation as to what success implies. The indus-

Sunset in Berlin

Photo: robokow, 2007 | Flickr cc

trial revolution has definitely helped mankind to come up with technical solutions to many societal problems. However, if we look an inch deeper, many of these solutions are not regenerative and at the least, sustainable. Plus there is a lot of waste generated as we have failed to attain closed-loop systems. The way nature evolves is a fantastic way to observe cooperative systems at work incorporating resilient and adaptable designs. We need to learn from nature's clever design strategies. We need to change our mindsets from selfish to symbiotic in order to interfere with our immediate environment, with nature, and therefore with us in the most positive ways.

How are you sustained financially?

A plethora of funding opportunities exist and we are approaching various organizations in the European Union and independent institutions interested in promoting and supporting sustainable innovation and education. So far, though, this is in the initiation/application phase and we are glad to have amazing people full of energy, commitment and passion contributing to the development of our organization and helping the movement gain momentum.

What is you geographical "reach" within Germany, and where are your members, meeting places, project locations?

While we are based in Berlin and so are some of our partners, we do act Germany-wide and have partners in various places elsewhere. Currently, most of our active members indeed live in Berlin but the number of members joining the organization from outside the capital is increasing. Meeting places at this stage are based in Berlin. However, our projects already now transcend the city boundaries and we are travelling the country to present on conferences, in media and on stage.

What is the best thing that you've done within the last year? Ever?

Amongst the great things we have done this and last year was certainly having sit down, planed and formulated the launch of Biomimicry Germany. Germany has been at the forefront of technological innovations over the last decades and time is apt for launching this innovative win-win methodology to inspire various fields including science and technology, architecture, and the energy sector. Equally proud we are also of having partnered with the D.School, Potsdam which certainly is a great place to bring brilliant, multidisciplinarily-trained minds together to solve design challenges. Our biggest achievement in the industrial realm is our close ties to the 3D printing sector. ×

Contributed by Dr. Prateep Beed and Dr. Arndt Pechstein (founders at Biomimicry Germany e.V.)

German Research:

• Bionics | Technical University Berlin | Prof. Ingo Rechenberg

• Medical Engineering | Fraunhofer Institute for Biomedical Engineering (IBMT) http://www.ibmt.fraunhofer.de/en/Fields-of-work/ibmt-medical-engineering-neuroprostetics/ibmt-medical-engineering-neuroprosthetics-biomimetics.html

http://www.invitrojobs.com/index.php/en/aktuelles-archiv/182-fraunhofer-ilt-erzeugt-biomimetische-hybridstrukturen-fuer-die-regenerative-medizin.html

• Fraunhofer Institute for Laser Technology (ILT) http://www.kurzweilai.net/lasers-create-biomimetic-scaffolds-for-growing-cells

• Biomimetics-Innovation-Center (B-I-C)

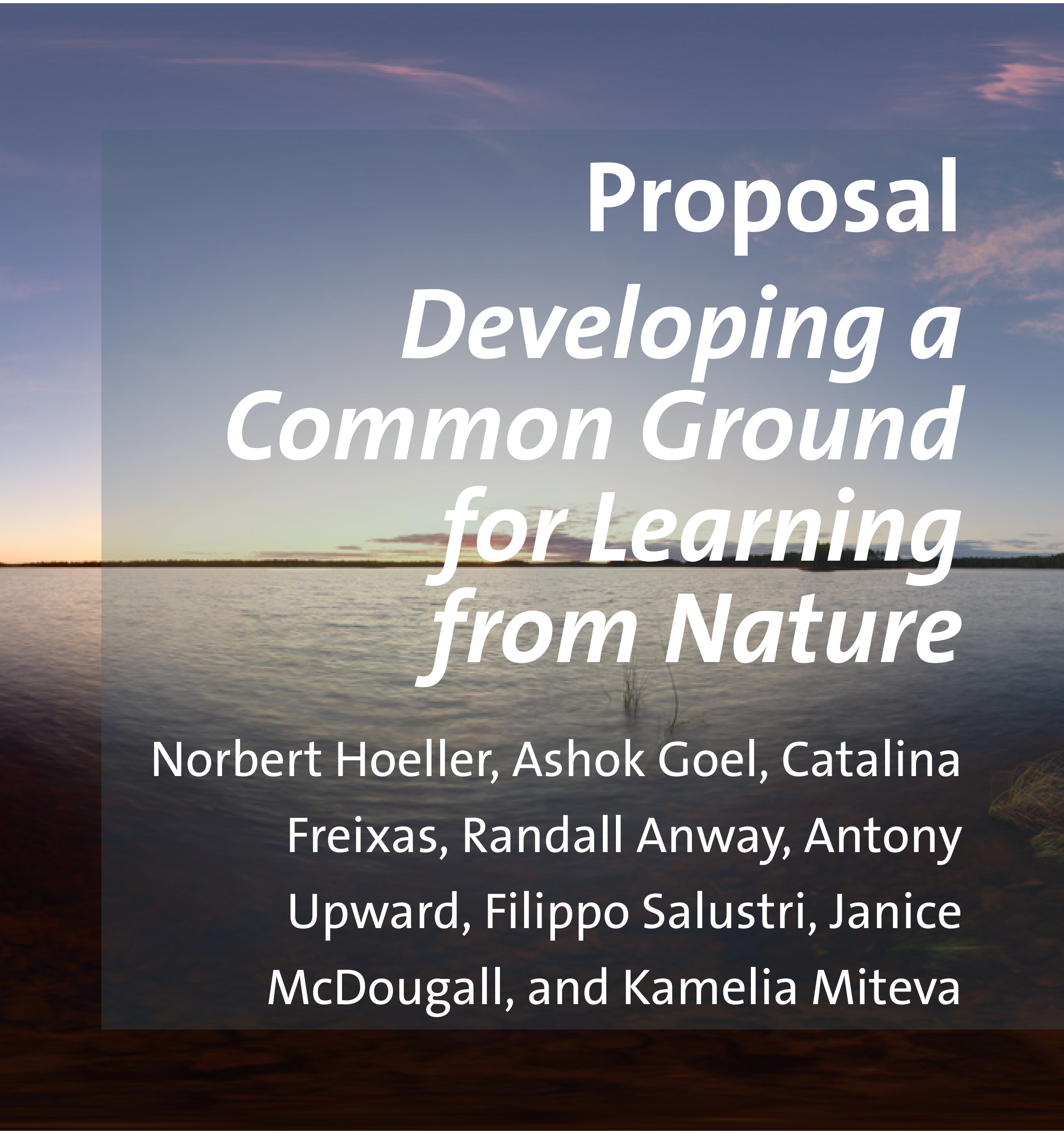
http://bionik.fbsm.hs-bremen.de/pages_english/bic_startpage.html

October in Berlin

Photo: ilya ginzburg, 2008 | Flickr cc

Tiilikkajärvi National Park, Finland | Southern and northern natural features mix in this park forming an ecotone of forest and swamp types.

Photo: Janne, 2012 | Fotopedia Commons



Proposal

Developing a Common Ground for Learning from Nature

Norbert Hoeller, Ashok Goel, Catalina Freixas, Randall Anway, Antony Upward, Filippo Salustri, Janice McDougall, and Kamelia Miteva

Background, Motivation and Goals

The potential for tapping nature's storehouse of solutions, solution pathways and systems' principles has captured the world's imagination, especially after the publication of Benyus' *Biomimicry, Innovation Inspired by Nature* (1997). A growing number of proponents have been using biomimicry, biomimetics and biologically inspired design (B3D for short, pronounced "B-cubed-D") in diverse contexts and employing a wide range of approaches. The language and cultural issues that challenge effective communication in the practice of B3D among experts in the biological and technological domains are well known. There are also communication issues within the B3D community itself, exemplified by the proliferation of terms used to describe what we do: biomimicry, biomimetics, bioinspiration, biologically inspired design, biologically inspired engineering, bionics, biognosis, bioreplication, biomorphosis, and so on. B3D is intended to represent the common elements underlying these diverse terms.

Proponents of B3D often adopt very different stances. Some are motivated by biophilia, a term coined by E. O. Wilson (1984) that refers to humankind's "innate tendency to focus on life and lifelike processes". Some are keenly interested in sustainability, repairing society's fractious relationship with nature and enabling "the possibility that human and other life will flourish on the planet forever" (Ehrenfeld, 2008). Others are seeking creative solutions for complex problems, with sustainability being one among multiple goals. While nature as the source of inspiration is common to all, B3D would benefit from a consensus on what B3D encompasses and what constitutes its 'best practices' in terms of methods and outcomes.

Perhaps the diversity of the B3D community is a consequence of its ambitious goals and rapid growth. Nevertheless, it is clear that this diversity has a cost. Gleich et al. (2010) identified four recognized biomimetic networks with academic roots in Europe (two in Germany and two in the UK) but found evidence for only low levels of collaboration within and amongst these networks. A search on keywords associated with the broader concept of "learning from nature" identified extensive B3D activities in Britain, China, France, Germany, Japan and the USA. These activities were often not associated with the official biomimetic networks but instead were aligned with traditional disciplines such as biology, chemistry, engineering, and material sciences. Again, these groups were largely working independently. B3D initiatives were often tied to specific institutions or even to specific individuals within those institutions. Furthermore, limited collaboration was found between B3D practitioners in industry or business and researchers in academia.

Building a consensus on the essence of what B3D means could encourage a productive dialogue across disciplinary boundaries, increase collaboration and lay the foundation of a B3D commun-

Mycena interrupta

Photo: JJ Harrison, 2010 | Wikimedia Commons ity. It could also help integrate the perceptual, analytical, cognitive and affective aspects of B3D. Fragmentation impedes the effectiveness of B3D practice by inhibiting the free exchange and discussion of approaches, methods and tools. Sharing and evaluating a broad range of approaches to practicing B3D would help improve scalability, repeatability and predictability, essential for defining the best models, methods and tools necessary to establish B3D as a credible community of practice and a recognized discipline.

The lack of a generally accepted standard for research and evaluation can lead to claims of uncertain authenticity that challenge the credibility of B3D. A web search of "biomimicry", "biomimetics", "biologically inspired design" or similar terms yields a large number of articles and images including the Mercedes-Benz concept car mimicking the aerodynamics of the boxfish and the Eastgate building in Harare (Zimbabwe) imitating ventilation in termite mounds. Questions have been repeatedly raised as to the depth of the biological research involved in these cases (Gebeshuber, Gruber & Drack, 2009), the completeness of the biological model and accuracy of its transfer to design (Turner & Soar, 2008) and whether nature was used to primarily explain, justify and communicate the designs after the fact.

In spite of the many genuine examples of B3D and the rapidly growing number of B3D papers, patents and products (Bonser & Vincent, 2007), dubious claims often found in parts of the popular media can damage the reputation of B3D in the eyes of pragmatic members of industry and business or researchers in academia. Working towards a common ground based on shared goals, values and practices would help increase the credibility of B3D by framing the development of a research-based body of B3D trans-disciplinary work that continues to promote innovation supporting social, economic, and environmental values.

Characteristics of a Common Ground for B3D

It is important to recognize the diversity of views in B3D. However, it is equally important to identify and build on the underlying unity of methods and outcomes of learning from nature. We propose the following main characteristics of a common ground for B3D.

Inclusive: At this early stage of development of B3D when there are many possible paths forward, a wide diversity of B3D perspectives and approaches need to be embraced.

Nurturing collaboration among scientists (such as biologists, physicists and chemists), designers (such as architects, engineers, industrial and organizational designers), entrepreneurs and innovators (business and social) is fundamental to B3D. Creating conditions that encourage boundary or edge effects similar to an ecotone (http://www.britannica.com/EBchecked/topic/178617/ecotone) can generate unexpected encounters leading to novel ideas and new perspectives on existing concepts. Julian Vincent et al. (2006), among others, emphasized the importance of convergence, not only in generating new concepts but also in identifying opportunities where B3D can demonstrate its unique value.

Embedded: For B3D to be effective, proponents must actively engage supporters and critics in institutional, industrial, regulatory, legislative and commercial settings. Effective internal and external feedback loops enmeshed within the complex networks of research, education and practice should be established. B3D needs to actively explore and strengthen its relationships to the other systems on which its success depends.

Flexible: In its current stage of development, rapid advances in different aspects of B3D can be expected. Instead of following a pre-determined path forward, B3D should adapt and take advantage of advances within its own and related fields.

One example is the recent interest in additive manufacturing and 3D printing to imitate some of the assembly operations in nature. Another involves fast-paced advances in nanotechnology that may solve current limitations in developing hierarchically structured and adaptive materials. Green chemistry is yet another promising area for rapid growth.

Trans-disciplinary: B3D practitioners have traditionally focused on transferring or translating knowledge between the natural and technological domains. For example, B3D is sometimes understood in terms of "challenge-to-biology" or "biology-to-design" pathways (http://biomimicry.net/about/biomimicry/biomimicry-designlens/biomimicry-thinking/). While these pathways are useful, a complementary approach involves identifying or creating shared spaces between domains that integrate knowledge across disciplines and inform both domains. In general, B3D enables innovation by engaging practices that span both biology and design, are distinct from methods used in either domain and encourage a deeper form of collaboration.

Annick Bay et al. (2012) explored the optical properties of the Photuris firefly's abdomen which led to ways of improving the efficiency of LEDs. Although Bay et al. collaborated with domain experts in biology and LED manufacturing, her team's unique knowledge of optics contributed new insights to both domains by applying practices that are distinct from those used in either domain.

Linked to Related Research: The development of B3D could be accelerated by building two-way linkages between B3D and other fields of research. This includes not only research in the natural sciences (such as physics, chemistry, biology and ecology) but also research in social, cognitive, design, systems, organizational and management sciences (including systems thinking, analogical reasoning, self-organization of complex systems, as well as cultural diffusion and economic impact of innovations). In addition to bringing an established and recognized body of knowledge to B3D, this collaboration could create opportunities for both pure and applied/action research in these related fields.

Situated: The practice of B3D should be deeply situated in nature and grounded in the study of dynamic, living systems. Nature is living: life in nature is not only situated in a context, but also evolves alongside the context. The products of B3D should connect with and live in their natural and technological contexts. B3D encourages looking beyond the artifact being designed to explore its dynamic "relationship to place" (http://www.regenesisgroup.com/Services/UnderstandingRelationshiptoPlace), not just in the present but over its entire lifecycle.

It is important to recognize that humans are an integral part of nature. Urbanization and industrialization have separated significant populations from nature; B3D can reconnect us with nature in ways that can help address the far-reaching social, economic and environmental challenges we face individually and collectively.

Results-oriented: Emphasizing results encourages the mobilization of knowledge to solve real problems. B3D programs should reflect the needs of B3D practitioners by organizing resources around design practices. This in turn requires a deeper understanding of B3D practice that is not only descriptive but also explanatory. Practitioners must be empowered to act, recognizing that the promise of success never comes without the risk of failure and that results have value, whatever the outcome.

Evidence-based: A commitment to building a body of verifiable evidence relating to the process (the 'how') and the outcomes or functions (the 'why') of B3D will enhance its credibility. As described previously, some case studies often cited as examples of B3D do not bear close scrutiny. In others, nature is used to explain or justify a design solution, rather than generate one. A deliberate effort at documenting, reviewing and re-evaluating the processes and results in the practice of B3D is critical. Developing metrics relevant to the practice discipline would appropriately recognize prevailing practice and encourage practitioners to exceed current levels of achievement.

For example, it is often claimed that nature is sustainable, in the sense that natural systems appear to be more sustainable than technological systems. Aside from issues of scale, this first claim is sometimes extrapolated to assert that therefore all B3D products, processes and systems are more sustainable than traditional designs. While the latter claim is intuitively appealing, supporting evidence is at present unclear. While it is important to embrace sustainability as an aspirational goal, it is also important to quantitatively demonstrate the sustainability of B3D systems in practice.

Transformative: B3D has the potential to drive significant, multi-faceted innovation, encouraging new ways of thinking about humankind's relationship with the natural world (which includes humans) and new approaches to driving change in society. Gleich et al. (2010) suggest that B3D is particularly well suited for dealing with complex challenges where existing approaches are no longer adequate. The practice of B3D will benefit from research into how complex natural systems develop and adapt while remaining resilient. B3D can deliver not just a novel building inspired by nature but also shape the building's relationships to the community and habitat such that the building plays a positive, multi-faceted role over its lifespan.

Interface, a carpet manufacturing company, is an example of how B3D can deliver both environmental and economic benefits (Anderson & White, 2009). The PAX Streamlining Principle (http://paxscientific.com/flow/) demonstrates that it is possible to leap-frog the small improvements in efficiency often associated with mature technologies. William McDonough and Michael Braungart's (2002) idea of creating a technical metabolic stream has transformed the way products are designed in those countries that have adopted 'manufacturer take-back' legislation. John Todd's (1984) Living Machines have helped break down the 'just move the waste elsewhere' mentality. Odum (1969) advocated the use of ecological succession in natural eco-

Beetle Lifecycle: Mealworm (Larva)
Photo: GeraldYuvallos, 2006 | Flickr cc

Characteristic	Benefits
Inclusive	Provides a common ground for discussion, research and action to create opportunities for rapid learning and growth
Embedded	Identifies and engages partners, builds strong feedback loops and seeks constructive discourse in diverse settings to firmly ground B^3D within its broader context
Flexible	Adapts to and leverages rapid advances in B^3D and related fields, encouraging a spirit of discovery and exploration
Trans-disciplinary	Transcends the exchange of knowledge between disciplines towards a true integration of methods and knowledge across disciplines that spurs advances in both disciplines
Linked to related research	Accelerates progress through engagement in ongoing work of related research disciplines, creating mutually beneficial opportunities for advancement
Situated	Grounds B^3D through observing, understanding and responding to the natural world, encourages recognizing and strengthening the relationship of design solutions to the natural ecosystems and human communities in which they are embedded
Results-oriented	Encourages addressing real problems, focuses on practitioner needs and reinforces the relevance of B^3D in a broad range of contexts
Evidence-based	Requires documentation to support claims and replication of results, increasing the credibility and relevance of B^3D
Transformative	Encourages innovative ways of thinking about humankind's relationship with nature and new approaches to driving changes in society that support growth, renewal and regeneration

Table 1: Characteristics of a Common Ground for B3D

systems as a principle for designing industrial ecosystems. Namibia Breweries, in which the waste of one industrial ecosystem is food for a related ecosystem, could be an application of this principle (www.sdearthtimes.com/et0101/et010157.html). Whenever possible, B3D practices that are similarly transformative should be promoted.

Table 1 summarizes the set of characteristics that could become the basis of a common ground among B3D proponents for learning from nature.

Next Steps

Thomas Kuhn (1962) famously described different stages in the development of a science: pre-scientific (no agreement on a paradigm or commonly accepted methods), normal (a single paradigm and related methods characterizing the discipline), and revolutionary (accumulation of data conflicting with the current paradigm leads to the emergence of a new paradigm). B3D as an emerging field of inquiry and practice is in the early, pre-scientific stage of development. The ultimate goal is to become a credible and recognized discipline supported by a network of trans-disciplinary research and practice. Yet, it is also important that as a new discipline B3D has room - and plenty of it - for exploration, experimentation, serendipity, risk-taking, and failure. Transformative work emerges through challenging limits and reframing the inevitable failures into opportunities. Computer science is an example of a modern discipline with a sound theory and well-established communities of practice that has also supported almost continuous discoveries, innovations and revolutions.

This preliminary proposal seeks to create a network by engaging a broad spectrum of B3D proponents, identifying areas of common interest, fostering a discussion of core principles and values, agree on an over-arching name and laying the groundwork for developing a set of best practices through applied research. It also suggests questions for further discussion and exploration through projects, studies, experiments and results which might demonstrate that B3D leads to solutions that are more likely to be sustainable. Stimulating discussions and encouraging broad-based research in the field can help build a stronger and closer B3D community that not only promotes sustainability, but is itself more sustainable.

Discussions are underway to plan for a face-to-face workshop that will attract a cross-section of the B3D community. The workshop will leverage the diverse perspectives and expertise of the participants to identify key initiatives that will further the goals outlined in this article. If you are passionate about building a B3D discipline, please see http://bioinspired.sinet.ca/content/b3d-workshop-initiative for the current status and ways to get involved. ×

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Author Bio

The authors are members of a Think Tank supporting the BID Community (http://bioinspired.sinet.ca) that was launched in 2010 to serve a growing community of practice. The BID Community is currently working towards a consensus on the core elements of B3D including an unambiguous way to investigate, define and organize its practice and knowledge. The Think Tank represents a wide range of perspectives and views through our backgrounds in science, engineering, architecture, computing and design as well as our roles as active B3D practitioners, educators and researchers.

Xylem element in the shoot of a fig tree (*Ficus alba*)

Photo: Zaoui58, 2005 | Wikimedia Commons

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