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Cover art

Cover: *Insectes* Plate 14 detail: 1. *Entymus imperialis*. Brésil; 2. *Curculionide*. Caracas; 3. *Entymus splendidus*. Brésil; 4. *Curculionide*. Brésil; 5. *Entymus*. Brésil | Artist: E. A. Seguy, 1920-29 | Special Collections Research Center at NCSU Libraries

pp. 2 - 3 & pp. 122-123: *Insectes* Plate 09: 1. *Nemopistha imperatrix*. Afrique Oc.; 2. *Tomatares citrinus*. Afrique Austral.; 3. *Neurolasis chinesis*. Asie; 4. *Aeschna Cyanéa*. Europe; 5. *Mnais earnshawi*. Indochine | Artist: E. A. Seguy, 1920-29 | Special Collections Research Center at NCSU Libraries

Design

Marjan Eggermont

Colin McDonald

ISSN

1927-8314

Peleides Blue Morpho | Photo: Gio'71, 2011 | Flickr cc

Endurance

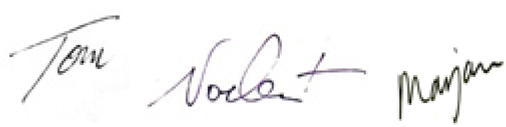
When Eugene Alain Seguy was producing the art you see on our cover, Europe was still recovering from the War to End All Wars, the Great War, which, in only two decades, would be given a number in sad recognition that it was not to be our last. The world was very different in the 1920's than today, and the technique of pochoir that he employed to mass produce his images seems quaint in an age in which the least technical of us can easily manipulate sophisticated visual effects. What endures, however, is the evocation of joy in the human spirit that the works produce. Part of that joy, in our opinion, stems from an innate biophilia, and part from a love of the craft of our fellow humans and our society. It is interesting that a picture of a lowly insect could spark this kind of reaction.

It is more than coincidental that Erich Maria Remarque in his classic novel All Quiet on the Western Front (originally *Im Westen nichts Neues*) chose the butterfly as the icon of a world of freshness that was forever lost to the soldier Paul Baumer. As Paul rejects the Great War and its hellish effects the insect serves ironically as his mortal undoing. He is shot by a sniper while deep in reverie caused by the sight of this fluttering life on the barren and quiet battlefield.

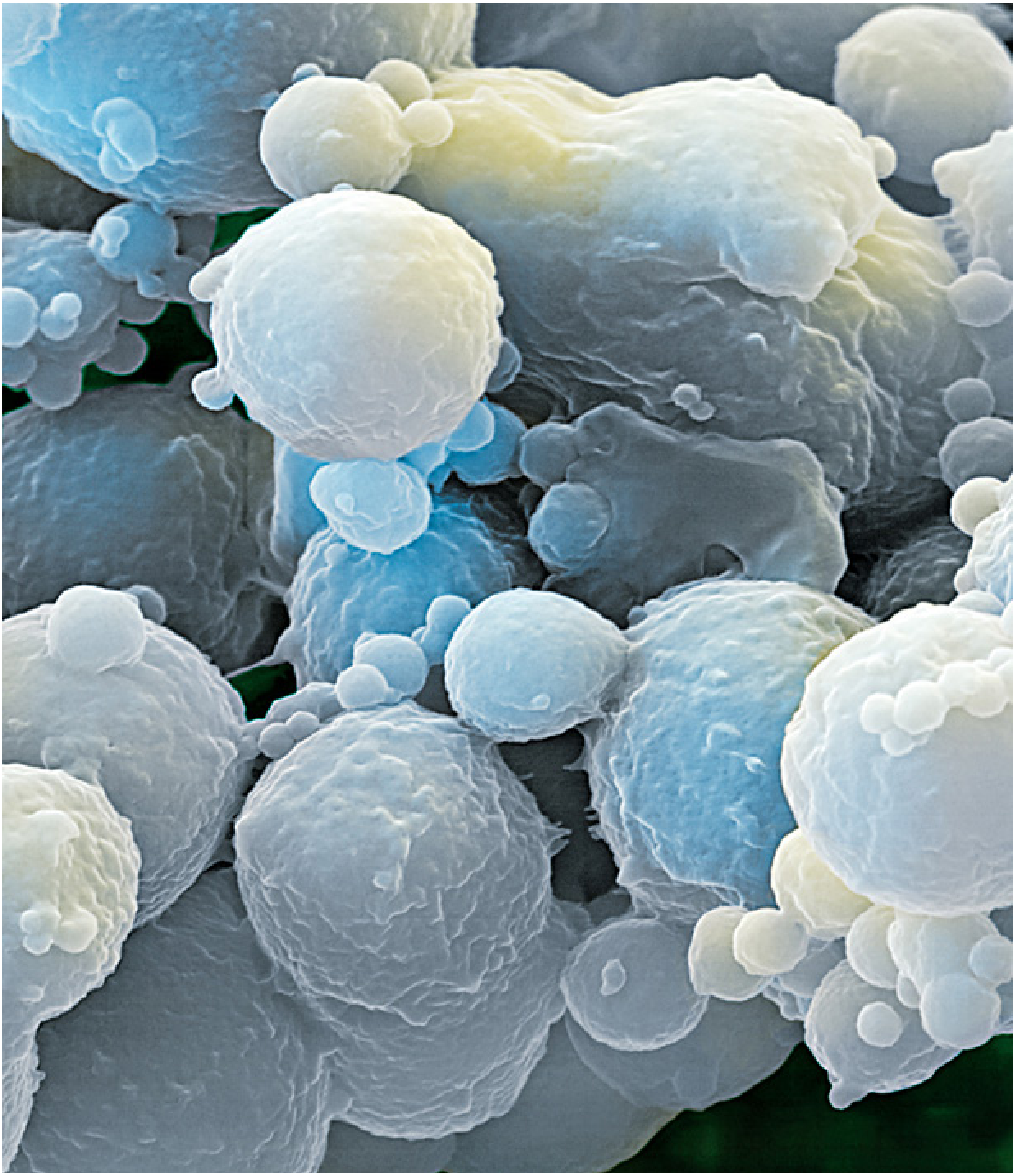
In the 85 years since both men's work, the world has indeed changed, but we continue to yearn for the natural world while we simultaneously revel in our own works. We are certainly a very clever species and must rely on our acquired wisdom to balance our most egregious impacts. A conscious relationship to the other species' world, in our opinion, will always be essential to striking the right balance of wisdom and cleverness in our own natures.

In this issue Pete Foley explores some of the aspects of our psychology in his opinion piece about nature inspired innovation. Heidi Fischer tells us about an amazing desert creature that can sense when the next flood might come. Our case study subject, Markus Buehler, tests the bounds of structural failure in a quest to understand how the microworld is put together. Jeff Karp, featured in our last issue, and Rick Dove give their thoughts on the state of the profession in our interview section. Björn Cederquist explains some of the concepts behind the urban development at Hammarby Sjöstad. Finally, four reviewers give their different perspectives on a new book about bio-inspired architecture by Blaine Brownell and Marc Swackhamer.

We hope you enjoy reading this collection as much as we have had putting it together for you. Happy reading! ×



Tom McKeag, Norbert Hoeller and Marjan Eggermont



Microstructures made from designer proteins | Biomaterials made of natural self-assembling proteins such as spider silk proteins or collagens have extremely interesting properties: For example, they have high tensile strength and elasticity and are at the same time biodegradable. Self-assembling R16 type proteins, pictured here, are able to form spherical structures. Magnification 5 000 :1 (12cm in width) | Photo: BASF We create chemistry, 2010 | Flickr cc

Case Study

Our Material World: A Composition in Major and Minor Keys

Tom McKeag

Our Material World: A Composition in Major and Minor Keys

The natural world is a complex place and sometimes those wishing to emulate it have to broaden their analytical tool sets. This is a story about an engineer who has widened the field of view in his profession of materials research by innovative thinking that not only joins previously separate research disciplines, but relates the arts with science.

Plenty of room at the bottom

When one thinks of civil engineering, images of large structures like highways, bridges and dams come to mind. The building of our technological world's infrastructure, all the things that shelter, provide utility, and allow us to move about, requires knowledge of materials as well as how to assemble them. Typically, most civil engineers look at the visible scale of how these structures are put together and the most basic properties of the materials they are made of.

Markus Buehler, by contrast, looks at the way small things in nature are connected to form the materials that often outperform our best products. In that search he and his colleagues have found that it is the way components are connected, rather than the strength of these individual units that creates superior performance.

Dr. Buehler is a Professor and the Head of the Department of Civil and Environmental Engineering at Massachusetts Institute of Technology, and teaches mechanics, modeling and simulation, and computational research. He is also active in editorship of several academic journals, one of which, *BioNanoscience*, he helped found. He was elected to the Editorial Board of the Journal of the Royal Society *Interface* in 2012, as Section Editor of *Nanotechnoloy* in 2014, and since 2015 as a member of the Editorial Board of Nature Scientific Reports. He also runs the Laboratory for Atomistic and Molecular Mechanics (LAMM) at MIT (http://web.mit.edu/mbuehler/www/).

Here his researchers have observed how natural arrays are made of just a few parts, recombined multitudinous ways under countless different environmental conditions and traversing many different linear scales. Recognizing these complex interactions and the impact on performance of materials, they have developed a conceptual model of what they consider essential parameters for superior mechanical properties. They call this model “materiomics”.

Their research approach combines the methods and concepts of structural engineering, materials science and biology in order to investigate hierarchical structures. They work at the atomistic scale up through the macro in order to understand the geometry of material per-

Spider Butt: Spinnerets of *Calisoga longitarsis* | Photo: ken-ichi, 2009 | Flickr cc formance. Their investigations are focused on proteins, specifically three kinds: collagenous types found in tendons, skin, bones and teeth; beta sheet types found in worm silk, muscle tissue and amyloid protein; and alpha helix types found in hoof, hair and wool. In particular the lab has published several papers on the mechanics of silk. They study the failure of materials in a biological context by analyzing computational models. From this they hope to identify the fundamental makeup of materials and how this knowledge can be applied to improved performance in our built world.

Failure as a vocation

The researchers at LAMM also get to break a lot of things! Structural failure of the materials they test reveals the design principles behind how functional properties are made and lost in the natural world. Director Buehler, explains:

> "We study failure to gain insights, and to make better materials from 'less'. Pushing a material or structure to the limit of what it can withstand, or the limits within which it can provide functional properties, enables us to understand the borders of what defines its characteristics. Failure of spider webs, for instance, enabled us to understand how the properties of its building material (silk) interplays with its specific structure (e.g. the orb web). By breaking spider webs, both natural ones and ones we created in our labs, we could systematically explore which characteristics in material and geometry are critical to the provision of properties."

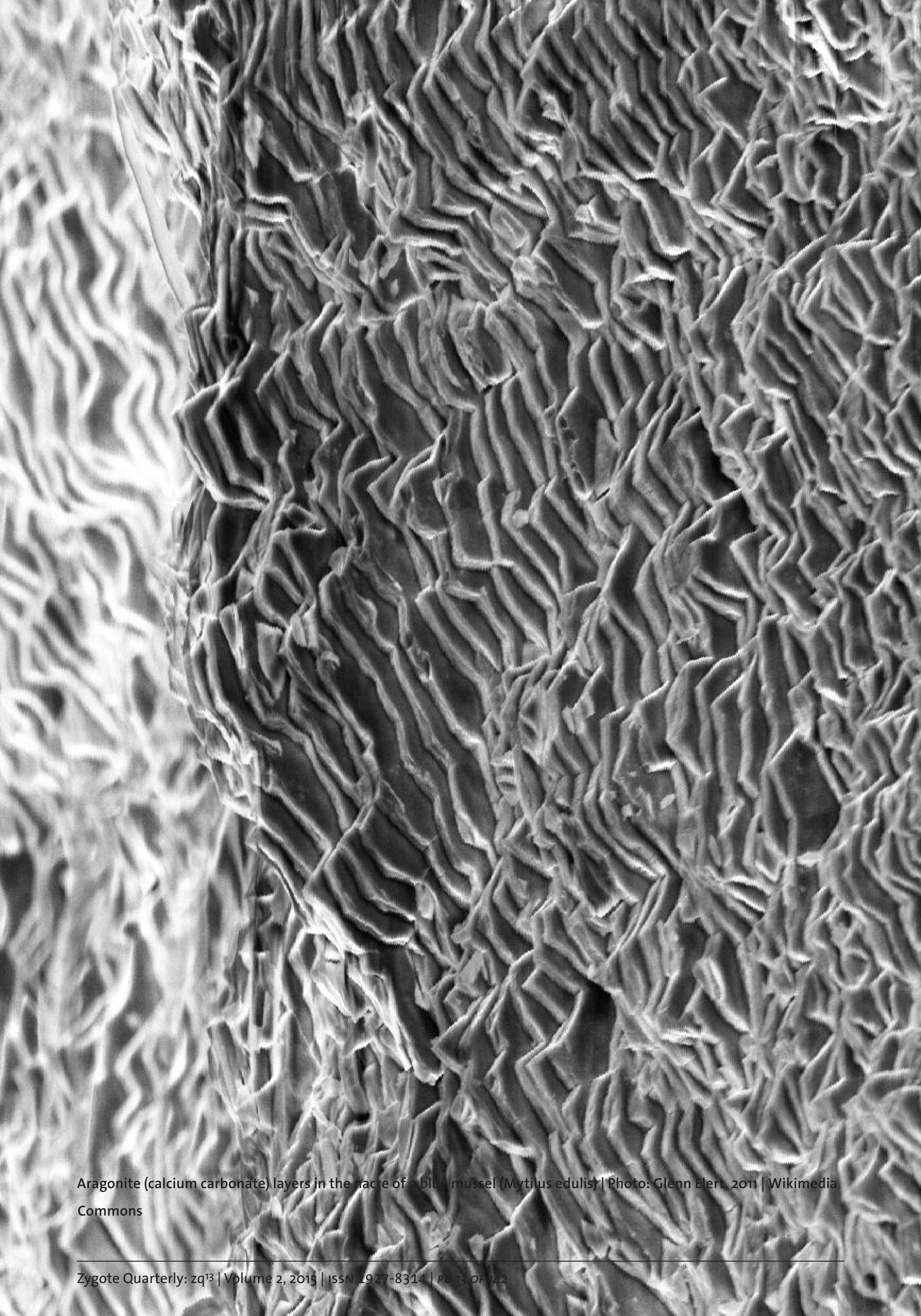
Random failures of engineered structures have often led to improvements in design, but Buehler and his team aspire to a comprehensive process that explores the limits of materials with the intent of improving their range of performance.

> "What we do is to accelerate this process by identifying the envelope within which function is guaranteed, and by identifying the mechanisms by which these functions are lost. We then reverse engineer these and discover new ways to either expand the functional envelope or to create new materials altogether."

The researchers are particularly interested in the combination of disparate properties in biological materials. They investigate the mechanical properties of strength, robustness, deformability, adaptability, changeability, and evolvability as well as mutability. They are also keen to know more about the phenomenon of hierarchical structures, how inherently weak materials are combined in cross-scale arrays to produce high performance structures. A well-known example is the nacre of mollusk shells, in which the soft material of chalk (calcium carbonate) is combined with proteins in hierarchical arrays that yield a material stronger than synthetic ceramics.

The Silk Road

One such material the lab has studied is spider and worm silk, made typically of the beta sheet type of proteins mentioned above. The group found a surprising characteristic of the



Aragonite (calcium carbonate) layers in the nacre of a blue mussel (Mytilus edulis) | Photo: Glenn Elert, 2011 | Wikimedia Commons

Australian garden orb weaver spider spinneret | Photo: Jason7825, 2014 | Wikimedia Commons

silk that contributes to its legendary strength and durability. Most materials sacrifice durability for strength: the stronger the material, the more brittle it tends to become. Silk does not suffer from this compromise, however, and overcomes the seeming contradiction between strength and durability by capitalizing on what would seem to be a structural flaw.

In silk rigid sheets of proteins are joined together in a stack by filaments and relatively weak hydrogen bonds. The sheets are oriented in different directions, allowing neighbors to collectively resist external forces. The weak bonds are easily broken, yet easily re-formed which means that failure from external stress is gradual rather than sudden as is characteristic of brittle materials. The team also found that the more constricted the beta sheets were initially, the stronger the material. These insights into the mechanical structure and properties of silk were reported in *Nature Materials* on March 14, 2015: http://www.nature.com/nmat/journal/v9/n4/abs/nmat2704.html.

The LAMM has not restricted their analysis to just the molecular components of the silk material. In a study that had appeared in the journal *Nature* the team also investigated the geometry of a spider web in its relationship to the silk spun by the spider. Here they found that the hierarchical structure of the material and the geometry of the web itself worked together to make the web less prone to catastrophic failure as happens on many man-made structures. The team made a very accurate computer model of the material structure of this hierarchical array, starting with proteins that comprise fibrils that comprise fibers that constitute the web. They subjected this model to various external stresses and found that the web failed in very local areas, sacrificially. They confirmed their model predictions qualitatively by testing actual spider webs (http://www.nature.com/nature/journal/v482/n7383/full/nature10739.html).

The spider silk material itself will go through several distinct regimes when stretched. At first it will extend as the pulling lengthens and straightens many of the convoluted beta sheet proteins embedded in the fiber matrix. As this pulling becomes more extreme, however, the material changes its characteristics: the straightened beta sheet proteins now form beta sheet nanocrystals that stiffen the entire material.

This softening at select yield points and then stiffening under large strain is crucial to localizing the load-induced failure in the spider web. This means that the entire web will yield under moderate loads such as wind, but fail selectively and sacrificially under more extreme stress. This saves the spider from the expensive job of rebuilding the entire web when forces act to break it apart.

The lessons learned from a closer look at the material and structure of spider webs from the bottom up could produce important engineering innovations according to Buehler, say in impact loading or seismic safety. This would require a studied analysis of both material and structure to design a similar non-linear, selectively sacrificial response, but the reduction in system-level loading and catastrophic damage would be significant. He believes that there are other areas outside of civil or structural engineering where these concepts could be beneficial.

> "The breakthrough may come in the area of medical materials, for which silk is an outstanding candidate due to its biocompatibility. In other fields, silk properties will have to be rescaled and transferred to other material systems. If we can mimic the principles by which silk performs so incredibly well in say, sugar or mineral-based systems, then we may be able to achieve large-scale impact. Disruption may come from either the fact that such materials are similarly tunable and flexible as silk (i.e. achieve many diverse properties without changing the fundamental chemical structure) or from the fact that we can take advantage of alternative resource streams. The feedstocks for many high-volume materials such as concrete or steel rely on high-energy and high carbon emission processes, whereas silk-inspired materials can provide a carbon negative and low-energy route to production. The energetic advantage alone may be a key feature that drives economic success, by disruption (of) classical supply chains and material streams."

The Bigger Picture

The ultimate prize for Buehler is the ability to create so-called "designer materials", so understanding the fundamental principles of a material is critical to all application breakthroughs.

> "The biggest impact (we can have) will be in materials by design – in other words, to build materials that have tailored properties. Ultimately, what we hope to achieve is that we can dial in any material property or combinations of properties, in a material by design."

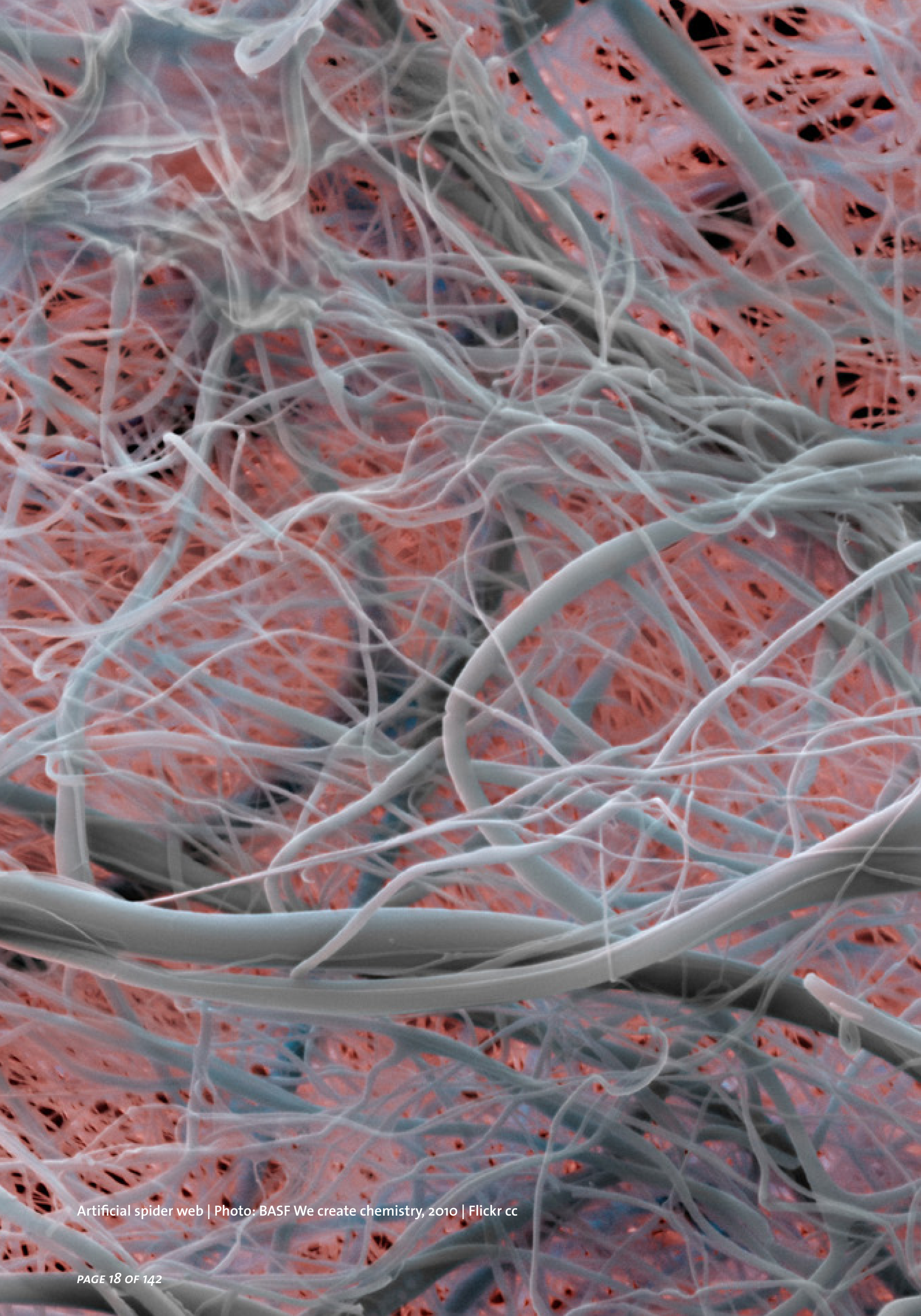
He believes, moreover, that this approach will not only lead to new materials but will revolutionize the very process of design.

> "This will fundamentally change the way we design integrated structures and systems as we can design the material while we realize certain structural features. The dynamism that is achieved through these mechanisms can have remarkable consequences, in that the design process is revolutionized to view materials to build with (as) not static but part of the design equation (e.g. think of an architect or product designer). This poses serious intellectual challenges on both the material design process and the artistic expression or human appeal of a structure or product, but once an equilibrium is found, new avenues (will) open that were not imagined before."

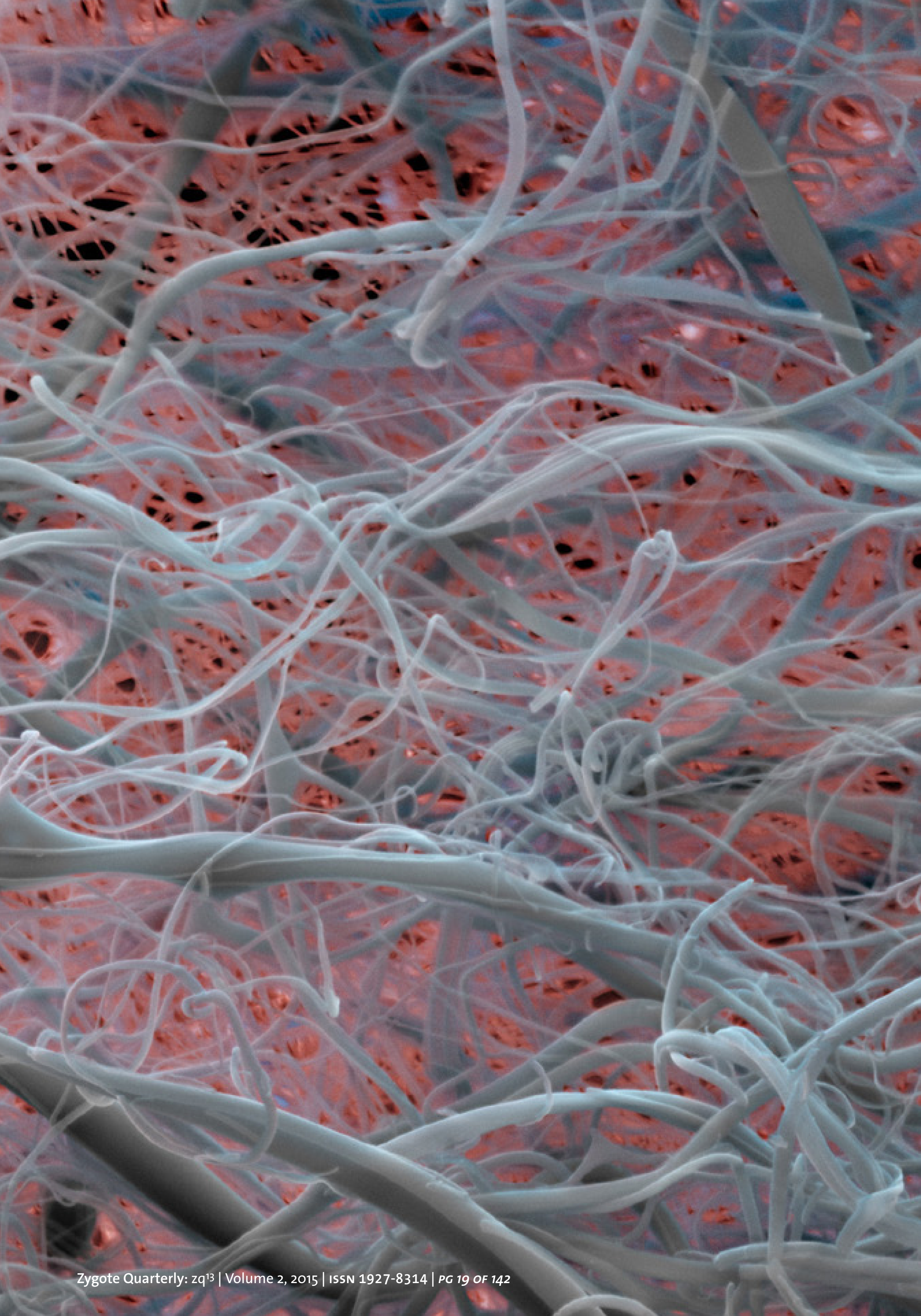
This broad vision of a world in which technicians dial up custom products at the material level is the impetus for Buehler's work on Materiomics, a holistic concept of materiality modeled after the way the human genome has been studied.

Materiomics

Materiomics is defined by Buehler as "the study of the material properties of natural and synthetic materials by examining fundamental links between processes, structures and properties at multiple scales, from nano to macro,



Artificial spider web | Photo: BASF We create chemistry, 2010 | Flickr cc



by using systematic experimental, theoretical or computational methods". As in the discipline of genomics, all relevant processes, structures and properties are studied to understand a material through all its linear scales. The integrated view of these interactions at all scales is referred to as a material's materiome (http://www.springer.com/us/book/9789400716100).

He described the genesis of the concept:

"This idea came out of our quest to provide a description of a material's functions (and potential for functions) based on the fundamental level of the building blocks that make up a material. We realized that many biological materials in particular derive functional properties (e.g. strength, color, biological functions, etc.) from a set of universal components that are for instance alpha-helix proteins, beta-sheets, certain fiber geometries and others. The interplay of a set of relative-

Bone morphogenetic protein 6: Bone morphogenetic proteins are known for their ability to induce the growth of bone and cartilage. Visible are alpha-helix proteins (green) and beta sheets (red and yellow).

Figure: Pleiotrope, 2011 | Wikimedia Commons ly few, universal building blocks, assembled into complex shapes across multiple scales, defines properties. Materiomics is the framework to characterize these relationships. We have also applied similar concepts in studies of artistic works such as music or literature, and realized striking similarities once we developed mathematical categories of each of these systems. In other words, a mathematical model of music or bone is indistinguishable at the abstract level, and the very same mechanisms of universality, structure, hierarchies, etc. define its functions."

Buehler believes that the field of materials research is at an important turning point due to increased capability in two areas: experimental methods and predictive numerical studies. In the former, scientists have an unprecedented ability to precisely examine and analyze phenomena at the molecular scale, and in the latter they can now model, with simulation studies, everything from DNA structure to the continuum of material composition in bone or collagenous tissue.

This has exciting implications for studying structure at a larger time and length scale if these basic molecular principles are understood. Buehler reaffirms his debt to prior scientific exploration:

> "The field of genomics (and related "-omics" concepts) has certainly inspired us to build on a similar platform, but focused on materials function. Other key insights were derived from earlier work that focused on distilling the complex structure and behaviors of systems into a few key governing principles and interactions between essential entities. Such thinking has been pursued in physics, and in the reductionist approaches fostered in systems biology. Reducing a complex system to a basic level of building blocks and how they derive functions is an innate drive that many scientists have pursued, whereas new computational power and analysis tools opened recently."

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Case Study
Our Material World

Author:
Tom McKeag

The search for a universal framework within the material world has led Buehler to consider the metaphors and mathematics of other fields. In particular he has turned toward the art of music in exploring the potential for a modular system model.

Beethoven and Bone

Through their work with silk, the researchers at LAMM had explored the structure and behavior of hierarchical arrays, modeling these arrays from the bottom up, starting with how

Excerpts from the compositions (by John McDonald) corresponding to the two silk sequences studied

Figure: Joyce Y. Wong, John McDonald, Micki Taylor-Pinney, David I. Spivak, David L. Kaplane, and Markus J. Buehler, *Nano Today* (2012), http://dx.doi.org/10.1016/j.nantod.2012.09.001

individual proteins are constructed and paying particular attention to connections across molecular and metamolecular space. Was there a way to predict and recreate high performance protein fibers without the usual trial-and-error routines?

A universal language of materials would be a powerful paradigm and could open up whole new fields of discovery. Its foundation would be in the proteins, and, as importantly, how these were joined together and then used to build emergent structures as one went up the linear scale. Buehler saw an analogy with music.

As 20 amino acids are combined variously into thousands of protein types that are in turn folded or pleated and aggregated to make tissue like bone, so notes are strung in sequences and patterned into hierarchical compositions comprising such components as pitch, range, dynamics and tempo. Both can be abstracted in mathematical ways and the patterns observed and analyzed. Buehler thought that this could be an effective tool for prediction and could speed up the rate of discovery of useful materials.

He assembled an interdisciplinary team that included a composer, a mathematician, bioengineers and a dancer. Their intent was to take the experimental results of the lab's spider silk research and abstract this through category theory into a set of rules for constructing material. This set of rules would be translated into music and scores created from these rule sets. The team would then compare different musical scores for insights into the usefulness of this process as a new paradigm.

The results were fascinating as the composer, using the rules translated from the silk protein observations, created two quite different types of music. The researchers have observed two main types of proteins; one that strongly bonded and one that weakly bonded. Where strong bonding dominated, the music was harsh and somewhat discordant. Where weak bonding dominated, the music was smoother, more melodic. In a fascinating extension of this experiment, the composer will be tasked to create his own musical score using some simple rules of construction. The bioengineers will then translate this back into the language of protein construction and analyze the performance of the resulting material.

They have published their findings in a recent issue of *Nano Today*, http://www.sciencedirect.com/science/article/pii/S1748013212001041. In the article the authors for the first time express the structure, mechanisms and properties of a material through the language of music. This integration of science and art through categorization of structure-property relationships was unique and distinctly novel.

As if taking a cue from the very proteins that he and his colleagues study, Markus Buehler is intent on making cross-boundary connections in order to innovate. Mixing disciplines and domains and techniques is bringing him closer to better materials with strong performance but made with common and weak materials and low energy. That would be sweet music to a world in need of a greener infrastructure. ×

Giant Water Bug

Photo: wcdumonts, 2012 | Flickr cc

The Science of Seeing
Early Warning

Adelheid Fischer

Early Warning

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

In his 1982 travel book *Blue Highways*, William Least Heat Moon included an entry about a visit to Cave Creek, a stream that flows through a canyon on the eastern flanks of the Chiricahuas. To get to these remote mountains in the far southeastern corner of Arizona, the author described how he drove across the "flat, hot scarcity" of the Chihuahuan Desert, until he encountered a stockade of vertical rock columns with no obvious passageway in sight. Baffled, Least Heat Moon motored on when suddenly the road seemed to slip through the façade. Sun-shot desert scrub gave way to a gallery forest of alligator juniper, sycamore and white oaks. Threading through the shade of the trees was a flowing stream, something that even seasoned desert dwellers might regard as nothing short of improbable here; miraculous even. From time to time the canopy opened to reveal ruddy pinnacles encrusted with yellow and green lichen. Pitted and shaved by the elements over eons, the towering outcrops, he said, "might have come from the mind of Antonio Gaudi."

"How could this place be?" he asked himself, enchanted.

This is the question that occurs to me over and over again as I accompany two graduate students from Oregon State University into Cave Creek Canyon one early morning in June. Our route retraces the first leg of Least Heat Moon's journey, leaving the desert valley to pass through the hoodoo sentinels that stand guard at the canyon entrance. As we gain elevation into forests of Apache and ponderosa pine, we veer from the main road to detour to our destination: a tiny tributary known as Turkey Creek.

We park the car in a small turnout, grab plastic buckets and small hand nets, and follow a trail through a forest so dry that it crunches underfoot. It will be another month before the summer monsoon begins, when enough moisture will well up from the Pacific Ocean and Gulf of Mexico to fuel the muscled thunderheads that pummel this landscape with hard, violent rains. I am surprised, then, when I hear the splash of running water as we draw nearer to the creek. Unlike Cave Creek, which is considered an intermittent stream, Turkey Creek hosts a perennial flow, even though it may shrink during droughty times of the year. At that time it can become little more than a series of stepped pools that are connected by a thin trickle of water; like pearls on a string. Today, however, we settle around a large pool, about the size of a six-person Jacuzzi, which is fed by a gentle waterfall of clear, cool water. Nodding from the stream banks are the delicate spurs of yellow columbine blooms. Somewhere a hermit thrush sounds its call from the forest, a song that is halting, discontinuous

Yellow columbine flower | Photo: wplynn, 2014 | Flickr cc

Cave Creek area, Chiricahua Mountains | Photo: insect safari, 2008 | Wikimedia Commons

and slightly off-key, like an atonal score for clarinet. With it, riding on a downstream breeze, comes the fresh smell of sweet water. I inhale deeply.

This is a mountain in the Chihuahuan Desert. The *desert*, I remind myself. *How could this place be?*

It turns out that this is just the beginning of the day's wonders. We are here to collect the top predator of these tiny streams: *Abedus herberti*, a giant water bug. Student Kate Boersma is exploring how the presence or absence of these bugs can structure the community of organisms that live in these streams and, in turn, regulate some of their basic conditions such as the growth of algae. The "borrowed" bugs will be temporarily put to work in controlled experiments on the grounds of the Southwestern Research Station a few miles down the road.

To simulate the environments in which *A. herberti* live, Boersma has filled a series of plastic tubs with creek water and seeded them with a suite of organisms typically found in Chiricahua waters. Giant water bugs are released into only some of the artificial pools so she can better understand changes in the food web when *A. herberti* is the dominant predator or when, in the absence of the bug, secondary predators such as dragonfly larvae and diving beetles take over. Boersma uses a Sharpie to carefully mark each water bug so that she can return them to their natal waters at the end of her experiment.

Deb Finn, a fellow graduate student in Boersma's lab at OSU, has volunteered to help us harvest bugs from the stream. An experienced bug nabber, Finn wades in first, heading for the deepest parts of the pool. She slowly slides her hand along the undersides of submerged boulders. This is prime real estate for *A. herberti* and where the biggest adults, which grow to about 1.5 inches, can be found clinging to the rocks. I am far more squeamish. If provoked, the bug can sink a beaklike instrument, known as a rostrum, into human flesh. The rostrum serves as a syringe for injecting digestive enzymes into the tissues of their prey and then doubles as a straw for slurping the liquefied remains. Experts maintain that the bite is no worse than a bee sting but I'm not taking any chances. Surely, they haven't earned the nickname "toe-biter" for nothing! So I head for the shallows where I begin to gingerly turn over smaller, palm-sized cobbles and scoop the fleeing bugs with an aquarium net.

Finn is undaunted. Within minutes, she captures a trophy-sized bug and sloshes over to the stream bank to place it gently into one of the buckets. I bend down to get a closer view and yelp with surprise. The bug bristles with club-shaped eggs. A female has laid them end to end in tidy cornrows on the flattened shield of the male's back, one of a series of egg clutches that he is likely to brood that year. Shaped like a high-clearance Hummer that is perched on segmented stilts, the male will stay close to the water's edge, performing slow push-ups that bathe the eggs with oxygen-rich water. This paternal care of offspring, though common in giant water bugs, is rare among insects.

Although this behavior has earned *A. herberti* marquee billing in the annals of entomology, it isn't the insect's only extraordinary adaptation. David Lytle, an associate professor of zoology at OSU and faculty advisor for Boersma and Finn, recalls one of his discoveries. Standing on the banks of Turkey Creek as a monsoon storm

Abedus herberti

Photo: Greg Hume, 2011 | Wikimedia Commons

suddenly appeared overhead, Lytle observed how the wingless water bugs, unlike their fellow aquatic organisms, were able to avoid being washed away by the resultant flash flood. While he and his student team scrambled out of the active stream channel to higher ground, dozens of giant water bugs were doing exactly the same thing.

Suspecting that the physical process of falling rain was the trigger for this flight-to-safety behavior (and not changes in barometric pressure or ion concentrations in the stream) Lytle and his student researchers returned on a sunny day, this time packing in a fire hose to spray pools containing *A. herberti* with water. Surprisingly, the responses from the bugs to the simulated rainfall varied stream by stream. Those in watercourses that were rarely flooded were slow to respond to the artificial cues. Some never even budged from the stream channel despite a continuous flow of water from the hose. Those in streams that were often scoured by floodwaters, on the other hand, began their evacuation after only about 20 minutes of simulated rainfall. "It seemed that over hundreds or even thousands of years, evolution had fine-tuned these isolated populations so that their behaviors suited the flood regime of individual streams," observes Lytle in the 2011 book *Wading for Bugs: Exploring Streams with the Experts*.

Could the mechanisms of this flood-detection system in giant water bugs be emulated in early warning devices for humans? Among those to benefit from such a system would be backcountry recreationalists who frequent remote landscapes that are subject to flash floods. In many desert canyons in the Southwest, for example, a blue sky overhead provides unsuspecting hikers no clues that a heavy rainstorm further upstream is sending a roaring wall of water, boulders and tree limbs directly toward them.

The researchers have not determined the mechanism by which the giant water bugs sense the changes in their environment. Vibrations created by powerful monsoon downpours, for example, are known to rouse desert frogs and toads from their underground torpor. Are water bugs responding similarly or is it the sound of raindrops that elicits flood-escape behavior? Furthermore, the interest in potential human applications doesn't end there. Other aspects of the bug's life history could prove useful as well, including mimicking the chemical constituents of the underwater adhesives that females use to glue their eggs to the backs of the males.

Sadly, it is unclear whether giant water bugs in the Chiricahuas will be around long enough for teams of biologists and engineers to pursue these investigations. Genetic research has shown that populations of *A. herberti* have persisted in the perennial streams of the Chiricahuas since the end of the Pleistocene, about 10,000 years ago. Despite this long residency, the research by Boersma and her fellow doctoral students in Lytle's lab, suggests that giant water bugs now face uncertain prospects here. Many climate change researchers predict that the Southwest will become drier in the future. The perennial waters that giant water bugs rely on could disappear in the Chiricahuas, as they already have in the neighboring Whetstone Mountains, where fellow student Michael Bogan has documented localized extinctions of *A. herberti*.

Despite the clear threat, piquing interest in these organisms among natural resource agencies, much less the general public, can be a hard sell. Water bugs, as well as the other stream organisms they prey on, aren't considered pests of timber or agricultural crops or food for a lucrative fisheries industry or vital to maintaining the quality of drinking water for humans.

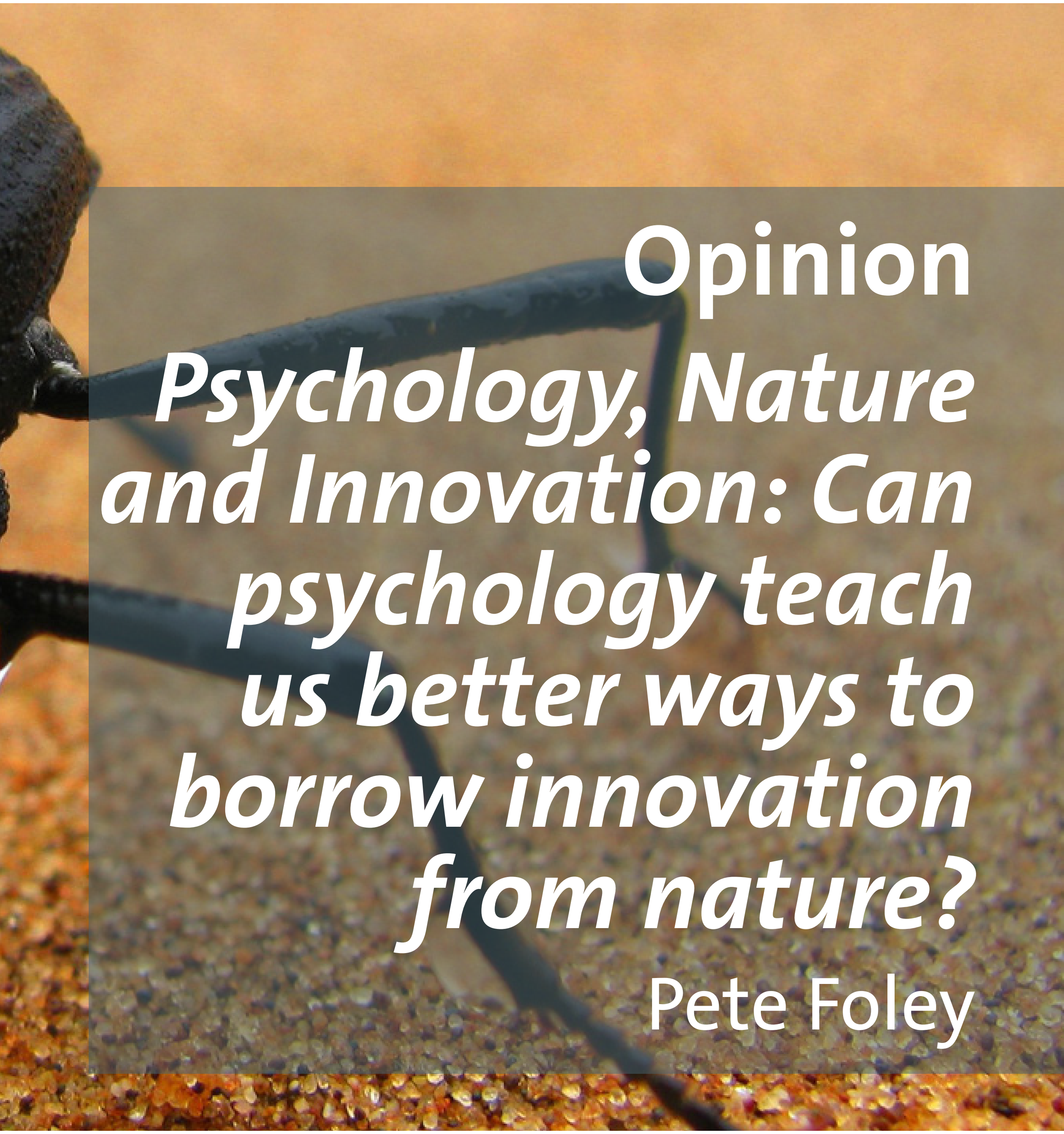
Could the very etymology of their name ironically predict their future? “The word ‘bug’ derives from the Middle English word ‘bugge’ meaning ‘spirit’ or ‘ghost,’” Lytle observes, “and was originally associated with the bed bugs that disappeared in the morning after biting their human victims during the night.” Could these extraordinary organisms become the ghosts of desert streams, vanishing long before we discover the miracles of their ordinary lives? ×

Hermit Thrush

Photo: K Schneider, 2011 | Flickr cc

Onymacris unguicularis close-up

Photo: james.harris.anderson, 2008 | Flickr cc



Opinion

Psychology, Nature and Innovation: Can psychology teach us better ways to borrow innovation from nature?

Pete Foley

vol 2 | 2015

Opinion:
Psychology, Nature and Innovation

Author:
Pete Foley

Psychology, Nature and Innovation: Can psychology teach us better ways to borrow innovation from nature?

Pete Foley is an Innovation Consultant who specializes in applying Psychology, Behavioral Economics and Perceptual Science to business challenges. He blends experience gleaned from 25 years at P&G as a serial innovator, where he published over 100 patents, with 8 years of working with some of the world's experts in the Behavior Sciences to apply their expertise to business needs.

Natural selection, in my opinion, has probably solved just about any problem we can imagine[1]. Borrowing and adapting these pre-existing solutions can be faster and smarter than innovating from scratch, but this comes with some unique challenges. Dissimilarities between human technology and 'natural engineering' can make it hard to adapt nature's solutions to our world. Furthermore, the staggering amount of innovation in nature can make finding these solutions feel like looking for a tiny needle in a huge haystack. Finally, there are several cognitive biases that can get in the way of finding the underlying similarities that enable innovative connections between the two worlds.

The last two in particular are challenges that arise from how we think. Fundamentally, psychology is thinking about thinking, so in this article I will explore how borrowing concepts from psychology can help us do a better job of borrowing innovation from nature.

The Problem with Problem Driven Innovation

There are all sorts of problems we may need to solve, but I will focus mostly on problem driven innovation. I will rely here on Ashok Goel, who formally clarified the difference between *problem driven* and *solution driven* innovation[2]. The latter describes when we have a brilliant idea, but need to find a way to execute and commercialize it. Conversely, *problem driven innovation* is when we have a specific problem that we must solve, but don't know where to look for answers. This leads to three related, but different challenges:

1. **It's a People Problem.** While nature itself may be the ultimate source of the inspiration we are looking for, in most cases, the answers we seek lie with humans. Specifically, the collective intelligence of the world's natural scientists. Looking at nature through the lens of biomimicry has had a powerful influence on how I personally view the importance of biodiversity. Ultimately, however, I typically need expert help to understand the natural world

Onymacris unguicularis | Photo: james.harris.anderson, 2008 | Flickr cc

Namib Beeetle | Photo: JochenB, 2007 | Flickr cc at the level of detail necessary to obtain useful insights from it. For example, standing on the magnificent dunes of the Namib Desert last year, I would never have found a reclusive Namib Water Beetle, or understood its elegant water capturing design without this kind of expert help.

I would still strongly recommend visiting that breathtakingly beautiful place, but in reality I could probably have gotten the information that I initially needed via an Internet search and perhaps a Skype call. This does not diminish the fundamental importance of conserving our environment and biodiversity, but for most innovators, it is the world of human knowledge about nature that we need to search. More than anything, therefore, we need to be good at communicating with people!

2. **It's a Needle in a Haystack.** I have mentioned already that the wealth of innovation found in nature is both a blessing and a curse. Moreover, this challenge is compounded by several of our cognitive biases. Nearly four billion years of R&D is an awful a lot of data to sift through; when we do, we have to resist our natural compulsion to satisfice, or accept the first solution that is just good enough. This is a bias that has almost certainly served us well in our evolutionary past. If your life is in danger, it doesn't pay to hang around to find the best possible solution, just one that is good enough for survival in the moment. However, jumping on the first half decent solution we find can actually be a barrier to finding the really great ones.

Another related bias is "functional fixedness". Once we have connected something to one problem, it becomes difficult to look for other uses. So if we have made a strong connection between the Namib beetle and water collection in the past, we are less likely to see its potential to help with an analogous problem. As an example, imagine you needed to improve the efficiency of ethanol distillation in alternative fuel manufacturing. At a functional level, how nanobumps condense water from the desert air is highly analogous, and hence also applicable to condensing ethanol in a distillation process. When we pull 'Namibian Beetle' from memory, however, the concept of water automatically comes with it, and inhibits extending the analogy to ethanol. This is just a function of how memory works, requiring us to suppress obvious connections before new opportunities can even come to mind.

3. **Experts Care About Their Interests, Not Yours.** When we find a potential solution to our problem, we usually first have to understand it at a deep causal level before we can to reduce it to practice. There is another bias called the "Illusion of Understanding" which means we often assume we understand things more deeply than we do. When we are faced with actually making a prototype, however, the devil is often in the details, and partnership with an expert is frequently the best way to get at them. Unfortunately, there is a real possibility the expert may have little interest in our problem. There are those who end up finding solution driven innovations, but most experts tend to be far more interested in learning more about their area

of expertise than applying it to what may appear to them a vaguely relevant business or engineering problem.

These are all hard problems, but insights from behavioral and cognitive psychology can help us to navigate them and mediate their effects. To do this, we first need some deeper causal understanding of innovative thinking itself.

Innovative Thinking

1. **Eureka!** The 'Ah Ha' moment that often accompanies innovation typically comes to us as a flash of insight. However, while this may seem to come from nowhere, this is almost always a cognitive illusion. In reality nearly every new idea relies on some form of past knowledge. In fact, innovative ideas commonly arise from taking existing information from one domain and reapplying it to a new one. This can happen consciously and methodically, but more often than not, it occurs below our awareness. This creates the illusion of an answer coming from nowhere, because our unconscious does the hard work of putting the pieces together. Our conscious mind then takes the credit for a flash of brilliance that apparently comes out of the blue!

2. **Eureka and Analogy**: Some insights come from borrowing ideas from within the same domain, or from one that is very similar. For example, borrowing aerodynamic attributes for a car from another car, or a plane or speedboat. However, big, breakthrough ideas usually come from making less obvious connections, or at least, ones that are only obvious in hindsight. This is where we need to venture into the realms of analogy, and connections that are based on similar function as opposed to literal similarity.

The world of innovation is full of these examples. Early computer programming was adapted from punch-cards used in Jacquard tapestry looms[3], Alexis Carrel won a Nobel Prize for developing the suturing techniques used in heart surgery by reapplying techniques from lace making[4]. Even the pace maker is derived from a musical metronome[4]! One of my favorite examples is the Dyson Vacuum, which borrowed filterless separation achieved via centrifugal force from a sawmill. Of course, these analogical leaps are exactly what we try and do with biomimicry or bio-inspired design: taking a pre-existing innovation from nature, and applying it to solve a problem in the human world.

Analogy is a natural, intuitive and human way of making innovative connections, but it is harder than the everyday thinking of using literal similarity. Improved analogical thinking can reduce the unwanted impact of cognitive biases such as satisficing and functional fixedness. So how can we make using analogy more systematic and consistent?

Context can help. It is no coincidence that many insights occur in the shower, or in bed. Analogical connections occur more readily when we are not trying too hard, and not under pressure. This is a little like that word that is on the tip of your tongue. The harder you try and think of it, the harder it becomes to remember it. Then when you stop thinking about it, it comes to you. Your conscious mind

Punched-card loom | Photo: Bjoertvedt, 2013 | Wikimedia Commons

Five hole and eight hole perforated paper tape as used in telegraph and computer applications | Photo: TedColes, 2010 | Wikimedia Commons

is no longer getting in the way of your unconscious mind doing its job of retrieval, or making connections!

3. **Knowledge Representation**: The right context may take away a barrier to analogical thinking, but if we want to make it systematic, we need to do more than relax and hope our unconscious will put the pieces together. A great option is to borrow Knowledge Representation and Structure Mapping from Cognitive Psychology. Creating a relational map forces us to incorporate a high level of causal knowledge into our problem definition[5,6], and to break our problem and the system it inhabits into key components and relationships. This does several things:

a) Avoids the illusion of understanding, and instead forces understanding of causal relationships in both the problem and the system.

b) Helps us to automatically see relational patterns, and hence draw analogies to other systems that share similar relational characteristics.

c) Challenges assumptions around levels of abstraction, overcomes satisficing, and thus builds longer analogical bridges that lead to bigger breakthroughs.

Take Dyson's vacuum, borrowed from a sawmill, as an example. While he didn't follow a formal mapping process, analysis of his inventive steps follows a similar 5-step process diagrammed on the next page:

a) Define the system. This is harder than it looks, as the illusion of understanding is quite common, even in systems we think we know well. Forcing ourselves to map out our system ensures everyone has solid causal knowledge of how it works, and often flushes out false assumptions, or gaps in our understanding.

b) Translate this into a relational map. This puts our problem, which in this case is filtration, at the center of a systems view. More importantly, it maps relationships and functions in a non-domain-specific context.

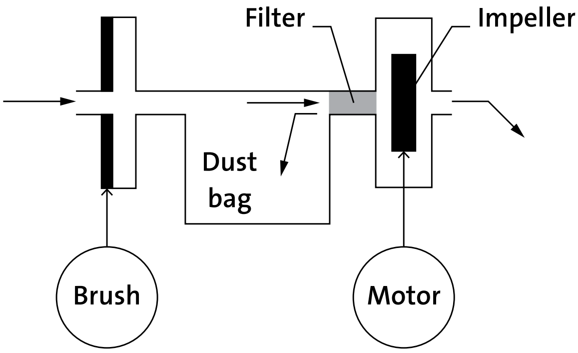
c) Challenge our 'givens' and assumptions. This allowed Dyson to reframe a filtration problem, which is what everyone else was working on, to a more abstract separation problem.

d) Make the analogy to the sawmill.

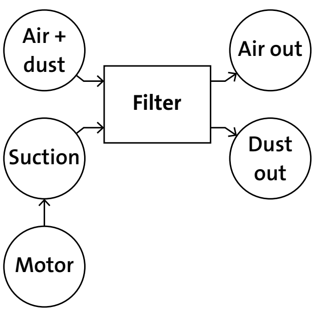
e) Create the bagless vacuum, which replaced the troublesome main filter with cyclonic separation.

Of course, people like James Dyson or George de Mestral see analogies without a formal process. But making explicit the implicit process that lies behind their inventive thinking makes it easier for us to imitate them in a repeatable manner, as part of virtually any innovation process.

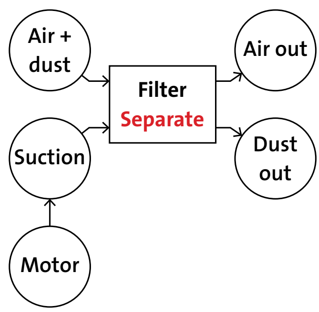
4. **Multi-Layer Mapping**: Another advantage of mapping is that it enables seeing analogies on several different levels at the same time. In this example, the analogical bridge was the function 'separation'. It could just as



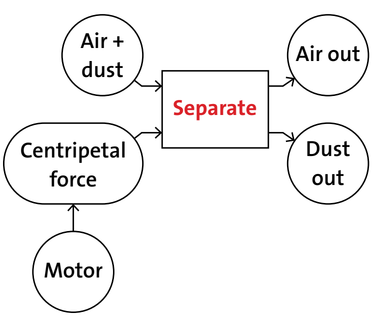
a) Define system



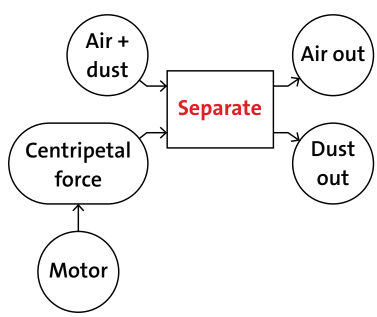
b) Relational map



c) Abstraction
Conventional vacuum



d) Analogy
Saw mill



e) Solution
Dyson vacuum

easily have revealed a system, or a generic problem type that had useful analogs. For example, common systems like chain reactions link virology, forest fires, and nuclear physics. Generic problem types can also link domains that are superficially very different, but analogous. For example, collateral damage is common to homeland security, immune response, politics and oncology. There are many generic problems and systems that have signature maps, including arms races, tipping points, bubbles, vicious and virtuous circles, non-linear relationships, trade-offs, disequilibrium and punctuated equilibria. These become increasingly easy to spot as you become accustomed to building relational maps.

5. **Partial and Compound Analogies:** Another advantage of mapping is that we can use it to find partial or compound analogies. Some complex maps may contain multiple problems. Visual mapping helps isolate and identify these, making it possible to break big complex problems into smaller ones, and then look for different analogies to solve different parts. Consider desalination, which needs to improve efficiency, cost, and the collateral damage associated with salt disposal and the potential ecological impact of vast sea-water intake valves. A map can isolate these, and divide and conquer using different analogies to solve the different parts of the problem.

Purpose Driven Innovation

Dyson's 5,000 prototypes amply illustrate that even when we have an analogy, adapting it back into our original domain can still take considerable work. In the case of biomimicry, recent advances in 3D printing, nanotechnology, materials science and technology in general are making this easier every day, but the differences between nature and human materials and engineering are still not trivial. Often the answer to this lies in detailed comparison of the two systems, and a process of analogy-disanalogy. This in turn requires detailed understanding of the natural system in question. There are numerous groups doing excellent work creating databases that can help us map nature's innovations onto our original system. The details of completing this reverse mapping can be challenging and this often means we need to turn to an expert.

I had mentioned earlier that experts might have limited interest in our problem. This can ultimately help us to solve a problem mentioned earlier. While most people involved in biomimicry are sympathetic to sustainability, innovation derived from nature is not guaranteed to create sustainable innovation. Velcro is a case in point. But the need to engage experts who typically care deeply about sustainability often requires a more sustainable framing of the problem. This in turn drives both short-term behavior and long-term awareness. In the short term, enlightened self-interest makes teams more likely to pursue a sustainable option to solve a problem, while in the long term, simply exposing innovators to the value of biodiversity can prime sustainable thinking over time.

Systems, Processes, and Innovating Innovation

At the beginning of this article, I referenced problem and solution driven innovation. I believe there is also a third type, a hybrid, systems innovation, that knowledge representation can help us solve. There are already some terrific examples of nature inspired systems innovation. The use of slime mold to map transport networks, and swarm intelligence by REGEN Energy to optimize electricity grids are two of my favorites.

I believe further that mapping can give us insights into really big spaces, where we may not know what either the exact problem or solution is. I will finish by sharing two examples. The first is innovating how we innovate, and the second is sustainable corporate growth.

Innovating How We Innovate

Nature has evolved many different approaches to innovation. These are influenced by constraints such as speed and cost of prototyping, and the level of complexity and instability of the environment. So, can we learn from these constraints?

Coccomyces dentatus on Oregon Grape

Photo: wanderflechten, 2009 | Flickr cc

1. **Innovation is Sex:** If we map the innovation process, we see three big challenges: idea generation, prototyping/execution, and communication. If we then look for equivalents in nature, sexual reproduction covers the first two, and is therefore probably the oldest innovation process on the planet. Sex creates a variety of semi-randomized prototypes, and tests their performance in changing environments. Nature has evolved a variety of different reproductive strategies, and I believe we can learn from them.

2. **Are you an Elephant or a Salmon?** One way of categorizing reproduction strategies is often referred to as "r" and "K". Like a salmon spawning, the "r" strategy throws huge numbers of cheap prototypes into the 'market'. Attrition is high, but the cost of each prototype is low, and selection is made under real market conditions. For "K", exemplified by the elephant, selection occurs early in the process, at the moment of fertilization, and considerable resources go toward nurturing the resultant "prototype". There are, of course, many examples that lie in between, and there is no right or wrong approach. However, mapping makes it obvious that many of the variables that make one strategy more effective than the other, such as size, complexity, degree of specialization, and the stability and competitiveness of the environment are common to both reproduction and innovation strategy.

We can use this analogy to ask if what we are innovating is more elephantine - large, long-lived, complex and expensive to prototype, existing in a relatively stable environment. Or is it more salmonesque – cheap and easy to prototype, and living in a dynamic environ-

Salmon jumping up the waterfall | Photo: Scott Ableman, 2010 | Flickr cc

ment? If we look through this lens, it provides a conceptual framework to challenge if we have the right strategy. If we can prototype quickly and cheaply, are we getting to market, failing fast and innovating in real time? Or if prototypes are expensive, are we being selective enough early in the process, freeing up enough resources to truly nurture an innovation through a difficult childhood? Or are we dinosaurs - large, sophisticated, highly optimized, but living in a rapidly changing market? If yes, we may want to "disrupt ourselves" before facing extinction.

Penetrating the analogy further provides more detailed, but instructive variations in reproductive strategy. For example, optimizing the timing of innovation investment. Should we invest heavily in innovation when external conditions are challenging? This somewhat counter intuitive approach is the strategy of hydra, a simple creature that 'innovates' only when food becomes short. It then switches from asexual 'budding' to sexual reproduction, thus increasing variety in its next generation 'prototypes', and hence the chance that one or more will be better adapted to a more competitive world. This "r" type of strategy is highly efficient in a world where change is rapid and unpredictable, and prototyping is fast and cheap. Conversely, some more complex animals, like rats and humans, take an opposite, wait and see approach. They slow reproductive investment when times are hard, becoming infertile as caloric intake drops below a certain level, but then start reproducing when things pick up.

Get it wrong, and take a "K" strategy in an "r" world, and we risk being left behind by more agile competition when change occurs. There are a lot of different timing approaches to reproduction, and so lots of opportunities to see and develop innovation strategies through this lens. For example, sheep will time mating to birth in the resource rich spring, and birds will relocate to resource poor but safe places to rear their young. All can have analogs in innovation strategy.

Redwoods, Wall Street and Sustainable Growth

Redwoods have mastered long-term, sustainable growth. They live longer, and grow bigger than most other organisms on the planet. It is something that many corporations would love to emulate. So what, if anything, can redwoods teach us?

1. **Time Machines**: The cool thing about trees is that when they die, they become time machines. A cross section through the trunk lays bare a life story. Each tree-ring usually marks the passage of a year, and their width corresponds to how much the tree grew in that period. This can vary dramatically, slowing when it experiences drought, or perhaps suboptimal temperatures, but growing rapidly when conditions were favorable.

   This reveals that while growth is maximized over the long-term, it is rarely linear or smooth. Instead, it is agile and opportunistic, changing in response to variations in external conditions.

2. **The Tyranny of Consistent Growth**: Contrast this to corporations that strive (and of-

Redwoods | Photo: wolf4max, 2014 | Flickr cc ten struggle) to deliver quarter over quarter uniform growth, despite changing external conditions that lie outside of their control.

3. **An Illusion of Consistency**: Several human psychological biases combine to make us desire linear growth. We extrapolate small-scale observations to linearity over large scales, prefer short-term gains over long-term ones, and are more comfortable when we perceive things as smooth and linear. There is no question that it would be difficult to persuade Wall Street or industries that have fixed costs to live with a lot more year to year variation. However, non-linear growth is the norm in nature, and if we could adopt this from the masters of long-term sustainable growth, maybe it would ultimately produce a healthier global economy.

In summary, tools borrowed directly from cognitive science, such as knowledge representation and the use of analogy, can help us to more effectively borrow and reapply pre-existing solutions found in nature to solve tough human problems. They do this by making those connections easier to see, and by reducing the effect of certain cognitive biases that can get in the way of innovative thinking. We can also use these tools to extend this process to innovation at a systems level. This opens a door to potentially solve really big problems, such as how to innovate more effectively, or deliver sustainable corporate growth. All innovation is ultimately about thinking. Better understanding how we think can lead us to be more effective on *how* we innovate, and can help us to expand the scope of *where* we innovate as well. ×

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Gnarled branch | Photo: ac4lt, 2004 | Flickr cc

Insectes Plate 05 detail: 1. Scolia procer. Asie Tropicale; 2. Eulema dimidiata. Brésil; 3. Stilbum splendidum. Cosmpolite; 4. Bombus lapidarius incertus. Arménie; 5. Xylocopa tenuiscapa. Asie Tropicale

Artist: E. A. Seguy, 1920-29 | Special Collections Research Center at NCSU Libraries

Portfolio
E.A. Seguy
Pochoir Insects

Artist:
E. A. Seguy

Eugene Alain Seguy was a fin-de-siecle artist practicing in Paris in the first three decades of the twentieth century. He produced eleven folios of artwork, all drawing inspiration from the observed natural world. His focus was on design rather than fine art or science, but his work shows a faithful and meticulous reproduction of organisms as well as a high style that bridged the transition between Art Noveau and Art Moderne.

During this short period a form of mass reproduction of prints that was popular with artists was pochoir (pronounced "po͞osh' wär"). This was an iterative method of line and color application that used a series of stencils to apply the different paints and thereby build up a final multicolored image. This was done assembly line-fashion, but all the applications were done by hand so each finished print had an entirely custom appearance. Brushstrokes, transparency, texture and gradation could all be expressed by an artist of Seguy's caliber. The final products could even have a level of three-dimensionality with the buildup of hand-applied paint. As many as 100 stencils might be used on one print and could be made of metal or oiled cardboard or celluloid. Its intensive labor requirements eventually outweighed its artistic effects and the technique lost favor to methods like lithography. ×

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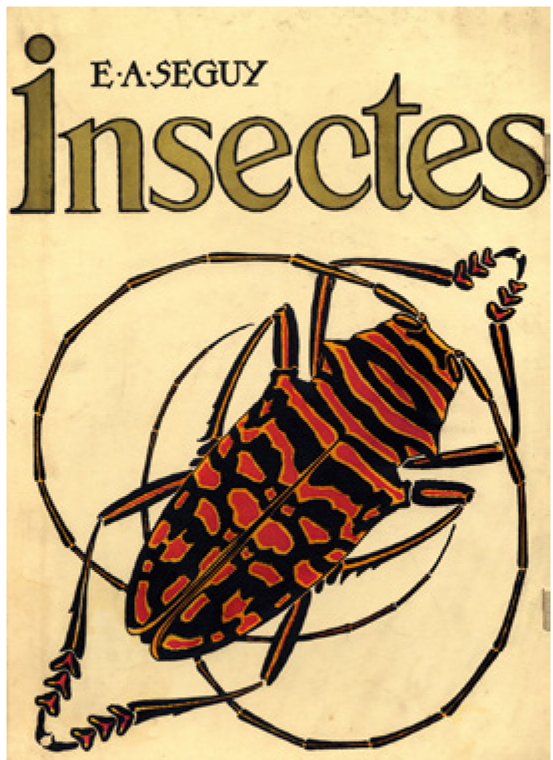

Insectes

Artist: E. A. Seguy, 1920-29 | Special Collections Research Center at NCSU Libraries pp. 58 - 73: *Insectes* | Artist: E.A. Seguy, 1920-29 | Special Collections Research Center at NCSU Libraries

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Pl. 3

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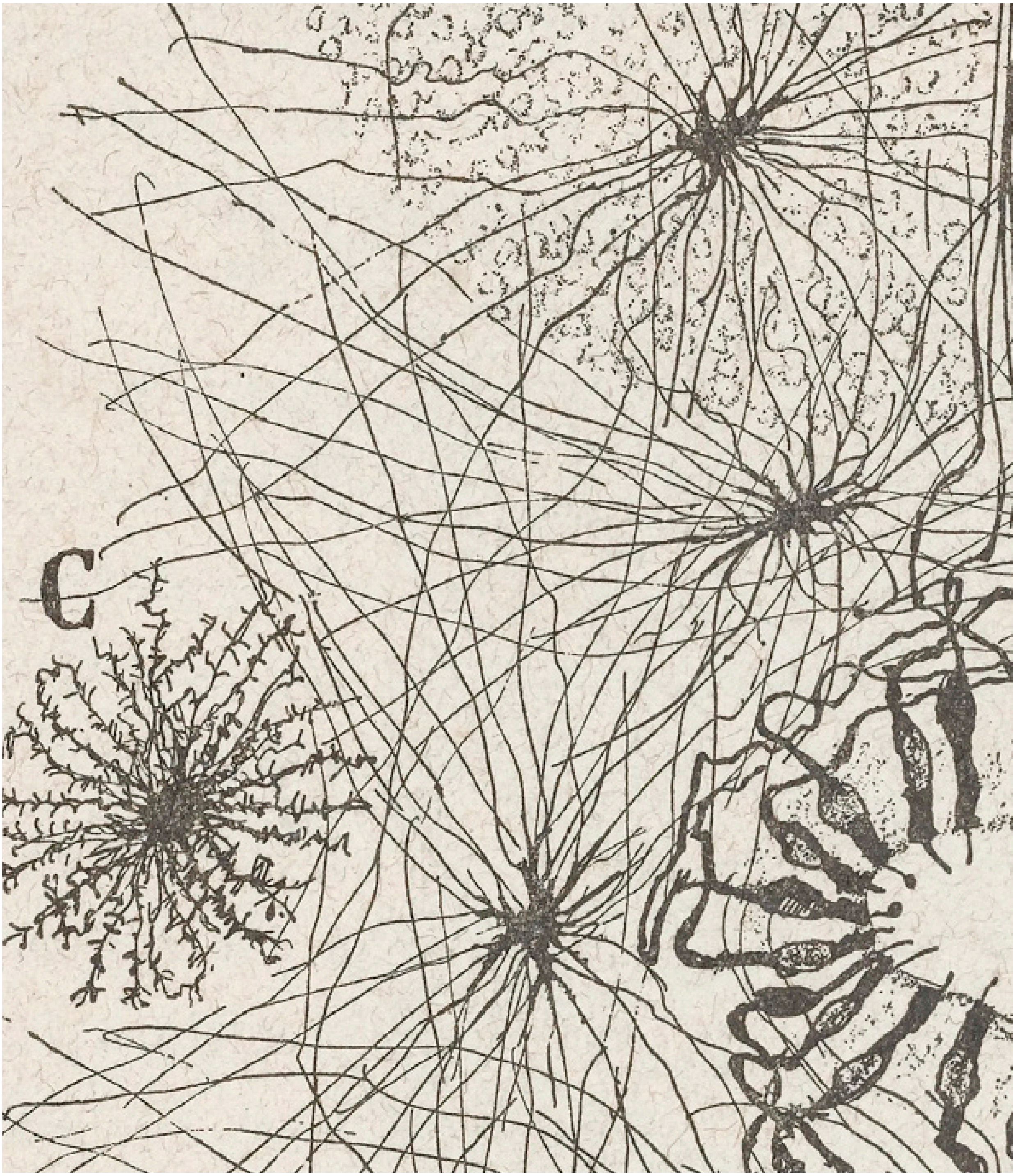
King vulture (*Sarcoramphus papa*) | Venezuela, Caracas
Photo: Paolo Costa Baldi, 2012 | Wikimedia Commons

People
Interviews with
Rick Dove and Jeffrey M. Karp



Neuroglia (detail) of the grey central region and neighbouring portions of the white substance of the spinal marrow of a boy of eight days (method of Golgi)

Drawing: Santiago Ramon y Cajal, 1899 | Wellcome Library, London | Wikimedia Commons

Interview

Rick Dove

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People:
Interview

Authors:
Rick Dove and Norbert Hoeller

Rick Dove lives in Taos County, New Mexico, on eight acres in the mountains at 8,200 feet. Rick has an entrepreneurial background with founder and management experience in all C-level positions, and has dispatched a variety of interim executive problem-solving and program-management assignments in established organizations. He is co-inventor of the first deployed electronic postal metering device, and led its initial engineering and subsequent market introduction that established this now ubiquitous technology world-wide. In the late eighties he led the development of the first research agenda for the National Center for Manufacturing Sciences, and organized its collaborative-consortia research mechanisms. He was Co-Principal Investigator on the 1991 Lehigh study funded by the US Department of Defense that introduced the concepts of agile systems and enterprises, and led the subsequent DARPA-funded research during the nineties that established basic system fundamentals for agile systems of all kinds. In the late nineties he led industry collaborative workshops introducing agile concepts across a variety of industries through a process called Realsearch, a form of collaborative action learning.

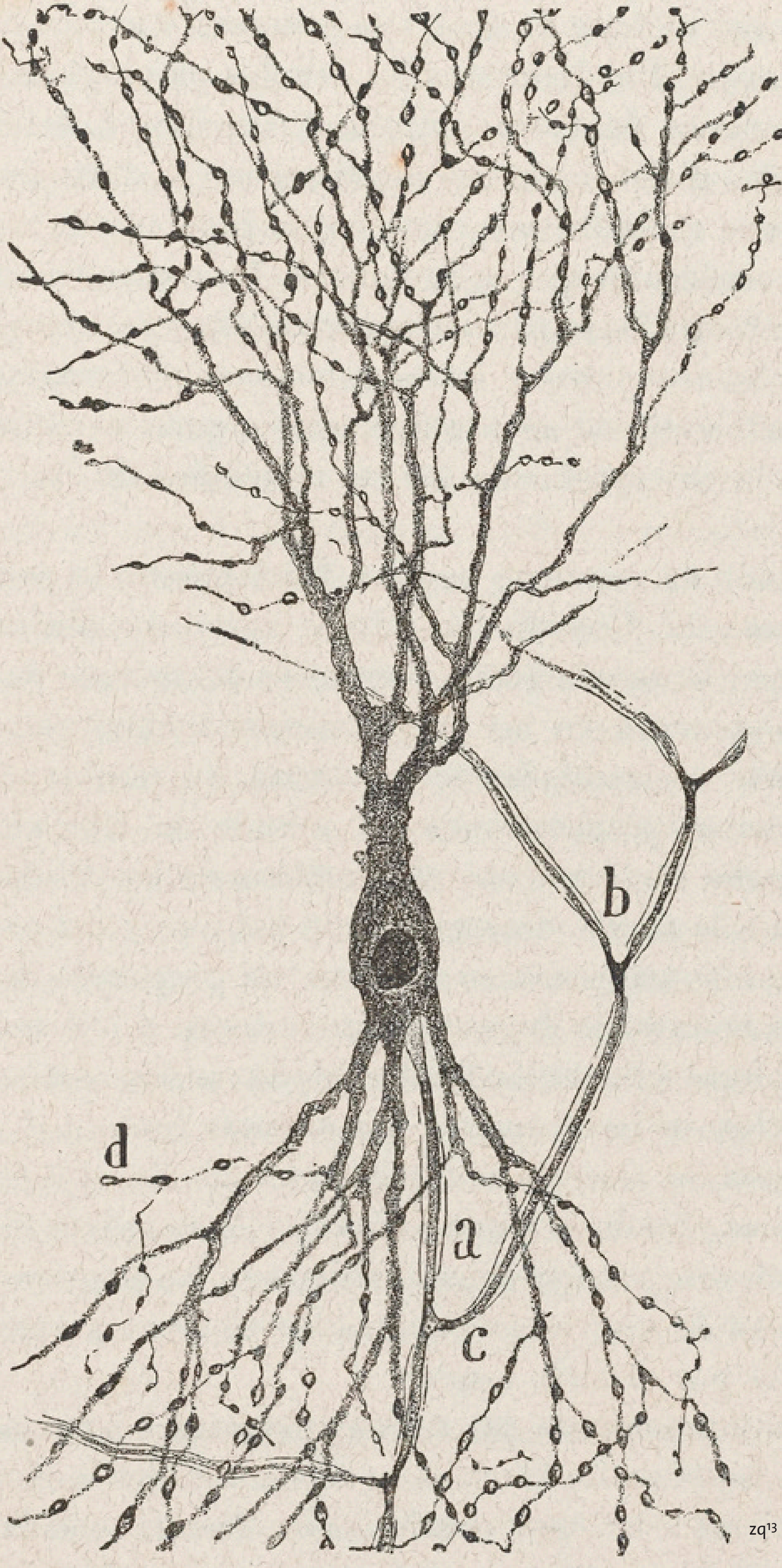
He is CEO/CTO of Paradigm Shift International, an applied research firm specializing in agile systems concepts and education, and leads agile self-organizing system security research and development on US DHS and OSD funded projects. He is a partner in Kennen Technologies, and was the Principal Investigator on the DHS funded projects that showed proof of concept and built prototypes for applying Kennen's patented VLSI pattern processor technology to advanced bio-inspired problem applications. This pattern processor technology is entering the market in 2015. Rick is an adjunct professor at Stevens Institute of Technology, where he develops and teaches basic and advanced graduate courses in agile systems and systems engineering. He holds a BSEE from Carnegie Mellon University.

Norbert: At a presentation you made to the Natural Systems Working Group for the International Council on Systems Engineering (INCOSE), you talked about a pattern discovery project that is abstracting security patterns in natural systems. What took you down this path?

Rick: Applied research is where I like to work. In the natural systems security area, I had to do the research before I could apply it. System security is becoming increasingly asymmetric with

Celula gigante de la porcion inferior del asta de ammon del conejo. Metodo de Ehrlich-Bethe. a. axon. c, colaterol de este ramificada en b, d varicosidades de las expansiones dendriticas

Drawing: Santiago Ramon y Cajal, 1899 | Wellcome Library, London | Wikimedia Commons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attacks changing far faster than our ability to respond. New approaches are required based on self-organizing systems and agile system architectures "that exhibit the ability to survive, even thrive, in uncertain and unpredictable environments" (Dove & LaBarge, 2014). Patterns are traditionally abstracted from a mature body of work which does not exist in this area so I looked for patterns found in natural systems. The path was instigated by Maslow's hierarchy of needs, Carl Woese's horizontal gene transfer work, and Christopher Alexander's work in architectural patterns. The fact that security strategy is generally failing provided the impetus to focus on this area, and provided a value proposition for funding pattern-application development work. We spend more on security every year and lose more every year to security breaches. Biological evolution only works because biology has found strategies to stay alive in an uncertain and unpredictable world.

Norbert: So security is your field of focus?

Rick: It is just one of a few areas of specific focus, which all fit with a more general focus on adaptable systems engineering. Twenty-five years ago I was Co-Principal Investigator on a project that identified agile enterprise and agile systems as a necessary capability to cope with increasing uncertainty and unpredictability in system operational environments. This has been my mission ever since. I carry this out by discovering and exploring what enables systems to be highly adaptable. Early on this work looked at man-made systems, and produced a book in 2001 that exposed fundamental agile-system principles with application examples and reference models. These systems are in a class I call *reconfigurable systems* that can be adapted to changing requirements, a subject I teach at Stevens Institute of Technology in the Systems Engineering graduate department. In 2005 I started looking at systems I class as *reconfiguring systems*, ones that have self-organizing systemic capabilities. My work in this area led to natural systems for inspiration and the development of a second graduate course that explores a wide variety of different natural system types, looking for common underlying principles and patterns. Parallels can easily be drawn to the natural systems security area. Organisms deal with food and security first in order to live another day. Similarly, the security space is contending with a self-organizing community of agile attackers and is in desperate need of defense strategies with at least equal agility.

Norbert: First tell me more about those intriguing security patterns that were biomimetically inspired.

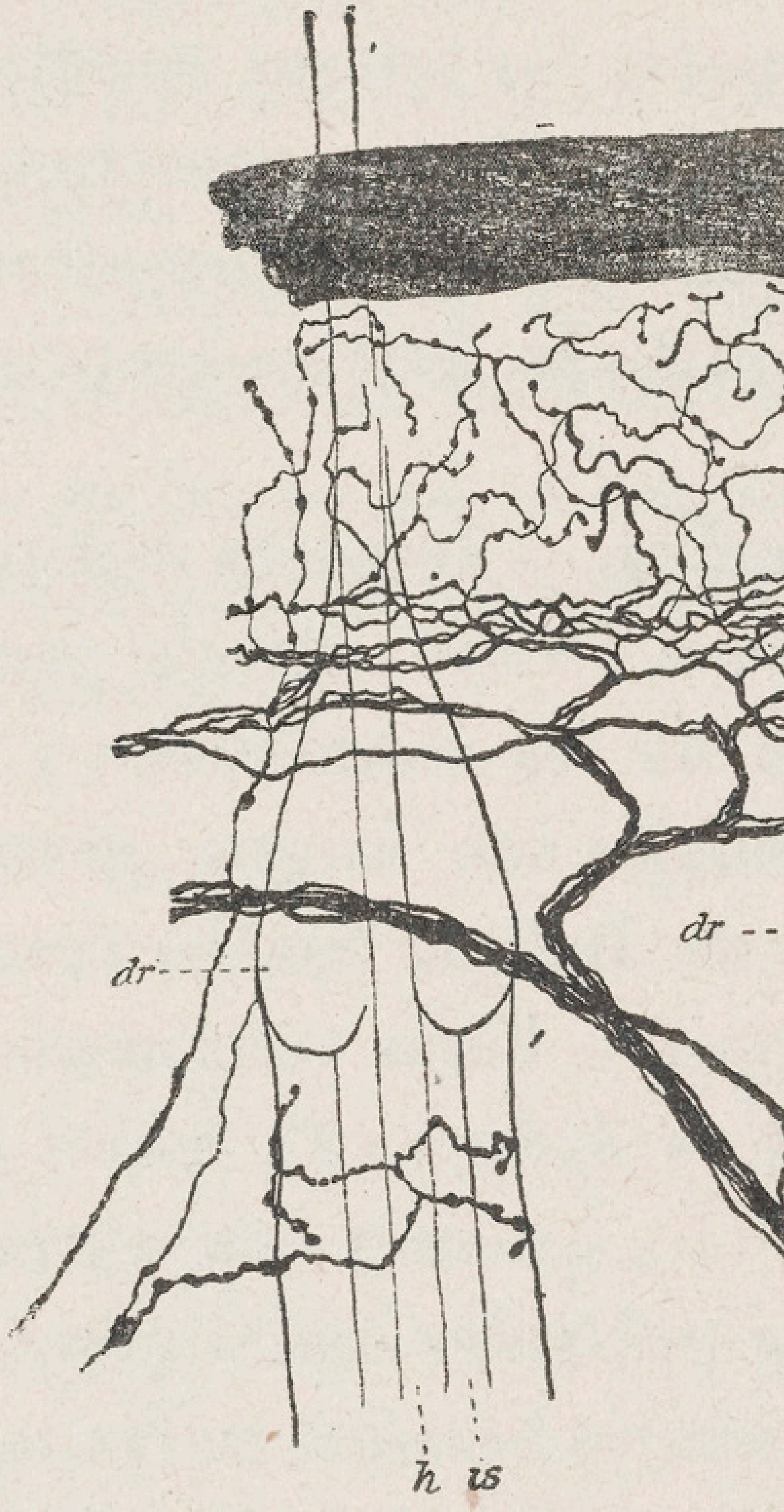
Rick: As you saw in the INCOSE presentation, we've learned and applied a very useful mechanism modeled on the adaptable immune system. Groundbreaking early work by Stephanie Forrest at the University of New Mexico and the Santa Fe Institute pioneered immune system models for security. But translating that work with high fidelity was elusive using current technology and techniques. The immune system fields about 10^9 different antibody detectors to cover the entire possible pattern space of biological invaders. It generates random detector possibilities over about a two-month continuous cycle. In cyber-security the number of possible invader patterns gets a whole lot larger, well beyond traditional computer technology's ability to detect never-seen-before invader patterns. With a new approach that is inexpensive enough to protect every individual node in a network, we showed how a space of 10^{15} patterns could be covered continuously at full data stream speed in a very small amount of pattern storage. 10^{15} patterns is not a limit, just what we chose for a proof-of-concept prototype. We mimicked and improved upon a high-fidelity model of immune system invader detection.

Norbert: In your presentation you also showed a learning and sense-making mechanism modeled on the brain.

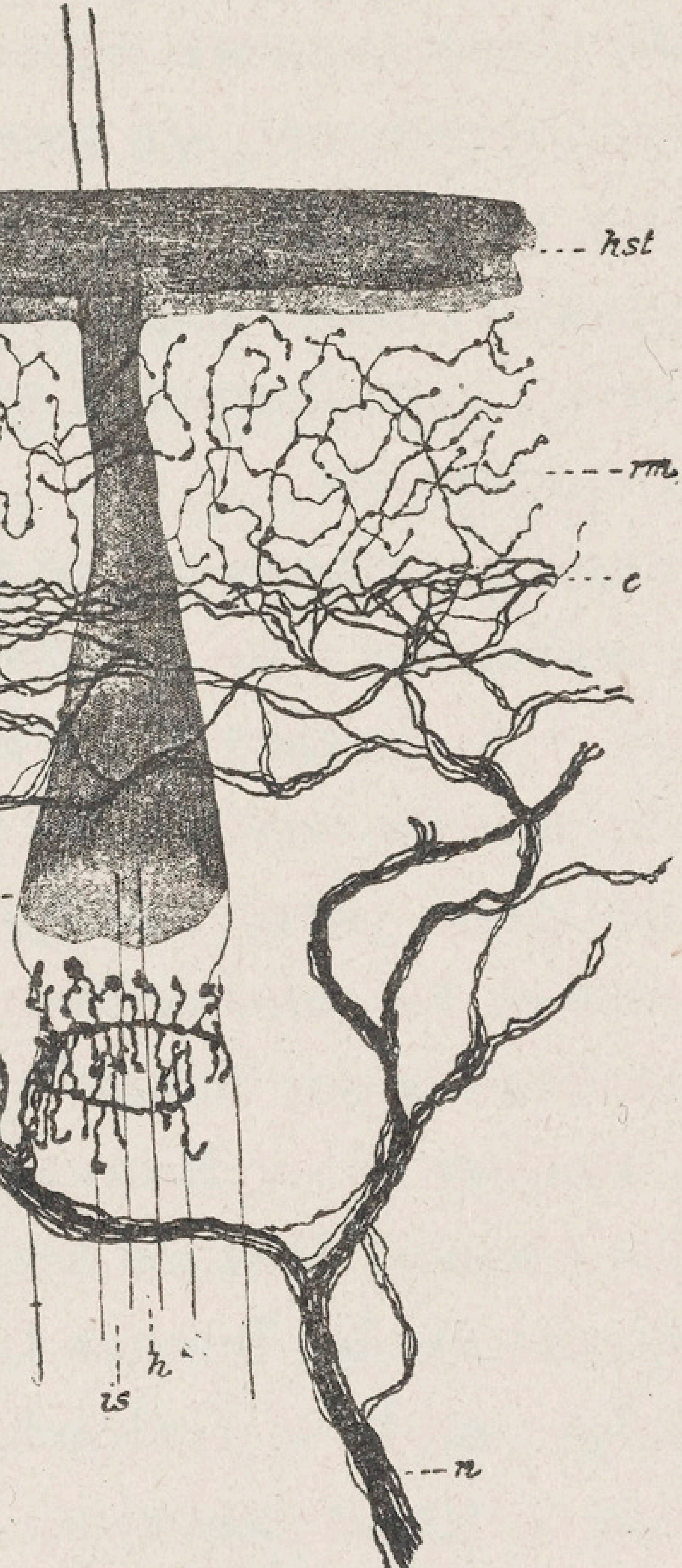
Rick: This is my favorite, as it employs only simple pattern recognition capability for learning, recognition and sense-making. And, it has application in many areas, not just security. I use the visual cortex and auditory cortex to explain the process, but the entire brain cortex works the same. The cortex has a hierarchical pattern architecture that chunks patterns at one level into primitives at the next level. The visual cortex, for instance, recognizes objects at the fourth level in about 100 milliseconds. It knows there is a face in the field of view. It doesn't know at level 4 whose face or what emotions are expressed - that happens at higher levels. The first level has about 100 pattern detectors, looking for edges represented essentially by multiple pixels that come in from the retina. The edge detectors recognize edges that are of different lengths, different angles, and black over white or white over black. An edge detector that matches the pixel stream chunks it into a single primitive for level 2. Level 2 looks for combinations of edges in spatial proximity. Again it seems that about 100 combinations are all that is recognized. Level 3 again does the same, but looking for combinations of combinations. The literature has some indication that again the number of pattern detectors at this level is about 100. At level 4 that same chunking process identifies general objects in what is known as "immediate recognition". I suspect the limit of 100 detectors evolved from biological optimization of energy propagation, speed of signal travel, and physical neuron-connection space. This resource-conserving simple architecture indicated that something less than a supercomputer might be able to accomplish something similar.

To switch metaphors, think about learning your native language as a child by listening to noises made by people. Conceptually, the same cortical architecture is employed. Level 1 learns repetitive sounds: phonemes. Level 2 learns repetitive combinations of phonemes as words. Level 3 learns repetitive combinations of words as phrase grammar. Level 4 learns repetitive combinations of phrases as sentence grammar.

We built a software feasibility prototype that sat in front of a network server and listened to the incoming data stream conversation, eventually learning to distinguish between normal server conversation and words, grammar and sentences not heard before. It is always in learning mode, but doesn't sound an alarm until it crosses a threshold of sufficient learning to understand reasonable conversation, and suddenly hears something new. At that point it asks for a human decision to classify this newness as benign, suspicious, or known bad. We achieved zero false positives and zero false negatives si-



Rat nerve endings | Drawing: Santiago Ramon y Cajal, 1899 | Wellcome Library, London | Wikimedia Commons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multaneously for an SQL server. We wanted to do this using industrial control system devices, where the conversations are more regular and the threat to national critical infrastructure is more pressing, but we didn't have ready access to those data streams, and the SQL server satisfied our need to prove the general approach.

A prime goal of this work was to accomplish learning somewhat like a natural neural net, without resorting to the computational math intensity typical of artificial neural nets. Backpropagation, for instance, is a respected artificial neural net learning algorithm for convergent discovery of the optimal parameters in a complex mathematical model of the network – a trial and error method that knows what the network output should be for a given input and feeds back the error magnitude for adjusting all of the equation's parameters for the next trial and error cycle. This algorithm effectively converges on optimal parameter values. There is no evidence that the brain does this, yet the brain continues to be the benchmark for pattern recognition.

Norbert: You made a big point out of horizontal gene transfer as an inspiration.

Rick: This is seminal work by Carl Woese. He showed that genes are transferred among species and even among plants and animals. In a real sense that's what we are doing with biomimicry – taking patterns we see in biology and employing them in other domains. Woese suggests that the real innovation that has occurred in the evolution of the species is principally from this horizontal evolution mechanism, and not from Darwinian vertical evolution that refines an existing theme. Fortunately for us these trans-species genes are rarely expressed, but lie dormant in our DNA. Expression in general occurs when an organism is under very high survival stress that apparently triggers gene-expression experimentation. If you think about it, we see this process reflected in Clayton Christiansen's book, *The Innovator's Dilemma*, where a functioning corporation suppresses radical ideas viewed as threatening to the organizational system that is already in place. Most real innovation we witness occurs from combining ideas employed in other domains to solve a problem in a specific domain in a very new way, a concept I call horizontal meme transfer. I also see this as the core of collaborative group diversity values. Diversity of collaborative thought and knowledge leads to new and relevant understandings that are unlikely to emerge from a single specialized mind blinded by what it already knows.

Norbert: What are you working on right now?

Rick: I'm trying to discover what's behind the art of embraceable system design – fundamental design thinking and method that make system acceptance and usage embraceable, rather than enforceable. Why do a few designers repeatedly get acclaim and following for the systems they design? The ones we are interested in are recognized for repeatedly designing works that are broadly embraced. I principally examine artists that span many domains because the effectiveness of their work requires that their work be embraced, and that their diverse users declare the artist's success by broad voluntary usage and acclaimed appreciation. Here again, I am looking outside the engineering community for the patterns of interest, attempting to find common threads that cause embraceable user acceptance and joy in usage. What made Frank Lloyd Wright's work stand out? What did he think about and bring to bear in his approach to design? The principles we want to find will be universal, and I suspect will have a lot to do with deep user empathy, a systems-thinking understanding of the usage environment, and synergy among all the parts of a simple but complex system. This discovery project will be done in a series of collaborative workshops this fall.

I'm also working on principles for meaningful innovative group work among volunteers. I chair the INCOSE working groups for Agile Systems and Systems Engineering and also Systems Security Engineering. All members are volunteers that have demanding day jobs scattered around the world. Keeping them motivated, inspired, and supported to produce effective project outcomes to schedule has been a challenge across INCOSE's 60 some working groups. For me this is a mission, currently being tested in my working groups and already demonstrating good results.

I'm passionately involved with a number of other projects as well, which appear to some as unrelated. I've found a way to understand them all as synergistic. For me the key is a focus on underlying systemic principles that beg application in diverse domains.

Norbert: What is your favorite inter-disciplinary work of all time?

Rick: There are three I consider favorites.

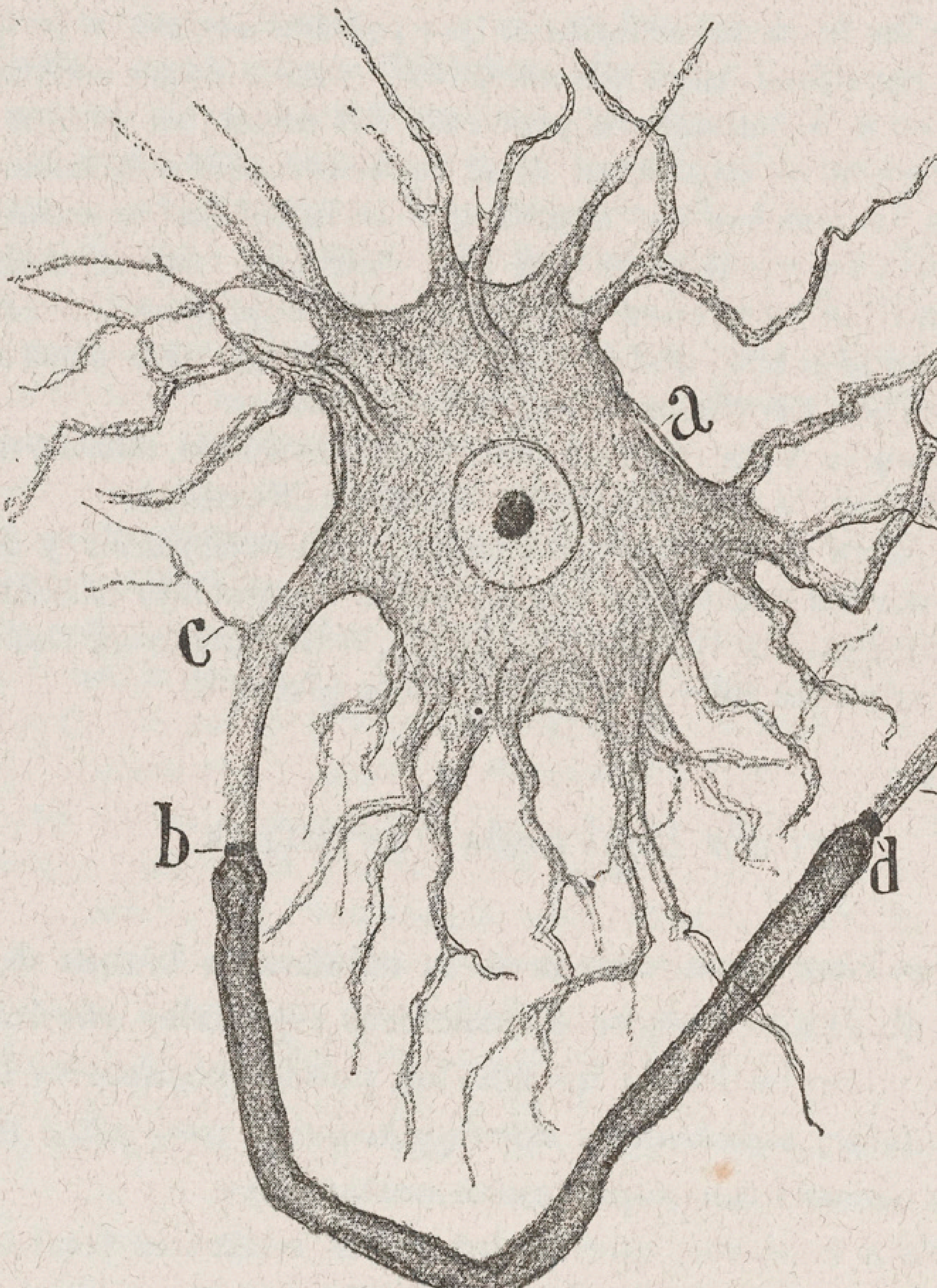
Dan Dennett, the philosopher, wrote a 1,000 page book on natural selection called *Darwin's Dangerous Idea*. I couldn't imagine how he'd keep me engrossed beyond a few chapters. What's awesome is how ubiquitous and powerful this algorithm is in driving the evolution of everything: ideas, technology, society, and of course organisms. Natural selection is a relentless algorithm with absolutely no objective, but very deep implications. The environment kills off what is less effective under continuous experimentation.

The book *Rethinking Innateness* (Elman, et al.) is masterfully written, surprisingly readable, and absolutely fascinating. It is about the architecture of the brain, which is born with virtually no content, but is organized for compulsive learning from its environment. I believe the only content at birth relates to the general features that indicate a face is present in the field of view, and it appears that the recognition of snakes is also innate.

Carlson, Doyle, and Csete have written a number of papers on complex biological systems, and show fundamental patterns that are mirrored in so many other domains that they could be universal natural laws of systems. They make the point that underneath all that seeming complexity in cellular biology are very simply system patterns that appear repeatedly in most complex systems of any kind. I highly recommend a look at what they call the Bow Tie pattern, for its simple elegance and broad application.

Norbert: What work have you seen recently that really excited you?

Rick: I just spent a full day looking through conference videos about Google's Advanced Tech-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nology and Products (ATAP) group. I'm blown away with the purposeful system design behind what and how ATAP, as an innovation machine, does what it does. It fits with all I've been working on and much of what we've talked about here. They designed a complex system with simple fundamentals that leverages truly remarkable resources organized in a Bow Tie pattern. ATAP functions as the Bow Tie knot, designing and providing a development infrastructure that enables a vast number of developers to service a vast number of technology application opportunities in what I consider to be a classic agile-system design.

Norbert: Who do you admire?

Rick: Carl Woese, because he was vilified for many years, but persevered and won out with major new and now accepted understandings; Frank Lloyd Wright, for the way he integrates system design with the environment and the humanism of his users; Christopher Alexander, because he looks for timeless truth; and Bill Gates and Warren Buffet, because they apply their time and resources to big problems that can make a large difference in the world. I could name some more, but that's enough.

Norbert: What's your favorite motto or quotation?

Rick: I expect our favorite quotations are pithy very-personal statements that articulate what we already believe. Nolan Bushnell, the founder of Atari, a long time ago in the San Francisco Chronicle was quoted as saying "Ideas are shit, implementation is everything. Anybody in the shower for more than ten minutes gets more ideas than can be implemented in a lifetime." I find frequent reason to inform people of this. Also William Gibson, for his oft quoted "The future is already here, it's just not evenly distributed." This thought drives my search for horizontal meme transfer opportunities.

Norbert: What is your idea of perfect happiness?

Rick: Pursuing a mission with passion.

Norbert: If not being who you are, who/what would you be?

Rick: In third grade when asked what I wanted to be when I grew up, I said from the heart, a wise man. That felt so much better than becoming a policeman or a train engineer. But I haven't grown up yet, so there's still time. A while back I started writing a book called *On Purpose*, with double entendre intended. I got far enough to know I'll not finish it. There's too many other things to do. ×

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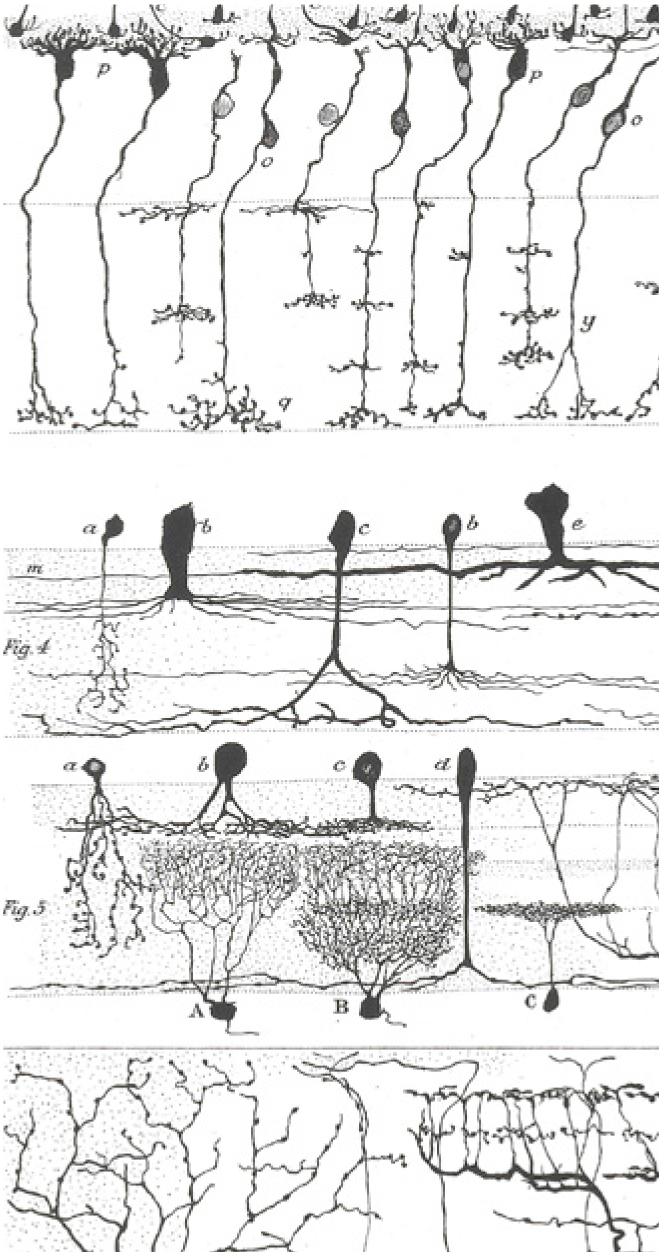
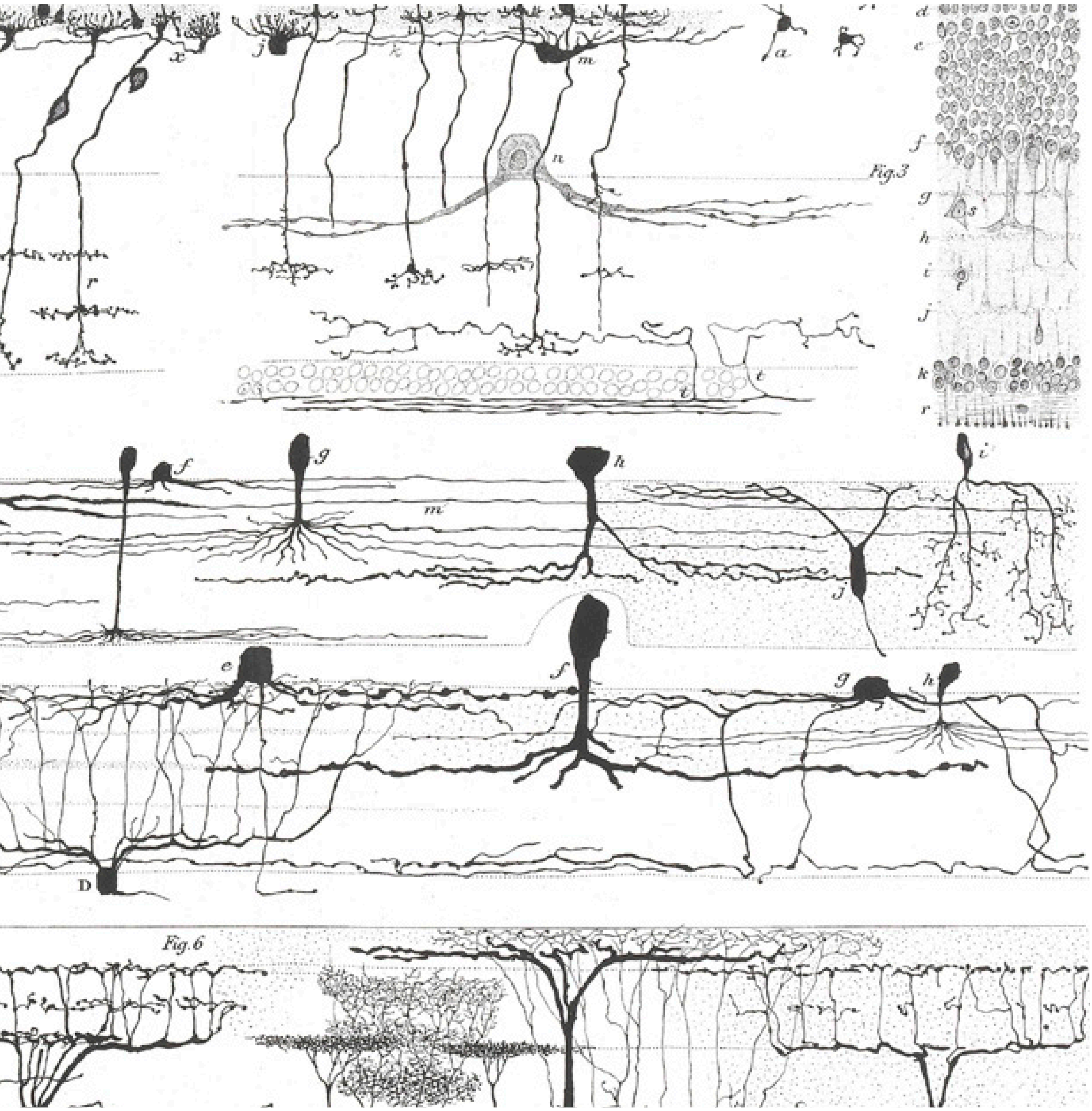




Line drawing of the retina (detail)

Drawing: Santiago Ramon y Cajal, 1899 | Wellcome Library, London | Wikimedia Commons

Sticky

Photo: J. Paxon Reyes, 2012 | Flickr cc

Interview

Jeffrey M. Karp

vol 2 | 2015

People:
Interview

Author:
Jeffrey M. Karp

Dr. Jeff Karp is an Associate Professor at Brigham and Women's Hospital, Harvard Medical School, and is Principal Faculty at the Harvard Stem Cell Institute and affiliate faculty at MIT through the Harvard-MIT Division of Health Sciences and Technology. His research harnesses materials science and stem cell biology to solve medical problems with emphasis on nanoscale/microscale materials and bio-inspired approaches. He has published more than 100 peer-reviewed papers and book chapters and has given over 160 national and international invited lectures and has 50 issued or pending patents. Several technologies that Dr. Karp has developed have formed the foundation for multiple products on the market and currently under development and for the launch of two companies, Gecko Biomedical and Skintifique. Dr. Karp's work has been recognized by CNN, NPR Science Fridays, Boston Globe, ABC News, MSNBC, Fox News, CBC Quirks and Quarks, CanadaAM, BBC, LA Times, Forbes, National Geographic, Popular Science, the Washington Post, the New York Post, and by Wired Magazine. In 2011 the Boston Business Journal recognized Dr. Karp as a Champion in Healthcare Innovation and in 2013 the Institute for Chemical Engineers (IChemE) awarded one of his technologies at the Most Innovative Product of the Year. In 2008 MIT's *Technology Review Magazine* (TR35) also recognized Dr. Karp as being one of the top innovators in the world under the age of 35 (3 members from his laboratory have already received this award). He has received the Society for Biomaterials Young Investigator Award and his work has been selected as one of *Popular Mechanic's* "Top 20 New Biotech Breakthroughs that Will Change Medicine". Dr. Karp was also elected in 2013 to the American Institute for Medical and Biological Engineering's College of Fellows and as a Kavli Fellow. In 2014 he gave a TEDMED talk on bioinspired medical innovation and in 2015 became a member of the TEDMED Editorial Advisory Board to help curate the stage program's themes, topics, speakers and performers. Dr. Karp is also an acclaimed mentor. He was selected as the Outstanding Faculty Undergraduate Mentor among all Faculty at MIT and received the HST McMahon Mentoring award for being the top mentor among all faculty who mentor Harvard-MIT students. To date, 17 trainees from his laboratory have secured faculty positions at institutions throughout the world.

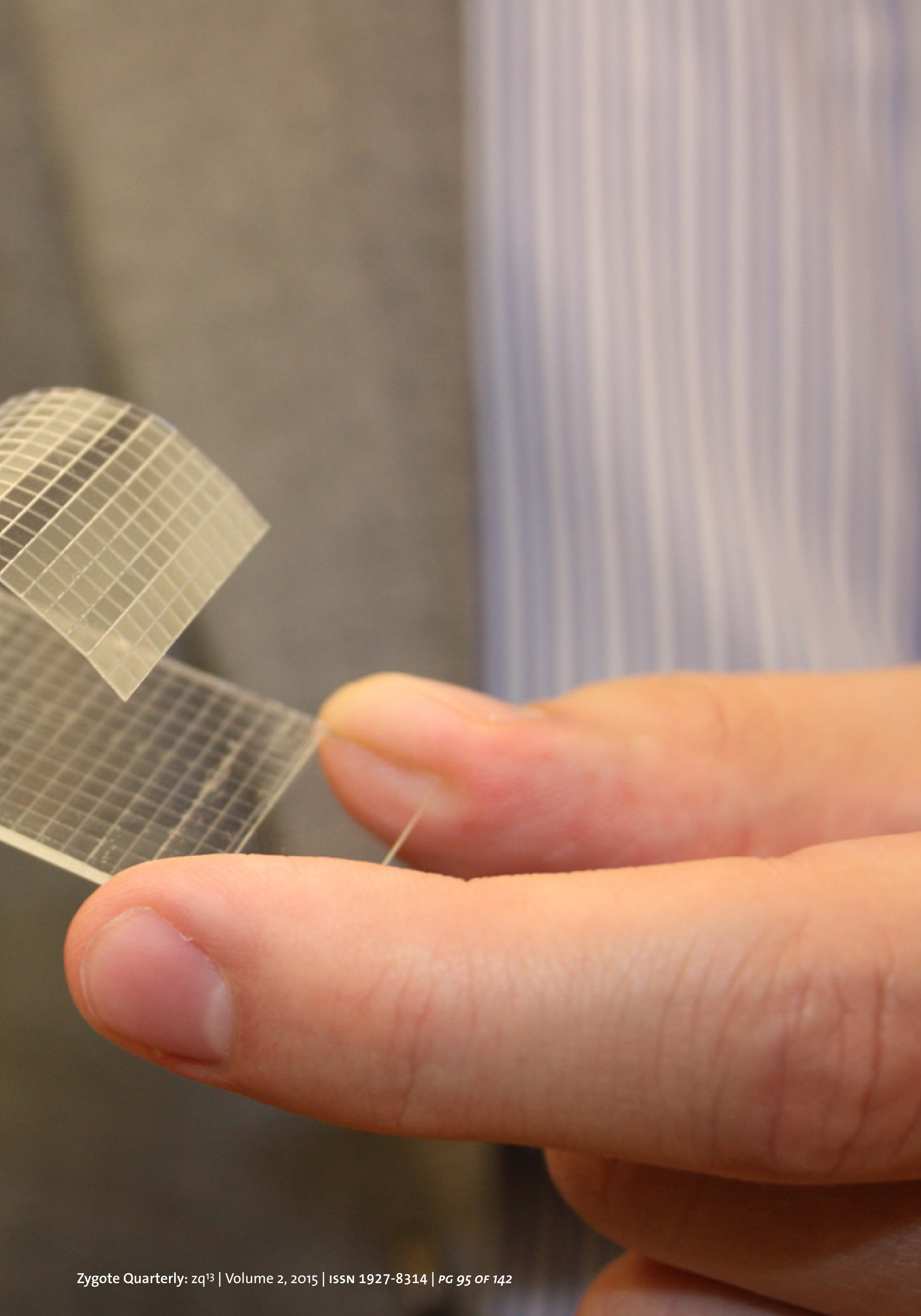
Jeffrey Karp

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

There are many niche groups working in the space, but they represent only the tip of the iceberg of possibilities, in my opinion.

The Business End of a Porcupine | Photo: Mark Dumont, 2015 | Flickr cc

Quick Release Medical Tape | Photo courtesy of Jeffrey Karp



What do you see as the biggest challenges?

As practitioners, we are limited by the tools that we have to uncover mechanisms in nature and by our passion to do so.

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

Knocking solutions out of the park, one by one. It would also be good to have a database for problem solvers to easily navigate nature's solutions.

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

I had read an article sitting on a colleague's desk when I was a postdoc at MIT. I was intrigued by this article in *Nature Nanomaterials* about the use of gecko-inspired adhesion (http://www.nature.com/nmat/journal/v2/n7/fig_tab/nmat917_F4.html).

I speak a little bit more about this in my 2014 TEDMED talk (https://www.youtube.com/watch?v=AshPR7OsZA0).

What is your best definition of what we do?

That is a good question. I will have to think about that.

By what criteria should we judge the work?

I believe that there are two most important questions we should be asking: "Are we doing rigorous science?" "Are we helping people?"

What are you working on right now?

We have dozens of researchers working at our lab in lots of areas from better targeting of mesenchymal cells, to a glue for repairing tissue to a "quantum coat" for button batteries that makes them more child safe (See previous *ZQ* issue #12, "Sticky Wicket: A Search for an Optimal Adhesive for Surgery").

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

There are so many things of all kinds that have interested me. A few from my twitter feed will give you an idea:https://twitter.com/MrJeffKarp. Here I pass on a lot of news about biotechnology, business, biomimicry, and, of course, important news about Canada!

One example is the use of bacteria as a diagnostic for early detection of colon and pancreatic cancer that metastasize in the liver. Using an orally administered probiotic, like found in yogurt, that has been bioengineered for luminescence, researchers have developed a telltale sign that shows the presence of cancer in the liver before spreading. Liver is a tissue that can regenerate itself, so it is a much better place to remove the cancer.

What is your favorite biomimetic work of all time?

I am not sure that I have one.

What is the last book you enjoyed?

I don't read much.

Who do you admire? Why...

People who are passionate.

What's your favorite motto or quotation?

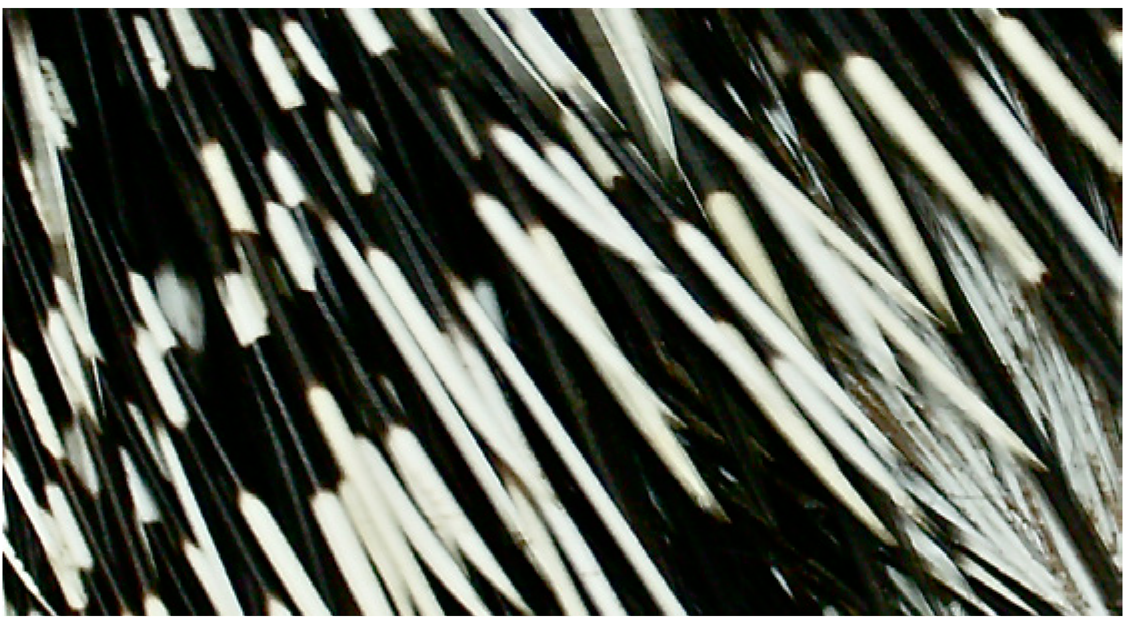
Paraphrased from *Walden*, by Henry David Thoreau: "Go confidently in the direction of your dreams, live the life you have imagined".

What is your idea of perfect happiness?

Loving yourself and then doing things that you are passionate about...then you become the spark to inspire others to do the same.

If not a scientist/designer/educator, who/what would you be?

A farmer. ×



Porcupine

Photo: kookookachoo047, 2011 | Flickr cc

Hammarby Sjöstad Miniature

Photo: Joopey, 2006 | Wikimedia Commons

Urban Ecology
Interview with
Björn Cederquist for Hammarby Sjöstad

Authors:
Björn Cederquist and Tanya Lynne Sakamoto

Large urban areas are unlikely sources of bio-inspiration, but increasingly city planners are using an ecosystem approach to community and infrastructure design. Stockholm, Sweden, was the first city named as a European Green Capital by the EU Commission in 2010[1]. The Hammarby Sjöstad development is a large (1.6 km² land area) inner-city conversion of a rundown industrial area to a modern and environmentally conscious urban community. Now in its later phases of development, the vibrant community is home to some 20,000 people[2,3]. Central to the development is an integrated vision of how energy, water and waste are cycled; a symbiotic eco-cycle termed the Hammarby Model (https://hammarbysjostad20.se/background/?lang=en). The City of Stockholm set an ambitious environmental goal for Hammarby Sjöstad: reduce environmental impact by half compared to the rest of the city[4]. The community produces 50% of its heat and electricity requirements, primarily through reclaimed heat from treated wastewater and energy from combustion of wastes[2]. Innovative green technologies abound in the community, including green roofs, solar thermal and photovoltaic installations, centralized vacuum waste collection, and sustainable building materials. Hammarby Sjöstad is designed to operate as a system, with connected greenspaces, extensive transit linkages and opportunities to live, work and play within the community. The lessons learned in the development of Hammarby Sjöstad, including its integrated planning approach and eco-cycle, are being applied to other urban planning projects in the city.

Björn Cederquist is head of communication for the Hammarby Sjöstad project, and an architect with the City of Stockholm.

What are your impressions of the current state of biomimetics/bio-inspired design for urban systems?

To me this was a new field. Ecology in lifestyle and design/construction has long interested me, but transformed to the scale of city planning it seems mind-shifting.

How are/were you involved in the project?

I have been involved in the project lead since 1996. My work has focused on social planning for the community, including schools, kindergarten, elderly care, health care, retail, library, church and other services. A vibrant community is important, so I have also been working to increase the diversity of residents, businesses and services.

Hammarby Sjöstad: Plaza with water feature | Photo: Design for Health, 2006 | Flickr cc

Hammarby Sjöstad | Photo: JohanFredriksson, 2014 | Wikimedia Commons

Sustainable housing, Hammarby | Photo: La Citta Vita, 2010 | Flickr cc


park inn

Who else is/was involved in the project, and how?

An integrated planning process has been key to the success of the Hammarby Sjöstad project, involving urban housing and landscape planners, ecological experts, real estate developers and building engineers. At an early stage a residents' association was formed spontaneously and has since grown to be the base for really strong local initiatives in energy saving, social sustainability, and traffic management.

What were the key components of an ecosystem that the project incorporated into its design?

Water, Energy (heat and electricity), Waste and Transports and green planning.

The Hammarby eco-cycle was part of our integrated planning approach to consider the interconnected material and energy flows of the community, including water, energy and waste. Many of these flows are part of a larger system for all of Stockholm where waste water and solid waste produce biogas, heat and fertilizers. Heat is produced in a few large combined heat and power plants and distributed by district heating which has radically reduced the emissions in the city. Locally the storm water is treated and the waste is collected automatically by vacuum. Transportation planning has also been a key part of both reducing the environmental impact of private cars and connecting the community to the rest of Stockholm. Transit and ferry linkages, combined with a carpool system and bicycle routes have reduced the need for private cars. Attempts have been made to start Home2you delivery needs to the homes. It failed but home delivery has expanded in other forms. During construction a local delivery store was set up for building materials to create just in time deliveries with environmental friendly trucks to the sites.

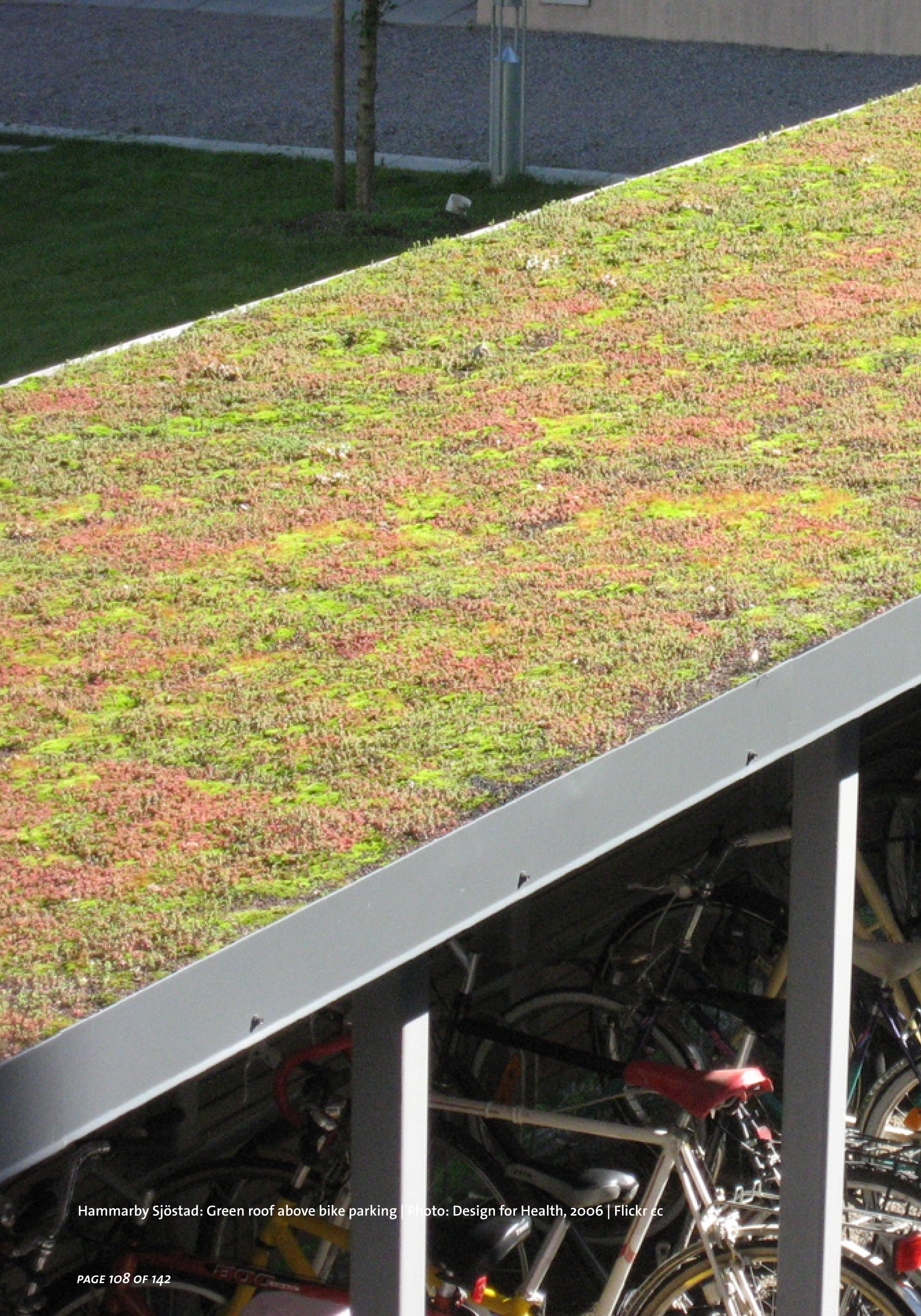
Were there any modifications made to the original plan for the development – did it evolve as you started building, and has it changed since then?

Very few changes have been necessary, but there have been some infrastructure issues that we have had to work around. Office buildings had to be relocated to shelter residential blocks from air pollution from roads or factories. A large tunnel project to reduce noise from traffic has not been completed due to unsolved financing. This might result in fewer apartments in that area.

What surprises were there during the course of the project?

Cleaning the soil was extremely complicated. The development is situated on a former industrial site and the soil required extensive decontamination and monitoring before construction could begin. Preparing the land and stabilizing the houses and other buildings during construction were challenges. In some parts piles up to 25 meters were drilled into the ground to reach rock.

Hammarby Sjöstad: Green roof detail | Photo: Design for Health, 2006 | Flickr cc



Hammarby Sjöstad: Green roof above bike parking | Photo: Design for Health, 2006 | Flickr cc


Boardwalk | Photo: La Citta Vita, 2010 | Flickr cc

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Urban Ecology:
Interview

Authors:
Björn Cederquist and Tanya Lynne Sakamoto

What are you working on right now?

Construction is still underway with completion of the residential buildings identified in the Hammarby Sjöstad master plan, and large commercial buildings. Transportation infrastructure is being improved, with construction of a large bus terminal for inner-city buses and connecting the light railway through the district.

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

Energy passive houses.

What is the last book you enjoyed?

Jadekatten, an autobiography by Danish author Susanne Brögger, and the poetry of Thomas Tranströmer.

What's your favorite motto or quotation?

The times are a-changing.

If you could choose another profession or role, who or what would you be?

I would be a musician or painter. ×

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Sickla Kaj station/stop in Hammarby Sjöstad is used by both buses and light rail | Photo: La Citta Vita, 2010 | Flickr cc

Morpho butterfly

Photo: daniele paccaloni, 2010 | Flickr cc

Infographic

Requiem for a Butterfly

Raul de Villafranca and Colin McDonald

vol 2 | 2015

Infographic
Requiem for a Butterfly

Authors:
Raul de Villafranca and Colin McDonald

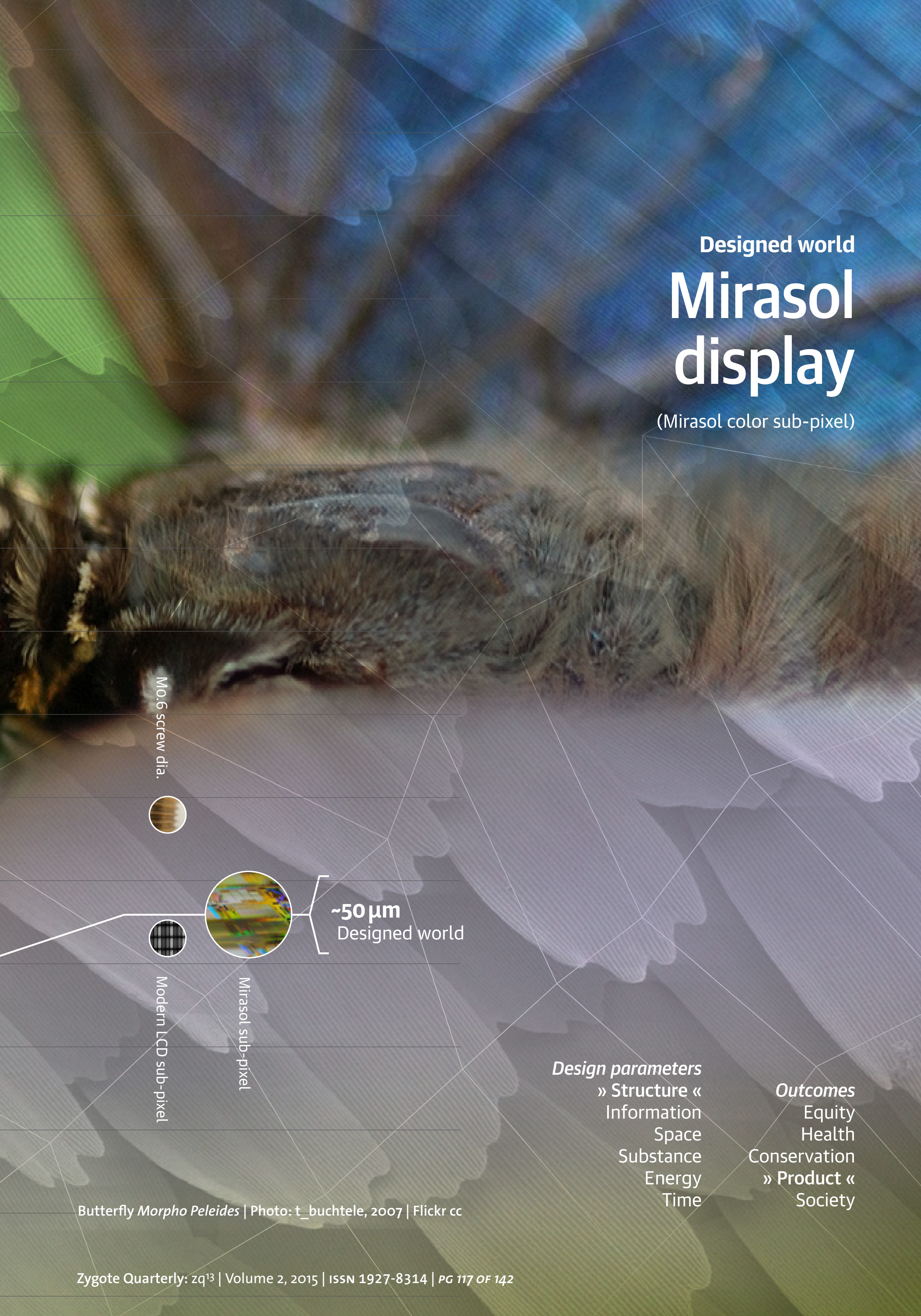
Natural world

Common Morpho

(*Morpho peleides*)

Kingdom
Monera
Fungi
Protista
Plantae
» Animalia «

Natural phenomena
Process
» Form «
System



Designed world

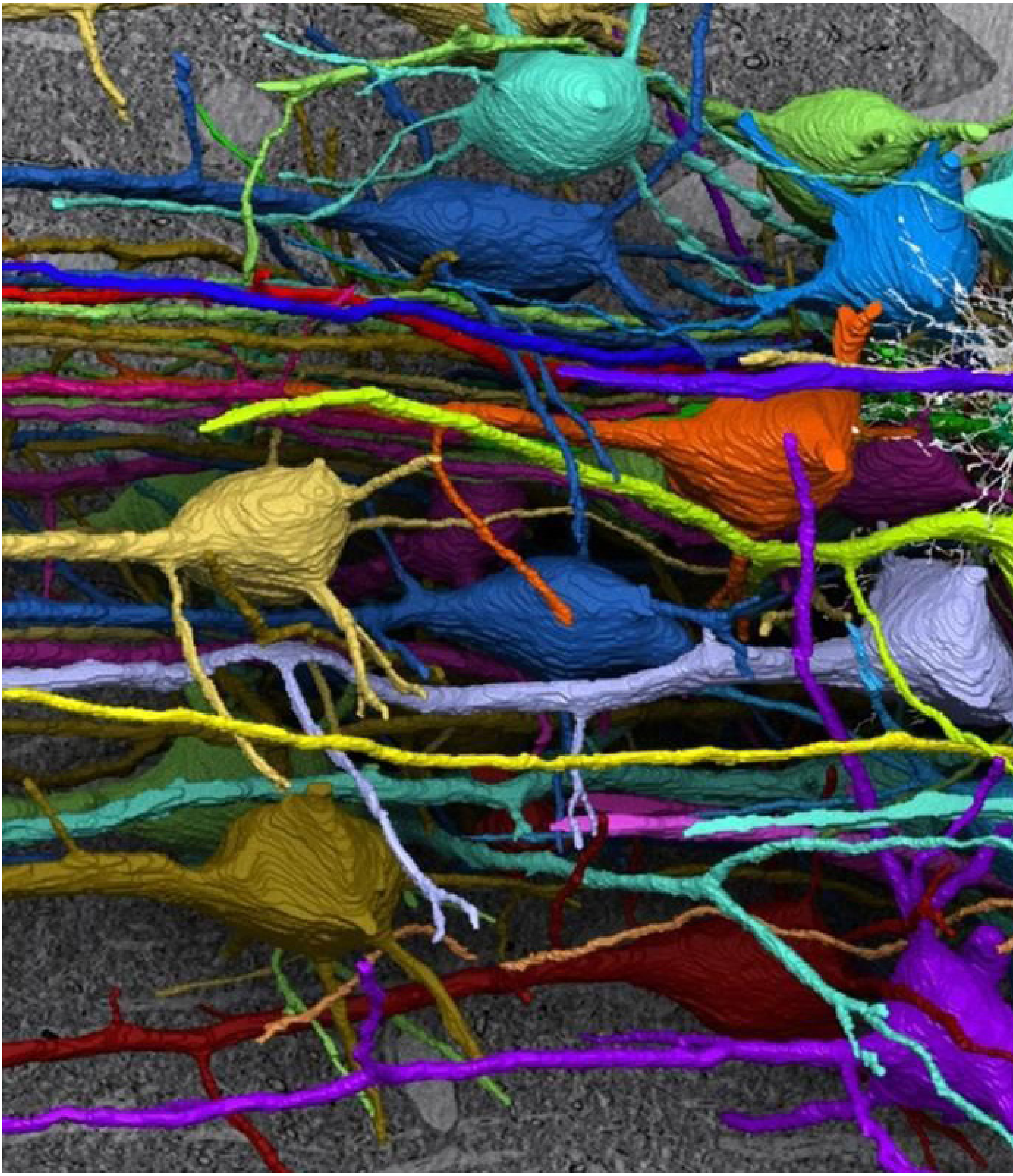
Mirasol display

(Mirasol color sub-pixel)

Design parameters
» Structure «
Information
Space
Substance
Energy
Time

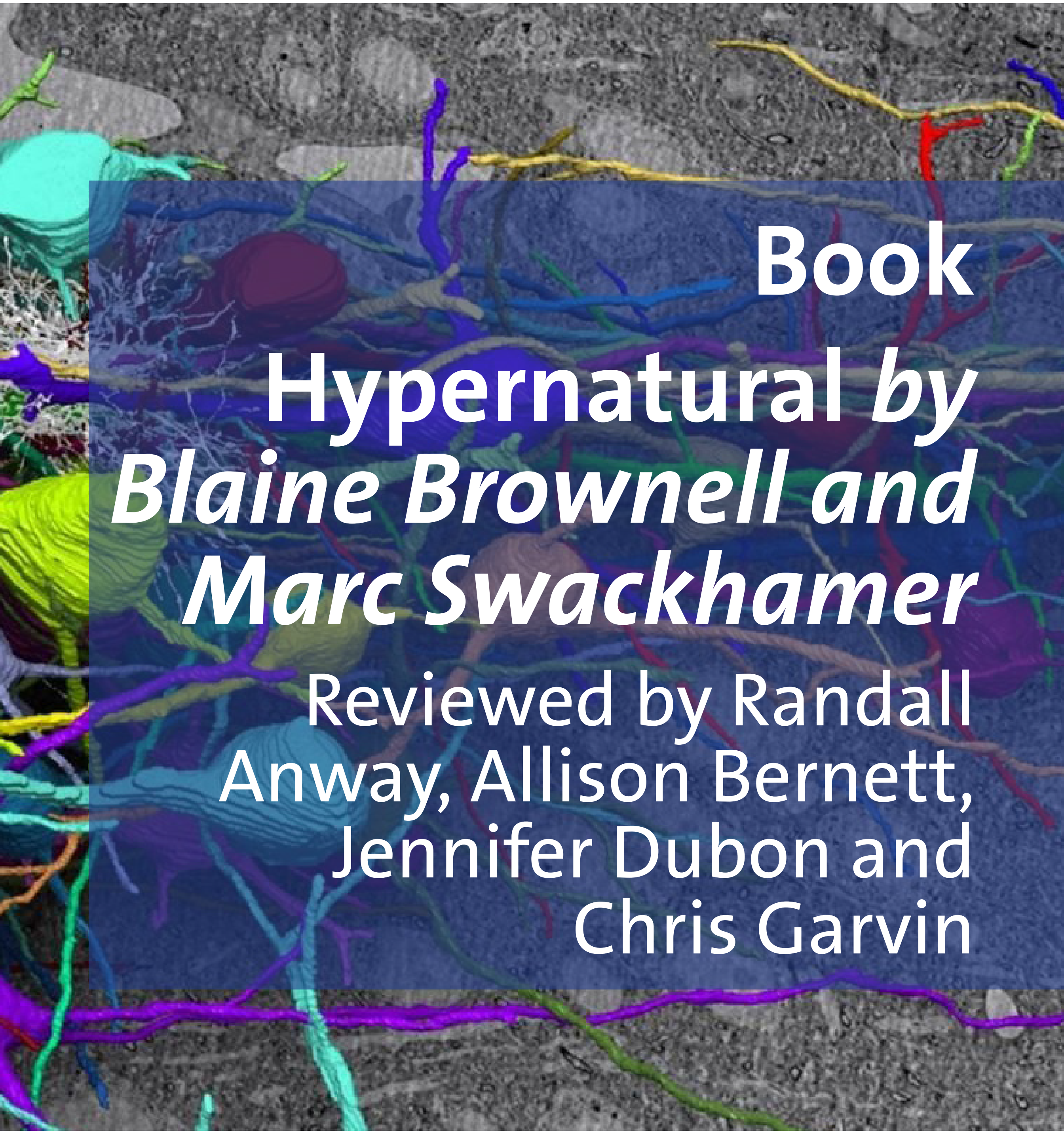
Outcomes
Equity
Health
Conservation
» Product «
Society

Butterfly *Morpho Peleides* | Photo: t_buchtele, 2007 | Flickr cc



3D reconstruction of neurons

Photo: ZEISS Microscopy, 2014 | Flickr cc



Book

Hypernatural *by Blaine Brownell and Marc Swackhamer*

Reviewed by Randall Anway, Allison Bernett, Jennifer Dubon and Chris Garvin

vol 2 | 2015

Book:
Hypernatural by Blaine Brownell and Marc Swackhamer

Reviewers:
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Hypernatural: Architecture's New Relationship with Nature by Blaine Brownell and Marc Swackhamer

Authors' Intent

Hypernatural undertakes the ambitious goal of articulating the changing relationship between architecture and the natural world as aided by technology. Intended to engage a wide audience of architects, engineers, artists and environmental enthusiasts, *Hypernatural* attempts to establish "an inclusive and coherent framework" (p. 25) that enables nature-related movements within design (such as biomimicry, biophilia and sustainable design) to be more fully understood. Brownell and Swackhamer particularly wish for the book to demonstrate the "positive capacity of technology" (p. 18) and the "transformative potential of design" (p. 25) to enable changes beneficial to humans and the planet.

For the most part, the authors use "hypernatural" as a broad term for constructed technology that integrates with the natural world, with a particular focus on how it impacts architecture. The authors begin by discussing how humanity is part of the natural world, rather than separate from it. The authors emphasize the shifting perspective in various fields from viewing nature as separate from culture to nature as coevolving with culture. As a result of this perspective, the authors encourage designers to allow natural processes to influence how their projects evolve.

Hypernatural aspires to leave readers with new insights into the integration of architecture and technology with nature, as well as to prompt them to explore this intersection in their future design work.

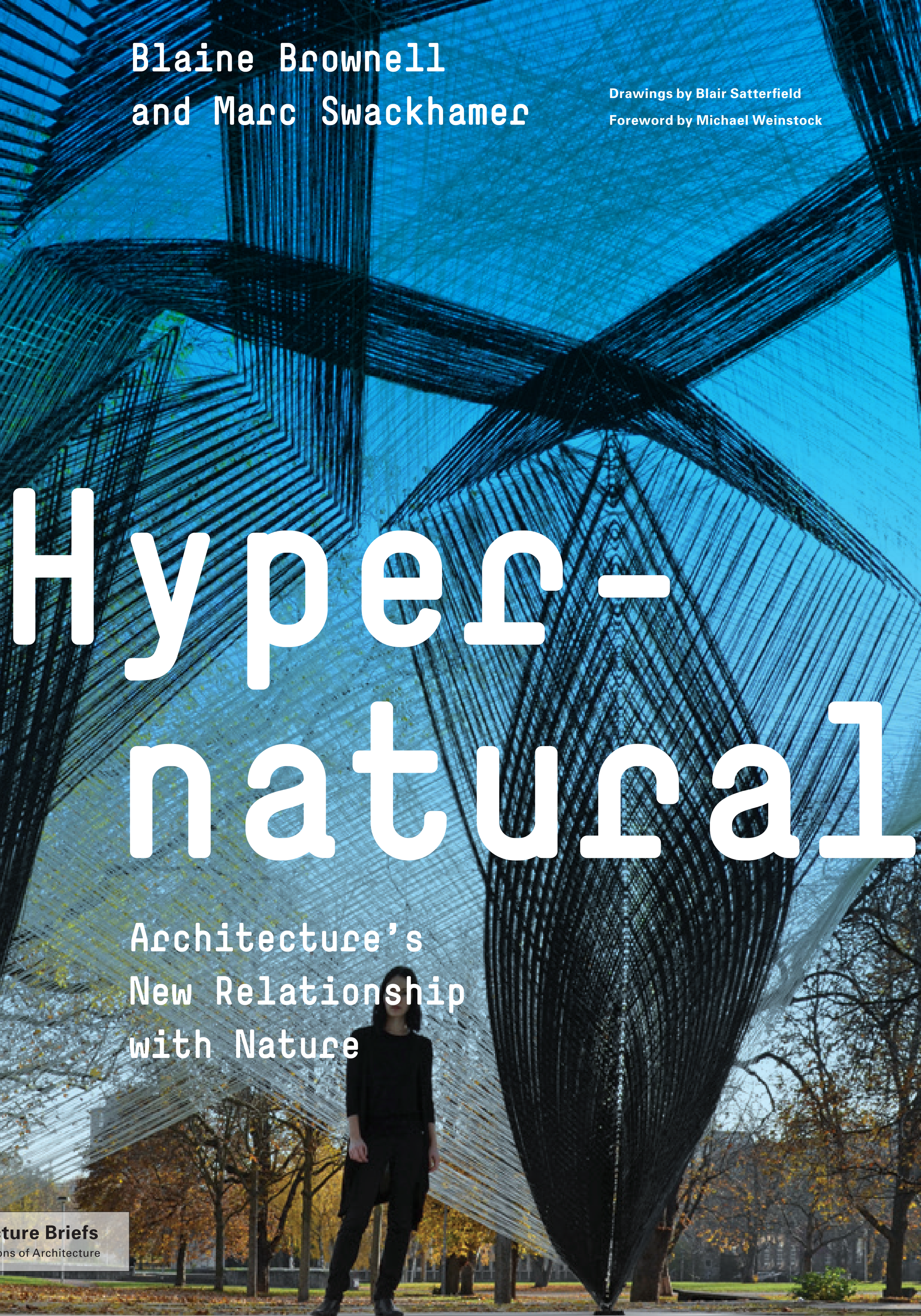
Structure of Book

The primary objectives of the book are "coherence, context, and application" (p. 25) which is supported by the book's repeating structure across seven 'spheres' of reference.

1. Each chapter begins with a detailed introduction of a novel project that captures the essence of the sphere of focus. The project is highlighted as a major case study with two pages of conceptual drawings that include a description of process, functionality and/or unique features.

2. *Background* includes a discussion on ancient practices and offers a pithy historical review with a focus on resource allocation and its relationship to architecture.

3. *Material Basis and Behaviours* touches on natural processes as well as science, engineering and architecture advancements or



Blaine Brownell
and Marc Swackhamer

Drawings by Blair Satterfield
Foreword by Michael Weinstock

Hyper-natural

Architecture's New Relationship with Nature

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Echoviren | Smith/Allen Studio | Photo courtesy of Princeton Architectural Press

technologies derived from the particular sphere's characteristics, properties, and behaviors with many real world examples.

4. *Application* refers to the ways in which the sphere of interest has been applied in recent architectural projects and installations

5. *Cases* at the end of each chapter contains a series of five minor case studies of architectural projects and art installations particular to the sphere of influence. These works aim to "demonstrate the transformative potential of design revealing its capacity to engage natural principles, systems, and phenomena in innovative ways" (p. 25).

The frame of reference that inspired the division of chapters is borrowed from the natural sciences and based on a "loose chronological order of planetary development": Geosphere, Atmosphere, Hydrosphere, Microbial, Botanical, and Zoological (p. 25). The final chapter on Noosphere, or the domain of human thought, is proposed by the authors as a "legitimate natural sphere worthy of consideration" (p. 25).

Chapter 1: Geosphere

An architecture attuned to this sphere must consider the rock cycle, mineralization processes, and geologic time. Its focus is on innovative structural frames where the designer "orchestrates" processes to produce a form. The architectural product is the result of natural forces and stimuli that ultimately determine the final outcome. The projects discussed in this chapter question the restrictive ways in which traditional architecture approaches building construction and a building's life-cycle.

Chapter 2: Atmosphere

Designs attuned to this sphere must consider atmospheric levels and the chemical makeup of the atmosphere. The authors present case studies that reinforce the idea of "architectural space as a microcosm or fragment of the firmament" (p. 54). Today, architects and engineers engage in hybrid approaches to indoor climate management that aim to reduce energy use and maintain optimal levels of indoor climate control. Environmental issues relate to climate change in the past, energy use and optimization, and attempts at controlling the climate.

Chapter 3: Hydrosphere

The hydrosphere encourages designers to integrate the water cycle into their designs. In the past, water has been considered an adversary to architecture, but the authors argue that using water as a material allows designers to benefit from "[a] most dynamic, powerful, and adaptable natural sphere" (p. 68). The projects in this chapter have capitalized on the unique chemical composition and characteristics of water to produce new forms of integration as well as a new perspective on the changing role of water in the architectural toolkit. Environmental issues relate to water scarcity.

Frozen Time | Takuji Shimmura, Paris | Photo courtesy of Princeton Architectural Press

Chapter 4: Microbial Sphere

Humans interact with the microbial world in diverse ways due to three factors: the diverse nature of microorganisms, the broad geographic presence of microorganisms, and our inability to see microorganisms with the naked eye. Rather than relying on the electromechanical solutions that have contributed to many of our current environmental issues, the authors suggest new ways of collaborating with the microbial world. This means that architects and designer working in this sphere must comply with biological processes in a harmonious way, as exemplified by the Microbial Home project (p. 88).

Chapter 5: Botanical Sphere

The designer's role in this sphere is similar to the Geosphere because designers must choreograph to the melody of ecological processes. An architecture attuned to this sphere must consider photosynthesis. The authors emphasize the similarity between plants and buildings: plants like buildings have circulation systems, foundation systems (roots), and are for the most part immobile (p. 113). Incorporating photosynthesis into buildings can significantly reduce greenhouse gas emissions.

Chapter 6. Zoological Sphere

This sphere discusses growth and form through the study of morphogenesis and evo-devo biology. Architects engaged in this sphere develop knowledge of animal properties with help from disciplines such as zoology. According to the authors, architects are increasingly focused on the function of animal characteristics and behavior, however it is not clear what purpose designs based on these properties serve other than identifying alternative materials and processes.

Chapter 7. Noosphere

The final chapter posits language and thought as the material foundations of noosphere architecture. This kind of architecture "navigates the interface between materiality and information" (p. 149). It is dependent on the exchange of data transfer in a variety of forms, which improves the ways in which architecture can communicate. The chapter briefly addresses the concepts of technosphere (human technology) and anthroposphere (human-modified environment) through a discussion on building construction methods and the use of buildings as communications platforms.

Environmental Design Student's Perspective

The authors take on a diverse range of topics supported by historical research and references to natural, scientific and engineering processes. There are attempts throughout the book to connect past innovations with present environmental conditions although the book does not provide a detailed analysis and critical perspective on important issues such as sustainability or unintended consequences. For instance, in the chapter on Atmosphere, the authors acknowledge that the ominous future we face has been shaped by the unintended consequence of our exploitation of fire that eventually led to the rise of modern industry, but it is not clear whether the featured projects alleviate further damage

The Cloud | Rasmus Taun | Photo courtesy of Princeton Architectural Press

Dune City | Ordinary Ltd/Magnus Larsson & Alex Kaiser | Photo courtesy of Princeton Architectural Press

or make it worse. One of the scientific advances listed is cloud-seeding. This geoengineering technology remains contentious, but weather-modification is presented to the reader as “an unprecedented human capacity” (p. 55) in which we can design the architecture of the atmosphere itself. The alluring qualities of many projects are promoted by the authors’ focus on the positive capacity of technology. At the same time, these alluring qualities can inhibit us from critical inspection.

By the last chapter, the framework seems strained. Presented as an extension of the biosphere, the Noosphere draws a parallel between the sophisticated ways in which language and architecture interact with an increasingly complex world. To enter into an architecture of the noosphere, designers must engage in diverse forms of data transfer. The authors admit that the net is cast widely in this sphere: “there is a bigger leap here than in previous chapters” (p. 155), a leap that necessitates the reader’s faith in the ultimate potential of the hypernatural framework. This chapter proposes a framework based on themes of architecture and technology of the past and present, but avoids any serious discussion of what it means for the future.

The authors aspire to provide readers with a more insightful comprehension of architecture’s new relationship with nature as well as inspire innovation in future design. The articulation of this new conceptual framework certainly inspires wonder, an important human emotion linked to curiosity and the motivation of intellectual exploration. The idea that the “hypernatural approach precipitates transformation, novelty, and mutation” (p. 20) is broad. The authors want us to see that the ultimate aim of technology is not anti-natural but instead ‘hypernatural’ when it is working with natural forces rather than against them.

The framework does not allow the authors to provide a critical assessment of technological fixes that often create more problems than they actually solve. This is further compounded by the authors’ support of a more inclusive definition of hypernatural that is “expanded to include all life” (p. 21).

Hypernatural provides a hopeful outlook for the future of innovation in architecture by presenting a vast collection of projects to showcase new ways in which the field of architecture can work more closely with the natural world and its processes. Those with an open mind will see possibilities to engage with the built environment in new, more environmentally-focused ways. It is up to the reader to critically analyse the information presented in this book.

An Architect’s Perspective

The authors express a sincere intent to address the crisis emerging across design professions as design practices try to adapt to changing operating conditions of the global physical and cultural contexts (p. 25). For example, “The greatest concern now facing the zoosphere is a rapid loss of biodiversity, with 25 percent or more land-based species expected to disappear by 2050” (p. 135).

Increasing awareness of the impacts of human activity fosters a new paradigm that promotes humanity as integral to natural systems and potentially capable of adhering to natural principles in order to promote and attain a more favorable ecological state. Rather than investi-

Megafaces | Asif Khan Ltd. | Photo courtesy of Princeton Architectural Press

The Truffle | Roland Halbe | Photo courtesy of Princeton Architectural Press

gating such principles, the examples provided in the book represent the authors' unquestioning belief in the positive potential of technological innovation and their expressed desire for unhindered invention.

Defense of technology - against whom?

The book is intent on demonstrating the positive capacity of technology by essentially inverting everything architecture historically tried not to be and displacing it with what hypernatural now embraces:

> "Decay, change, and unpredictability: these are three words to which architects have commonly exhibited resistance, but to which hypernatural designers enthusiastically flock. ...hypernatural architects deliberately resituate control, often to the predesign phase of a project, where they set up the conditions for work to unfold, organically and unpredictably" (p. 21).

By the construction of their arguments and illustrations, the authors suggest that technology needs to be defended from impediments to innovation as if technological innovation were patently the solution to serious design concerns. This belief seems curious as we are daily bombarded with human innovation that have allowed us to reach and in some cases surpass the natural limits of global carrying capacity. The idea that there could be a shortage of innovative ideas, materials, products and architectures seems hard to justify. Though biodiversity may be under siege, the natural world is still an incredible - and massively ignored - store of biological variation and information.

A new discourse?

The book "... also aspires to establish a new discourse on architecture's relationship with the natural world, exemplified by innovative approaches that architects and designers now use to integrate nature and human technology in profound ways" (p. 18). Early and often throughout the book, the authors offer the claim that the aim of technology is 'hypernatural' and this constructed term may apply to many fields of industry today. The authors further claim that through "a more comprehensive natural lens, technology and design become inseparable" (p. 20) through the context of the seven natural 'spheres'. However, the definition of 'hypernatural' conspicuously drifts throughout the book. By the end, it seems as though anything and everything human-made and many things in nature could be imbued with this supposedly special meaning.

The authors assume their "inclusive and coherent framework ... enables nature-related movements to be more fully understood" (p. 25). Rather than explicitly detailing and comparing such movements or opening a space for an informed discourse on them, the authors present narrowly selected and largely speculative works loosely categorized in terms of a framework "borrowed from the natural sciences" (p. 25). Examples veer decidedly toward the experimental, artistic, and spectacular with a particular emphasis on advanced materials and cutting edge contemporary designs covering the period 2008-2014. They seem to be vignettes relating to prototypical or conceptual building elements, disconnected from user or even builder experience, rather

H2o Headquarters | Ronald Dapsis | Photo courtesy of Princeton Architectural Press than works developed through disciplined interdisciplinary effort or in relation to substantive ecological concerns and purposes.

A less arbitrary and more scientifically grounded exposition of the hypernatural could promote interaction between and thus contribute to allied fields while helping to strengthen funding for research, development, understanding and implementation of meaningfully sustainable design. Such investments in design and construction methodologies merit consideration as given today's problems, humanity can scarcely afford costly errors or futile explorations. Putting diverse minds to work on the problems of our age is an important step, and by evoking a higher order curiosity, *Hypernatural* may be squarely on the path to engaging in an important discourse on architecture's role in relation to all living systems on earth.

Biomimicry Consultants' Perspective

Hypernatural provides an excellent survey of contemporary nature-inspired projects, accompanied with beautiful graphics sure to excite architecture students and practitioners alike. However, although we applaud the authors' intent to highlight designs that unite nature and technology, we expected a more rigorous, interdisciplinary analysis of hypernatural approaches and their potential to advance sustainable design.

The introduction acknowledges how engineers, architects and scientists pursuing nature-related fields are for the most part working in isolation from each other and fail to collaborate, a poor condition for furthering hypernatural design. However, the authors fall into the same trap. Most sections on "Materials Basis and Behaviors" and "Technology" awkwardly describe and often confuse scientific concepts. Several sections contain scientific inaccuracies, such as stating that "bacteria are the only example of prokaryotes" (p. 92) - archaea are also prokaryotes.

The lack of peer-review by scientific experts limits the book's appeal mainly to architects, a much narrower audience than the authors intended. Even for sustainability professionals, this book rarely connects the discussions or projects presented back to the contemporary movements of biomimicry, biophilia or sustainable design. The introduction stresses that hypernatural approaches provide solutions to environmental issues, but this theme is poorly carried through. The chapter discussions remain nebulous and broad with little connection to current thinking in these fields. Certain featured projects have the capacity to influence sustainable design, but this is not emphasized in their discussions. In our opinion, *Hypernatural* fails to adequately demonstrate the "positive capacity" of technology, especially in terms of environmental issues.

Hypernatural has compiled a set of compelling nature-related projects into a coherent, all-encompassing framework, something that is sorely needed to align the scattered movements of biophilia, biomimicry and sustainable design, among others. However, this is an undertaking that requires a thorough, rigorous, interdisciplinary analysis of each movement's methodology and influential projects, something far outside the scale of an architectural survey. We felt that the book suffers from too broad of a scope, and as a result lacks a critical perspective on hypernatural design and how it relates to environmental issues and the current discourse occurring within nature-related movements. *Hypernatural* is best suited as an inspirational piece for those readers new to the concepts of nature-inspired design.

Summary and Opportunities

Hypernatural offers an intriguing peek into the burgeoning practice of architecture inspired by nature and enabled by technology. It will no doubt provide fodder for discussion among students and practitioners as well as theorists of architecture, design, and environmental studies. The book piques readers' interests by presenting a diverse set of design projects that collectively demonstrate the innovative potential the natural world offers. Through these projects, *Hypernatural* attempts to reform the negative view of technology as a destroyer of the environment by showing how technology can seamlessly integrate with natural forces to produce hypernatural, sustainable and effective innovations. Perhaps the most ambitious component of the book is its "seven spheres" of natural inspiration that Brownell and Swackhamer propose as a new cohesive framework for all nature-related design and architecture.

Overall, the reviewers felt that *Hypernatural* fell short of the promise of demonstrating the "positive capacity of technology" and the applicability of this "cohesive framework" to nature-related design. *Hypernatural* highlights one of the largest issues facing the nascent field of nature-inspired design: the need for discourse leading to generally accepted methods for application. Brownell and Swackhamer have presented a useful opportunity to further explore and flesh out the possibilities of nature-inspired technology within architecture. Their framework provides a workable starting point. It is borrowed from the natural sciences, but it requires more rigorous development to demonstrate how it could be a useful framework for effective collaboration between designers, engineers, artists, and scientists. Specifically, how might well-established movements such as biomimicry and biophilia be better integrated into this framework? How will it allow for a comparison of varying approaches and applications? Perhaps most crucially, how can it add value to the evolving discourse about nature-inspired design?

The reviewers also wanted to see a deeper examination of how hypernatural design can positively impact sustainable architecture. Many projects presented in *Hypernatural* show potential to further sustainable design and construction. For instance, the Hydramax project (p. 80), a proposed biomorphic fog harvesting structure for the San Francisco waterfront, could potentially help support fragile wetland ecosystems, increase the resilience of vulnerable waterfront infrastructure to rising sea levels, and bring environmental issues like fresh water scarcity and preservation of the environment to the forefront of the public's awareness. The environmental and social implications of Hydramax and other projects presented in the book should be addressed more thoroughly in future iterations of the authors' work.

Hypernatural also strives to present an interdisciplinary view of each sphere of natural inspiration, but lacks rigorous fact-checking, and selects projects based more in the artistic and theoretical realms of the field than in the prac-

Satellite view of fog over the Golden Gate | Photo: NASA Earth Observatory image by Jesse Allen and Robert Simmon, 2012 | Wikimedia Commons tical. In a future volume, the reviewers would appreciate a wider variety of projects, more focus on the environmental implications of these projects, and meaningful contributions from experts in fields outside of architecture. Since hypernatural design combines science, technology, art, and architecture, this field should not be isolated to architects but instead draw from all specialties for more cognitively successful, sustainable outcomes.

In the foreword, Michael Weinstock articulates an ambitious goal: "This book sets out a cartography of the historical and current changes in the relationship between the societal understanding of the natural world, the material practices and technologies, and the production of architecture" (p. 17). *Hypernatural* could be the beginning of a larger exploration of more robust relationships between nature-inspired technology, design and the built environment. Such research and development is desperately needed to guide eager designers involved with shaping a future of sustainable, innovative and practical solutions that are conducive to health, resilience and prosperity. The reviewers encourage you to consider this unique work, awaken your curiosity, and set course for tomorrow. ×

Publication Details:

Hypernatural: Architecture's New Relationship with Nature **by Blaine Brownell and Marc Swackhamer**

Princeton Architectural Press, New York

http://www.papress.com/html/book.details.page.tpl?isbn=9781616892722

ISBN: 9781616892722 | Published April 2015

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In our last issue we thanked all our contributors, article subjects and ZQ team members for their contributions to three years of *Zygote Quarterly* issues. With sincere apologies for the omission, we would also like to thank Taryn Mead and Catalina Freixas for their welcome contributions to our magazine.

ISSN 1927-8314