

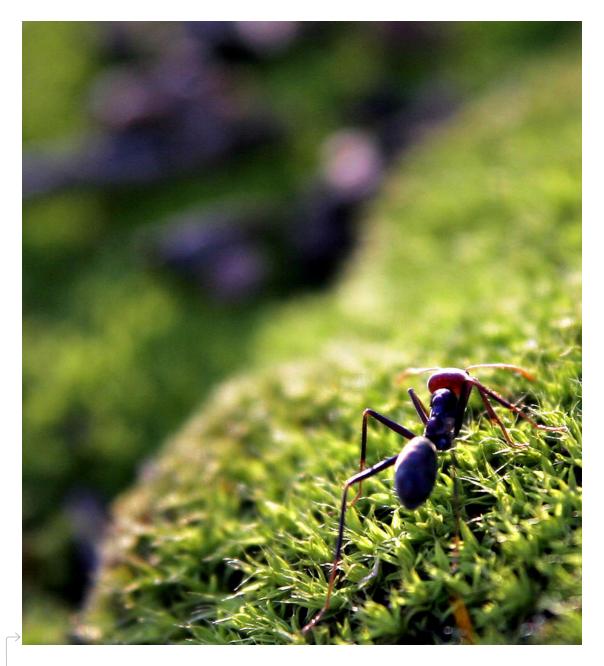




# About Zygote Quarterly

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Ant on mosshill Photo: Axel Rouvin, 2006 | Flickr cc

**Editorial** 

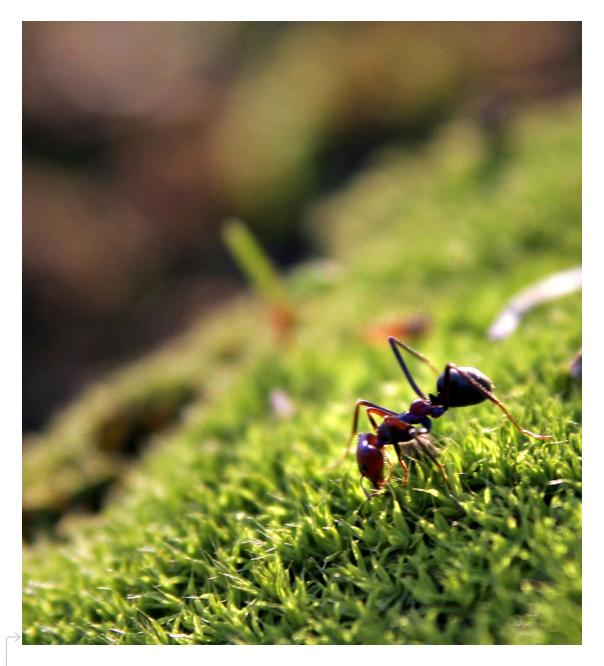
We close our first year in the business of digital publishing gratified and grateful. We were excited to have been nominated in two categories (Science and Nature, and Launch of the Year) for the Digital Magazine Awards, and Marjan traveled to London to attend the awards ceremony on December 6. We had stiff competition from magazines such as BBC Focus, Scientific American and Inquire. Although we did not win an award, it was an honor to be recognized. Our work has been a labor of love that would have been impossible without your help. Thanks to all our contributors, fans and supporters.

Our mission has been to highlight where science and design meet in the sphere of bio-inspired design. In this issue we are delighted to showcase some of architect/artist Philip Beesley's installations, research into the mechanics of swarm behavior, and the intriguing world of cephalopods, the family of animals that include squid, octopuses and cuttlefish. You are free to make your own connections among these seemingly disparate subjects. We are just here to offer the mix from the wonderful world of nature and the people who study it.

Connections are often the most important thing in natural phenomena, particularly at the systems scale. We hope that you enjoy and nurture all of your personal connections this holiday season and see their fruit in a bright new year.

Tom McKeag, Norbert Hoeller, and Marjan Eggermont

Tom Voice + major



Ant on mosshill 2 Photo: Axel Rouvin, 2006 | Flickr cc

In this issue

Thanks for visiting our final issue of 2012! Within you will find the delightful and provocative constructions of architect Philip Beesley, an in-depth look at Cephalopods by Tamsin Woolley-Barker, and interviews with serial inventor (and now author) Jay Harman and cognitive scientist Ashok Goel.

Clint Penick provides insights into swarm robotics and Tim McGee reviews a recent book about a theory of how thermodynamics shapes the biological world.

Heidi Fischer reminds us of the larger personal view in our opinion piece and we introduce a new regular feature, the infographic. Raul de Villafranca provides a graphic summary of the Shinkansen 500 bullet train innovations featured in Issue #2.

Happy reading!

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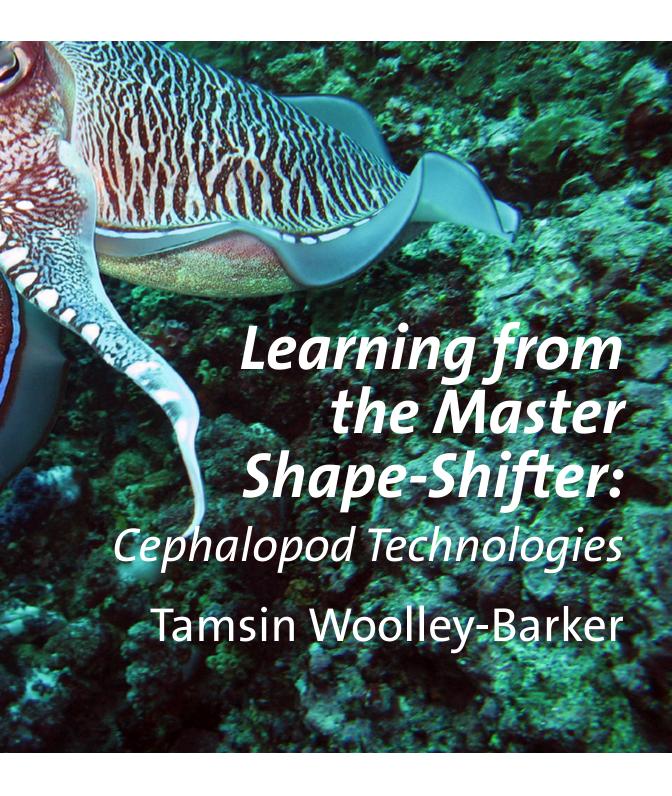


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Hooded cuttlefish

Photo: prilfish, 2008 | Flickr cc



**Article** 

**Author:** 

Tamsin Woolley-Barker

# Learning from the Master Shape-Shifter: Cephalopod Technologies

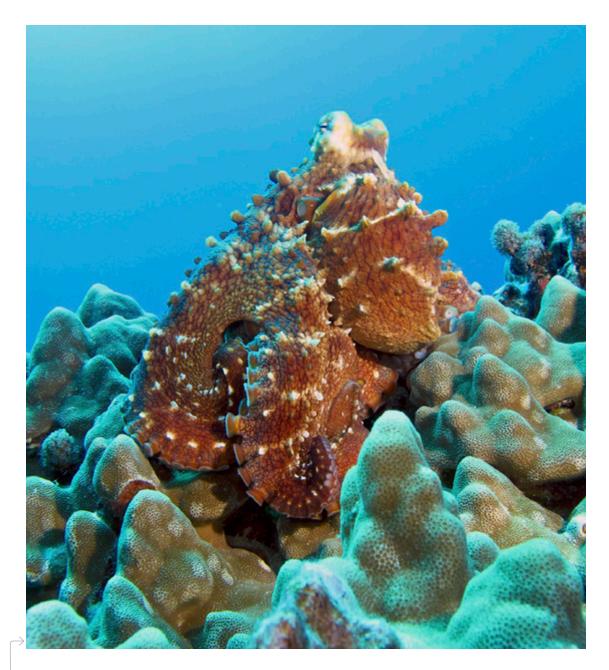
The Indonesian Mimic Octopus is a masterful shape-shifter, playing a cast of bold, flashy, frightening animals for an audience of wouldbe predators. Even much larger fish flee before a convincing deadly sea snake, a menacing lionfish with venomous spines at the ready, a boldly cruising stingray, a poisonous flatfish, or the bullet-fast claws of the mantis shrimp. Meanwhile, a lusty male crab is fatally attracted to an alluring, but murderous, 'female' looking for lunch. At the end of the day, the little octopus male repeats this deception on his own species, sneaking (in drag) to mate under the 'nose' of a larger male.

The Mimic is perhaps the most extreme examplar of cephalopod crypsis: the art of hiding in plain view, blending seamlessly with rocks and seaweed, while hunting for a tasty dinner. The cuttlefish, octopus, and squid are the undisputed champions of camouflage, successfully plying their cunning trade for the last 500 million years. While their relatives, the clams, stayed brainless, safe, and largely immobile, the shelled nautiloids and ammonites began a daring venture into the dangerous world of mobile hunting, culminating in the soft-bodied, vulnerable, but clever stalkers we see today. Cephalopods are now the most intelligent, mobile, and largest of the molluscs, with powerful and unique adaptations, like probing suckered tentacles, cameralike eyes, a shape-shifting skin, an inky escape

cloud, a fierce beaked jaw, complex learned behavior, and even symbiotic relationships with bioluminescent and neurotoxic bacteria.

Just as spiders have made an art form of innovative web and net technology, so the cephalopods have taken the art of camouflage to a level unmatched by any other organism. They can instantly modulate their color, shading, patchiness, mottling or stippling, transparency, heat, and even bioluminescence, light-polarity, or iridescence. They have complete and instantaneous control over skin texture, posture, and locomotion. They do not merely match the background they rest upon, but rely on a powerful visual system and devilishly flexible intelligence to scan a scene and become a single element within it: a rock or coral branch. That rock can match the speed and light characteristics of the ocean current, tiptoe-ing slowly across an open sandy plain, like Wile E. Coyote after the Roadrunner.

In the absence of significant background cover to blend with, the open-water mimic octopus uses a remarkably flexible strategy: it mimics the successful adaptations of other species. Humans, too, have hit on this technique: biomimicry allows us to consciously imitate the special powers of other species, broadening our ability to address novel situations by borrowing sustainable strategies honed by billion years of R&D.



Hawaiian Day Octopus, Kona, Hawaii Photo: Steve D., 2011 | Flickr cc

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### Emulating the Master?

Roger Hanlon of the Marine Biological Laboratory (MBL) in Woods Hole is one such devotee. He has spent the last three decades exploring octopus camouflage, both above and below the ocean surface, with single-minded purpose. A \$6M grant from the Office of Naval Research now allows him and others to peer into the cellular physiology of this remarkable piece of engineering, and ultimately, perhaps, to emulate it.

Hanlon and his colleagues focus on three basic research questions: how do cephalopods perceive their external environment; how do they process these perceptions neurologically; and how do they control their skin physiologically to create their exquisite deceptions? Hanlon's six-million-dollar question is whether humans can mimic these tricks to create octopus-inspired technologies and observant, responsive, and adaptable "squid skin" meta-materials that enhance human abilities in a sustainable future.

### Current Camouflage Technology

The potential of cephalopod-inspired crypsis technologies is revolutionary and wide-ranging across a broad array of applications. The United States military, in particular, has a long-standing interest in cephalopods. As early as World War II, the US was using rudimentary camouflage tricks gleaned from them. Today, the US military is intensely pursuing octopus-like 'active camouflage' technologies, using cameras to sense the visible background, while controlling panels or coatings to vary the subject's appearance.

Organic Light-Emitting Diodes (OLEDs), for instance, can be used to project images onto a sub-

ject in response to visual data from a camera. However, it is very difficult to effectively camouflage a moving object. Phased Array Optics (PAO) might get around this problem by using computational holography to project three-dimensional holograms of scenery onto the subject, camouflaging it independently of viewer distance or view angle. Thermal camouflage is another potential approach. One technology from BAE Systems, London, UK, for instance, employs thousands of infrared hexagonal panels onto a tank, rapidly heating or cooling them like thermal pixels to match the temperature of the vehicle's surroundings.

### How Do They DO That?

These 'cutting edge' technologies are in the theoretical proof-of-concept stages, still beyond our present capabilities. But even once realized, these applications will remain vastly inferior to the cryptic wizardry of the octopus. Octopuses (octopi and octopodes are also acceptable plurals) possess intelligence, emotions, and individual personalities. They dismantle Lego, open screw-top jars, and even pop the caps off childproof medicine bottles. They exhibit play behavior, and at least one aquarium has an Octopus Enrichment Handbook describing how to keep them entertained. In terms of a discrete organ, the octopus brain is small, no larger than that of a lizard. Consider that its' clammy relatives have no brain at all. More remarkable is that fully three-fifths of the octopus' brain cells reside in its arms, along with taste buds and photoreceptors remarkably similar to those in our eyes. If the number of neurons is a guide to intelligence,







**Article** 

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Untitled (Chromatophores)

Photo: Minette Layne, 2007 | Flickr cc

the octopus ranks alongside the house cat. Their whole body is an inside-out, decentralized brain, with the sensory organs built right in.

Octopuses not only have a centralized light perception system (the extraordinary cephalopod eye), but they also have a decentralized system of light sensors distributed throughout the skin. The entire body of the squid is, in fact, a series of cameras, sensing light from every direction. The combination of powerful eyes and distributed light sensors allows the octopus to detect and match its background completely.

Although highly developed, the eyes of cephalopods are generally colorblind, and yet they can reproduce almost any background color. How do they do it? Hanlon's colleagues (including Jules Jaffe, an engineer and research oceanographer at the University of California San Diego's Scripps Institution of Oceanography; Alison Sweeney, a post-doctoral fellow in the lab of a participating UC Santa Barbara researcher; and a multidisciplinary, trans-university staff of about 40 biologists, physicists, engineers and molecular modelers) have created a virtual reality environment for the squid in order to address this question. They use a special camera (an omnicam), that films in six directions, and a holodeck: a fish tank with plasma screens and projection TVs on every side. Various scenes are displayed into the tank, while the team records the squid's response. Resulting color shifts occur almost as fast as a movie, and you could watch one on their skin if the squid could project it. Hanlon's team is learning that there is a great deal more to the cuttlefish and his friends than meets the eye.

Skin Pixels

How do these creatures accomplish such radical changes in color, reflectivity, luminosity, and texture? The secret lies in pigment-filled, light-reflecting organelles in the skin: the chromatophores, iridophores (and for octopus, reflector cells), and leucophores. Each layer of skin has a specific function for concealment.

On the skin surface, chromatophores (tiny sacs filled with red, yellow, or brown pigment) absorb light of various wavelengths. Once visual input is processed, the cephalopod sends a signal to a nerve fiber, which is connected to a muscle. That muscle relaxes and contracts to change the size and shape of the chromatophore. Each color chromatophore is controlled by a different nerve, and when the attached muscle contracts, it flattens and stretches the pigment sack outward, expanding the color on the skin. When that muscle relaxes, the chromatophore closes back up, and the color disappears. As many as two hundred of these may fill a patch of skin the size of a pencil eraser, like a shimmering pixel display.

The innermost layer of skin, composed of leucophores, reflects ambient light. These broadband light reflectors give the cephalopods a 'base coat' that helps them match their surroundings.

Between the colorful chromatophores and the light-scattering leucophores is a reflective layer of skin made up of iridophores. These reflect light to create pink, yellow, green, blue, or silver coloration, while the reflector cells (found only in octopuses) reflect blue or green.

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Since octopi are colorblind, they most likely use the chromatophores to change their brightness or pattern, while using passive reflection of environmental light by the iridophores and leucophores to match background color.

This multi-layered 'pixel' system allows cephalopods to create incredibly complex, instantaneous color changes for communication, mating behavior, and camouflage.

But cephalopods can change far more than just color and patchiness. They also can demonstrate control over the transparency, temperature, bioluminescence, light-polarity, and iridescence of their skin, as well as its texture.

Two thousand feet below the ocean surface, sunlight fades into a shadowy world where predators with oversized, upturned eyes use bioluminescent searchlights to target their prey. Some cephalopods use their rapid chromatophore response to stay invisible as they range across this depth gradient. They are transparent under down-welling surface light, but a rapid reaction darkens them instantly as they dive.

Pelagic squid, like the Hawaiian Bobtail, also have a pair of 'light organs' within their mantle cavity. These contain a crypt (a small sac filled with luminous symbiotic bacteria) and a lens (a stack of tiny reflecting plates that sense and modify the luminescence). The bacteria receive a sugar and amino acid solution from the squid, and in return, they counter-illuminate the squid's silhouette when viewed from below, matching the amount of light hitting the squid from above. The squid are able to perceive and modulate the level of luminescence to match the illumination required by the depth, and the

bioluminescence can also be used to attract prey, entice mates, confuse predators, and to communicate with one another.

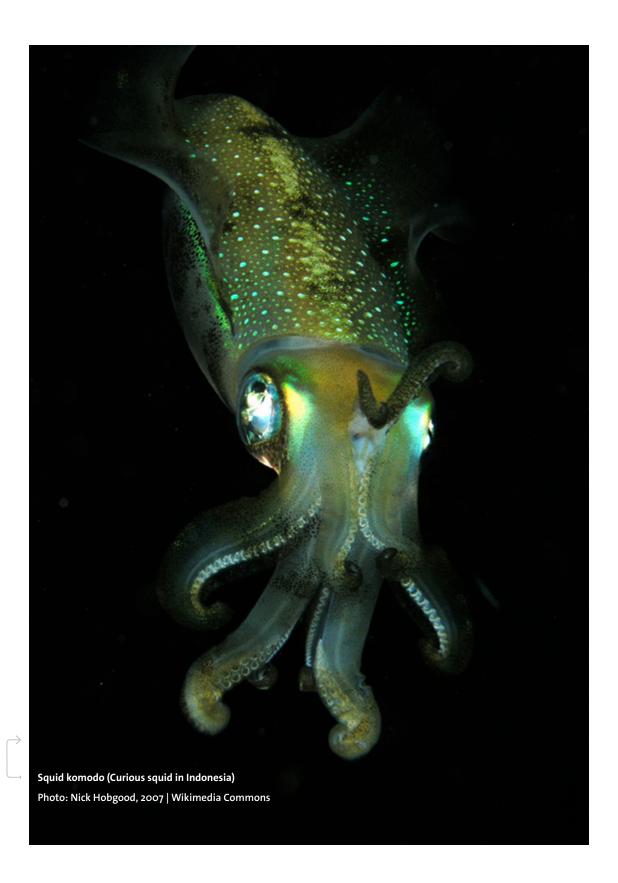
Today, the US Air Force places low-intensity blue lights on aircraft for counter-illumination camouflage in much the same way, making them invisible when seen from below.

### The Quest for Artificial Squid-Skin

Hanlon's team imagines applying these same processes to create an engineered 'skin' for human use. This meta-material would have a massively distributed system of embedded light-sensitive diodes, perceiving light from all directions, just like the squid, while incorporating dynamic color-, heat-, or texture-changing cells to respond in real time.

Hanlon imagines wallpaper, covering swaths of your home, creating a three-dimensional reconstruction of everything inside the room for virtual reality, security, and surveillance systems. He sees inexpensive, flexible displays for computers, tablets, e-Readers, and smartphones, as well as enormous panel screens that simultaneously sense and project images. These distributed light sensing systems could allow us to see underwater at visible wavelengths, or use acoustic wavelengths for sonar-like probing applications. Hanlon also envisions vehicles that not only blend into their visual, thermal, or acoustic landscapes, but also understand that background, perceiving and reacting to targets (like nearby fish and other submarines) nearby.

There is, of course, considerable interest in creating artificial squid skin. Robotics experts at Harvard University, for instance, have developed a



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soft robot with a web of interconnected microfluid channels flowing beneath its silicone surface. When triggered, these channels fill with dyes that allow the bots to blend in or stand out from their surroundings. These simple networks serve as "artificial muscles" that move when electricity courses across them. They can be designed to change the color, contrast, pattern, shape, luminescence, or surface temperature of the soft bot, for camouflage or display, in the visible or infrared spectrum. Squid-like innovations like this open up a new world of flexible "dynamic appearance" robotics, to be used in all kind of applications, including visual aids to complex surgeries, search and rescue efforts, and for pinpointing chemical leaks, spills, or contamination.

### E-paper Screens and Squid Skin

Cephalopod chromatophores are much like the pixels on 'e-paper' screens like the Kindle. Rather than using muscles to control the sacs of color, however, e-paper features light and dark pigment capsules, each with differing charges. These clump together and drop out of sight when an electrical current is applied. Once the charge is removed, the molecules diffuse and spread, creating visible color at the display surface.

While humans tend to use energy-intensive displays that actively produce light, many animals are extremely efficient at using available light to produce color passively. This principle is embraced by the cephalopods. E-readers and octopuses conserve energy with the same technique: they produce color by passively manipulating ambient light, rather than actively producing it

the way a glowing LCD screen would. 'Photonic crystal ink' used in these passive displays is similar to reflectin, a highly unusual protein found in the iridophores. This rigid, transparent material reflects light structurally (passively), producing brilliant coloration. Thin films made from reflectin have the highest known index of refraction of any naturally occurring protein, and when exposed to water, methanol, or ethanol vapors, these films swell and shift their reflected color from red to blue.

The properties of these highly reflective and self-organizing proteins may help us develop thin-film coatings for microstructure materials, bringing scientists one step closer to a real-life invisibility cloak. These lightweight polymers, when spatially constrained in single thin layers, 'tune' and deliver the same optical functionality provided today by heavy, noisy, power- and space-hungry devices. Raytheon, UC Santa Barbara, and the Army Research Labs are now developing synthetic thin films with electrically-driven, simultaneous changes in morphology and refractive index, to be incorporated into the optical devices of the future.

### Smart Clothing

Another material inspired by the cephalopod skin is being developed by scientists at the University of Bristol, where researchers have created a technology that may lead to dynamic smart fabrics. The Bristol team, led by Jonathan Rossiter, is using dielectric elastomers: stretchy polymers that expand when hit with an electric current, to mimic the squid's color-changing muscles. The scientists apply current to the elastomers, making them expand like the squid's

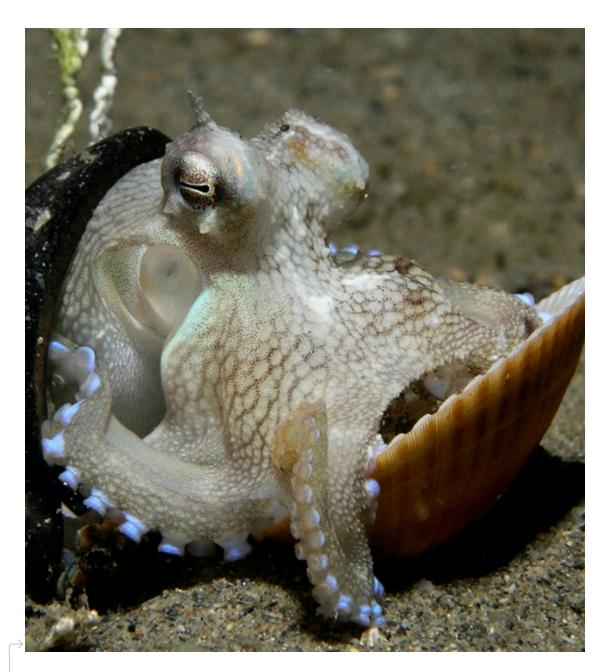


Cuttlefish changing color | Nick Hobgood, 2008 | Flickr cc

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Octopus marginatus

Photo: Nick Hobgood, 2006 | Wikipedia Commons

pigment-filled sacs. When the current stops, the elastomers return to their normal size, and the color disappears. These artificial chromatophores can be made into a pliable, stretchy skin, useful in situations where 'hard' surfaces are undesirable: for instance, smart clothing.

Such a skin could potentially deliver chromatic and textural response to external stimuli as desired. Imagine full-color, hyper-efficient iPads that roll up like newspapers, braille eReaders, touchable smartphone keyboards, and of course, a field day for the pornography industry (traditionally at the forefront of technology)!

### **Engineering Meta-materials?**

These technologies are clever, but they still don't come close to the dazzling array of technologies employed by the squid or octopus performing its shape-shifting repertoire. Can humans really mimic all these adaptations, assembled and fine-tuned over 500 million years of R&D, and bring them together to engineer a complete, functional, synthetic squid-skin? Hanlon and the other researchers and engineers believe we can, but their quest brings up more questions than we can currently answer. Could we replace the light sensors in the living skin and eyes with an artificial distributed light-sensing system? What form would this material take? Could we mimic the powerful light-reflecting and absorbing capabilities of squid to make a responsive, observant, and adaptable skin? Could our computers match the squid's central nervous system's ability to analyze background textures and colors, integrating information from the distributed light sensors and cameras to process the background texture of an object? Could we generate

electrical signals to absorb and reflect light at the right frequencies to make the synthetic skin blend in with its background?

The futuristic meta-materials imagined by Hanlon and his colleagues will have many technological advantages over existing human abilities, but they potentially offer other important benefits as well. One key component of good biomimicry design is that we emulate the systems found in nature, as well the forms.

In nature, all the designs we see today have been subject to rigorous and exhaustive testing. Is it efficient, flexible, and sustainable? Is it resilient to change and failure? Can it leverage webs of interconnectedness with other life? If not, even the cleverest idea will be removed by natural selection. This is the position we find ourselves in today, as we face climate change and scarcity of resources. It is a primary motivation for turning to nature as a mentor and measure of our success. Our future squid skin should be composed of organic molecules (making 'food' for other life), and be energy efficient, just like our inspiration in nature. Perhaps the cuttlefish and its relatives hold some of the answers to the sustainable future of human interconnectivity. The cephalopods have successfully honed their crypsis technologies for over 500 million years, and by emulating these clever survivors in spirit as well as structure, we just might be able to coexist on this small Earth for the next 500 million years.

Article

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Cuttlefish, Great Barrier Reef, Cairns, Australia Photo: Leonard Low, 2005 | Wikimedia Commons





South Mountain Park

Photo: Martin PHX, 2011 | Flickr cc

# Opinion There Are No Strangers in the World Adelheid Fischer

Opinion

**Author:** Adelheid Fischer

## There Are No Strangers in the World

I pull up a chair next to the low wall that separates my yard from South Mountain, a desert preserve of nearly 17,000 acres near the southern edge of the City of Phoenix. Out from the creosote thickets flushes a tiny buff-brown bird. Verdin. Although I've seen hundreds of these desert dwellers, which are as common in the city as they are in wilder parts of the Sonoran Desert, they'll still get a rise from my binoculars. From afar, verdins are just another LBJ (which in birdwatching parlance means "little brown job"). A closer look, however, reveals a flush of gold that spreads from face to crown like the soft, seamless glow in the desert sky just after a clear sunset. Equally extraordinary, but harder to spot, are crimson epaulets on each shoulder. Since these jittery birds never hold still for long, following them with binoculars is likely to give me a mild case of motion sickness. Today is no exception. The verdin beelines into the tall wands of an ocotillo and, clutching one in each claw, begins to pump the air until the branches whipsaw in the wind. He lets fly his customary greeting, a sharp two- and three-note command that sounds like a drill sergeant in a Buddhist boot camp. "Be here. Be here NOW!"

Where is "here"? Where is "now"? I've posed these questions to myself daily, ever since the night in 2005, when my husband of twenty-five years woke up in a coughing fit, mumbled a few incoherent words and died as I watched. In less than a minute, the man who was as essential

to me as breath and bread, gravity and water, air, sunlight and birdsong, simply disappeared. I became a stranger to the world.

For nearly a year, I hardly strayed from my backyard, leaving only to buy groceries, to meet friends or to hike a steep trail in South Mountain to a summit where I could look out for tens of miles in every direction, a temporary furlough from the dark, cramped halls of grief. Some evolutionary psychologists have speculated that our species often responds to loss with a predictable complex of encoded feelings and behaviors. Sadness and its attendant lethargy, for example, are protective since, in prehistoric times, they kept us close to home and away from the kind of distracted wandering that was likely to make us easy prey for hungry lions or, in modern times, from mindlessly stepping off the curb into oncoming traffic. By slowing us down and keeping us close, sadness may be psychologically adaptive as well, since by zapping our energy "it enforces a kind of reflective retreat from life's busy pursuits," observes behavioral science writer Daniel Goleman, "and leaves us in a suspended state to mourn the loss, mull over its meaning, and, finally, make the psychological adjustments and new plans that will allow our lives to continue."

For biophiliacs like me, there can be no new plans, no new meaning-making, no new life



√Verdin

Photo: carla kishinami, 2012 | Flickr cc

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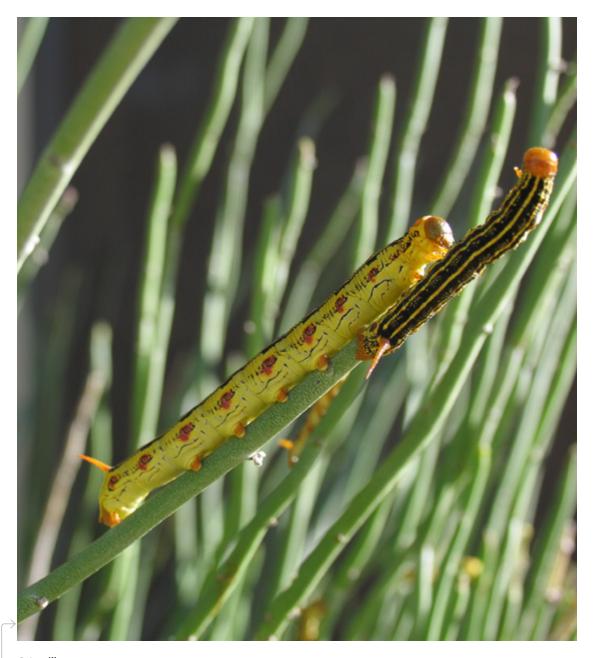
Author: Adelheid Fischer

stories that aren't as densely populated with the winged, the four-legged or chitin-coated kind as they are with people. As such, I was lucky to be living in the Sonoran Desert, the most biologically diverse of the North American deserts. Guides appeared almost daily with their own stories of transformative journeys and fantastical life histories. It was as if the plants and animals in my backyard were leaving a breadcrumb trail across the abyss that led to a reconnection with life. Fellow biophiliac Barbara Kingsolver describes this process in the conclusion of her essay "High Tide in Tucson." "In my own worst seasons," she writes, "I've come back from the colorless world of despair by forcing myself to look hard, for a long time, at a single glorious thing: a flame of red geranium outside my bedroom window. And then another: my daughter in a yellow dress. And another: the perfect outline of a full, dark sphere behind the crescent moon. Until I learned to be in love with my life again. Like a stroke victim retraining new parts of the brain to grasp lost skills, I have taught myself joy, over and over again."

Among the first to penetrate my quarantine of mourning with offerings of joy were the bees that favored the butterscotch blooms of Superstition Mallow next to my kitchen window. Tucson entomologist Stephen Buchmann pointed out that my visitors were undoubtedly members of the genus Diadasia, a solitary, groundnesting bee native to the Sonoran Desert. On warm afternoons, they would dive into the heart of the flowers, kneading their pollenpacked stores for hours without letup. But as the sun went down and temperatures cooled, they would suddenly cease and collapse onto

their plush stamen beds, like a weary baker at the close of his workday simply tipping over to sleep in a great vat of dough. The petals then slowly closed around the food-comatose bees, sheltering them in tiny hammocks where they could sleep, safe and warm. On stormy nights, I'd sometimes walk out in the dark to check on the mallows, smiling as the shuttered blooms gently rocked in the breeze. The next day, long after the flower petals had reopened in the sun, I'd find that many of the bees were still asleep, like teenagers tangled in bedsheets at high noon. Peering at them through a magnifying glass, their bristled body hairs patchy with gold dust, I'd gently nudge their drowsy backs with my finger. "Dudes, sleepyheads," I'd whisper. "Time's a-wasting. Chop-chop."

And then there were the odd two years when late-season summer rains triggered an irruption of the larvae of white-lined sphinx moths. Tens of thousands of yellow- and black-striped caterpillars inched down from the mountain summits. Like the marauding hordes from the Dark Ages (I half expected to hear the stomp of spears and clang of chainmail), they overtopped my back wall in droves, falling with an audible "plop" into the writhing mass of their cousins on the other side. They fanned out into the neighborhoods with a kind of blind determination, their inner compasses set in the unwavering direction of south. The invasion lasted for days and ceased as abruptly as it began. The greasy stains on the roads and sidewalks where the plump caterpillars crossed paths with cars and footfall remained the only evidence of their great, mysterious passing.



Caterpillar

Photo: Adelheid Fischer, 2012





Opinion

Author: Adelheid Fischer

And then there were the magical couplings of spring, when the clusters of matchstick-red buds at the tips of the ocotillos burst into flames of open flowers. Orioles suddenly appeared, as if conjured from their long migrations north, to prick the blooms and drain them of their nectar. Or the first hot morning in late spring when the rise of a few degrees on the thermometer seemed to cause white-winged doves to drop from the sky. "Koo-koo ka-choo," they called on cue, sounding none the worse for the wear of having trailed the great spine of the Sierra Madres in Mexico to feast on the flowers and fruit of the saguaro cactus, here on their summer breeding grounds in the Sonoran Desert.

It wasn't until I began to study biomimicry, though, that I gained a kind of genealogical framework for understanding—and not simply cherishing—this kinship with life. In 2007, I traveled to the Front Range of the Rockies for a weeklong training workshop hosted by the Biomimicry Guild. We had been ticking through a list of what guild biologists call Life's Principles (general rules by which nature operates and against which designers can test the overall fitness of their solutions) when we got to one now-familiar entry: "Nature Uses Simple Common Building Blocks." DNA, for example. The only nonbiologist in the group, I found myself stumbling through my foggy memory of Biology 101. I recalled that DNA, the fundamental script of life's operating manual, comprises a mere four nucleotides: guanine, adenine, thymine and cytosine. Four, I suddenly realized! Just four! It was as if blood began to pump through the veins of the rote learning of my high school days and insight took flight from the page: all living things are cut

from the same chemical cloth! The commonalities were nothing short of astounding: we share 96 percent of our genes with chimpanzees; 97.5 percent with mice; nearly 60 percent with fruit flies; and 26 percent with yeasts. It was my first epiphany. My second came when I realized that plant and animal adaptations—working solutions to the challenges that life presents—are not fixed and immutable in space and time. We are all drawn and erased and redrawn by the same restless, creative life force. We are all in a constant state of becoming—together.

In his Pulitzer Prize-winning book, The Beak of the Finch, Jonathan Weiner writes about this continual state of realignment, about life's propensity for making ongoing course corrections, as it is expressed in the finches in the Galapagos Islands. "The original meaning of the word evolution—the unrolling of a scroll—suggested a metamorphosis, as of moths or beetles or butterflies," Weiner writes. "But the insects' metamorphosis has a conclusion, a finished adult form. The Darwinian view of evolution shows that the unrolling scroll is always being written, inscribed as it unrolls. The letters are composed by the hand of the moment, by the circumstances of the day itself. We are not completed as we stand, this is not our final stage. There can be no finished form for us or for anything else alive...." For me this was biomimicry's most startling, most enduring lesson: we are the kin of living things, deep into the molecular recesses of our being. We are never alone, never strangers, in the world.

If scientists ever get around to sequencing the genome of Diadasia, perhaps I will have hard evidence for what I already know: that solitary bees and the solitary writers who love them wake to labor in sisterhood in the same generative light of creation. "Whoever you are," writes Mary Oliver in her poem "Wild Geese,"

"no matter how lonely,
the world offers itself to your imagination,
calls to you like the wild geese, harsh and
exciting—
over and over announcing your place
in the family of things."

×



White Lined Sphinx Moth Photo: Lorika13, 2007 | Flickr cc



Galápagos interlude 2 Photo: Max xx, 2010 | Flickr cc



Opinion

Author: Clint Penick

# Seeking Intelligence Inside the Swarm

At the beginning of 2012, a video of flying nanobots went viral on YouTube. The video starts off slowly: one robot is on screen hovering in front of a white sheet. Soon, other robots join in. They begin a set of complex maneuvers: hovering in formation, flying in figure eights, collectively avoiding obstacles placed in their path. As more and more robots are added, the sound of their rotors increases to a high-pitched hum. This hum, which is somewhat unsettling, is not unlike the sound made by a swarm of bees.

"I, for one, welcome our robot overlords," said Stephen Pratt, a collaborator on the project that produced the video. "But the thing is," said Pratt, "the robots in the video are flying in a room with infrared sensors. They have a centralized system to locate each other and access to a global view." Dr. Pratt is an Assistant Professor in the Organismal, Integrative and Systems Biology group in the School of Life Sciences at Arizona State University (ASU), where he primarily studies collective behavior in ants. Unlike the robots, ants accomplish complex tasks without access to a global picture of their environment, and they have to contend with fluctuating weather conditions and ever-changing terrain. For this reason, Pratt has been working with the Office of Naval Research funded HUNT project (Heterogeneous Unmanned Networked Teams) to find inspiration from social insects in order to program robot swarms.

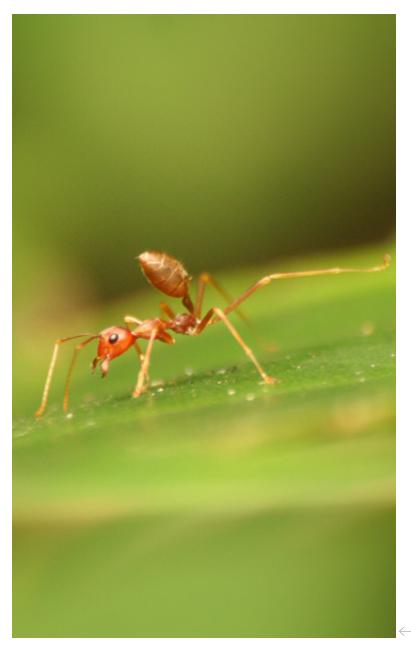
"Imagine a system where you have a million insects that are all blind and know very little about what they're doing," said Pratt, "but perform a task in a coordinated way. Essentially, you get collective intelligence from individual stupidity." The concept of swarm intelligence, or the idea that complex patterns can emerge from limited interactions among simple individuals, was originally coined by engineers before biologists adopted the term. Using this paradigm, computer scientists have been able to develop new methods to route Internet traffic, engineers have optimized electrical grids, and roboticists have built systems like the nano-bots that can mimic insect flight behaviors.

"While the cartoon of stupid individuals acting in large numbers proved to be a useful heuristic," said Pratt, "engineers eventually realized something that a lot of biologists already knew, which was that these individual insects weren't all that stupid." When the engineers on the HUNT team met with Pratt, they decided they needed to understand the ants on a more sophisticated level to develop better robot systems. The task they focused on was cooperative transport.

Imagine a swarm of cheap, dispensable robots that could be deployed to an area after a natural disaster. Perhaps there had been a chemical leak or physical hazard that would make the work too dangerous for humans. First, a robot would need to identify an object that needed to be moved and decide if it could move the object on its own. If not, the robot would need to recruit a team. Depending on the object's shape or size, the team of robots would have to decide

Termites, bees, ants and wasps belong to the so-called eusocial ("truly social") insects. To be a truly social society in the biologist's sense is to possess three basic traits: Adult members must be divided into those who reproduce and those who do not; these adults must coexist across two or more generations in the same nest; and non-reproducers (or those that reproduce less) must care for the young. All of these attributes have survived the natural selection numbers game because they perpetuate the gene pool so well.

These communities are superorganisms, a word coined by William Morton Wheeler in the 1920s, and discussed by the eminent biologists E.O. Wilson and ASU Life Science professor Bert Holldobler in their book, "The Superorganism: the Beauty, Elegance and Strangeness of Insect Societies." It is an apt description of these colonies of creatures, for they dominate our terrestrial world, accounting for more than 1,000 trillion individuals. Indeed. Wilson and Holldobler estimate that their global weight is equal roughly to Man's. The name also indicates a more systemic characteristic. The colony, rather than the individual, is what functions as a unit, adapts



Oecophylla

Photo: Axel Rouvin, 2006 | Flickr cc

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how to distribute themselves around the object and where to grab on. Once they had all taken hold, the robots would then have to move in a concerted effort over three-dimensional terrain while dodging obstacles like fallen trees or collapsed buildings. Finally, the robots would have to make this same set of decisions over and over again, each case a unique situation, until the job was finished.

This same activity, more or less, is accomplished by ants hundreds of times each day with little error. Instead of post-disaster debris, ants must scavenge for food. Pratt's studies at ASU focus on cooperative transport in the ant Aphaenogaster cockerelli, a species that lives in the Sonoran Desert. While some ants defend a large piece of food they have discovered until they have time to cut it into pieces and carry it back to their nest, Aphaenogaster will grab the food in one piece and run back to their nest as fast as they can. If the food is too big for one ant to carry, it will produce a high-pitched chirp using its abdomen and release a recruitment pheromone to attract ants nearby. Once a team has been assembled, each ant will grasp the piece of food and orient themselves towards their nest, using cues from the distant panorama to navigate.

Spring Berman, an Assistant Professor in the Mechanical and Space Engineering Department at ASU, has seen enough videos of Aphaenogaster to be envious at how simple they make this task look. "Not all ants are good at this transport behavior," said Berman, "but Aphaenogaster are very good. You can give them loads of different shapes and sizes, and force them to walk over crevices and around plants, but they still get it back to their nest. That's really impressive from a robotics perspective." Berman has

worked with bio-inspired robot systems since she was an undergraduate at Princeton, where she worked with underwater gliders that were designed using the principles of schooling fish. As a graduate student, Berman was introduced to Pratt through her advisor, Vijay Kumar, the lead researcher behind the flying nano-bots. Berman joined the faculty at ASU in June, 2012, and is now able to work with Pratt and his ants more closely.

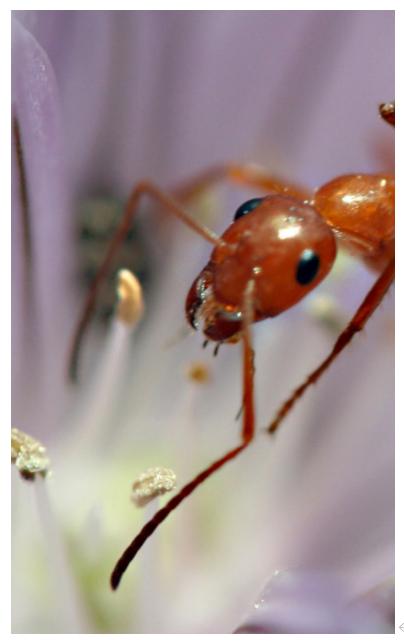
In order to study how the ants behave individually during cooperative transport, Berman and other engineers on the HUNT team have designed force sensors that the ants can carry. The force sensors would measure the efforts of each ant. The original designs, however, were too rigid. "The first time I went into the field was really exciting because I got to see how the experiments were performed," said Berman. "I didn't know you had to take a whole fig to bait the ants, and after they start recruiting you replace the fig with the fake sensor coated in fig juice. It's like a bait and switch." During her observations, Berman saw the sensor dragging on the ground and realized they had to change the design. She also got to watch the ants from the side and realized they were lifting. This led to yet another sensor design. "You really have to see them in action to see what you have to do next," said Berman.

While the bio-inspired approach is focused on taking ideas from biology and applying them to engineering, the HUNT project participants have found that professional insights flow both ways. At a recent meeting, Pratt revealed a robot designed by his HUNT collaborators to a roomful of biologists. He described the robot as a "robot ant." The robot was the size of a large rodent

to change, and is maintained and perpetuated. As such, argues Wilson, these societies are the perfect window into "the emergence of one level of biological organization into another."

Emergence is a key trait of biological organization. Emergent properties are everywhere in nature and can be seen from DNA to ecosystems. Whole systems cannot be explained by an examination of their individual parts because they are the product, rather than the sum, of these parts. The final formula and product, therefore, include the complexities of the array, relationships and interactions of those parts.

In the world of technology one can see system behavior that is similar to that of the eusocial insects. Often called multiple agent systems or MAS, it is exhibited in the fluctuations of the stock market or the formation of traffic jams. We have made use of these principles in a wide variety of applications to move information, to create architectural and engineering designs, to route data packets in telecommunications, to move material in delivery or repair routes, and to move energy in optimized power grids. Internet searches, customer preferences,



Ant

Photo: Bulldog Pottery, 2009 | Flickr cc

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and had two wheels resting beneath a mass of exposed circuitry. It was decidedly un-"ant-like," and Pratt's introduction was met with bewildered stares from the biologists in the audience. But when he showed a video of the robot in action, its function became clear. The robot moved beneath a tray where the ants were held, and as it moved it pulled a small magnet on the arena's surface. The magnet was covered with ant pheromone, and Pratt's team used the robot, like the Pied Piper, to lead ants out of their nest and across the arena.

"We still have a way to go," said Pratt. "But now we want to turn it around and see if there is interest in funding the project from the biological side." Engineers on the HUNT team have helped design force sensors, automatic tracking programs, and robotic tools to help Pratt's team tackle questions specific to the ants. Currently, students in Pratt's lab are using the "robot ant" to address questions about collective decision making that would not have been possible before. "Right now our biggest problem," said Pratt, "is that the ant robot works too well. I think we're using too much ant pheromone."

Clint Penick has a Ph.D. in biology and specializes in social insect research. He has taught courses in biomimciry for the Design School at Arizona State University, and in 2013 Penick will be joining North Carolina State University to begin a collaborative study on the ants of New York City among other projects.

and market predictions have all been enhanced by the use of these "bottom up" simulation models.

Swarm robotic systems are often able to solve highly complex tasks because they possess the qualities of parallelism, robustness, flexibility, scalability and low cost. A swarm of robots can accomplish a given task more quickly than a single robot by dividing the task into sub tasks and executing them concurrently. In a properly designed swarm, there is no single point of failure for the system. This is important since many potential challenges, say repair of a ruptured oil well, rely on continued progress even if some components in the system fail. As in nature, artificial swarm systems build up from a few components in an ever-increasing complexity of array. As the swarm of robots becomes larger, its relative performance in comparison to a centralized system becomes better. Since individual units are programmable and reconfigurable to adapt to changing conditions, swarm systems are generally very flexible. Heterogeneous units can be specialized and these specialized units coordinated for a virtually unlimited combination of complex tasks.

Tom Mc Keag

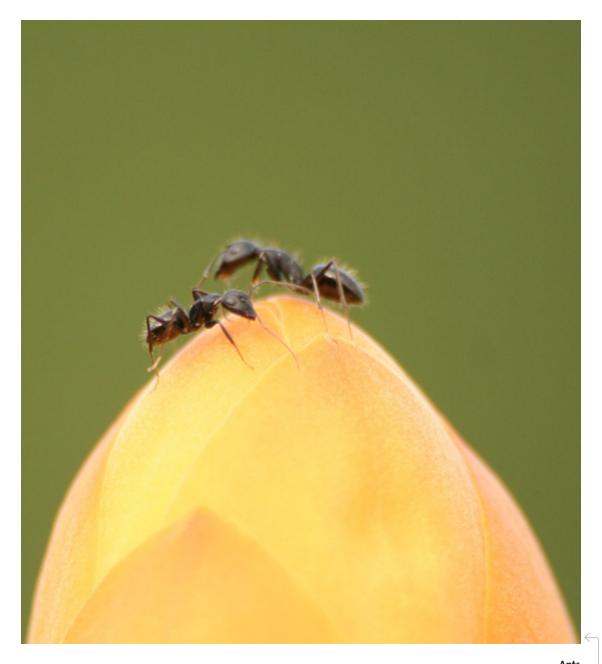


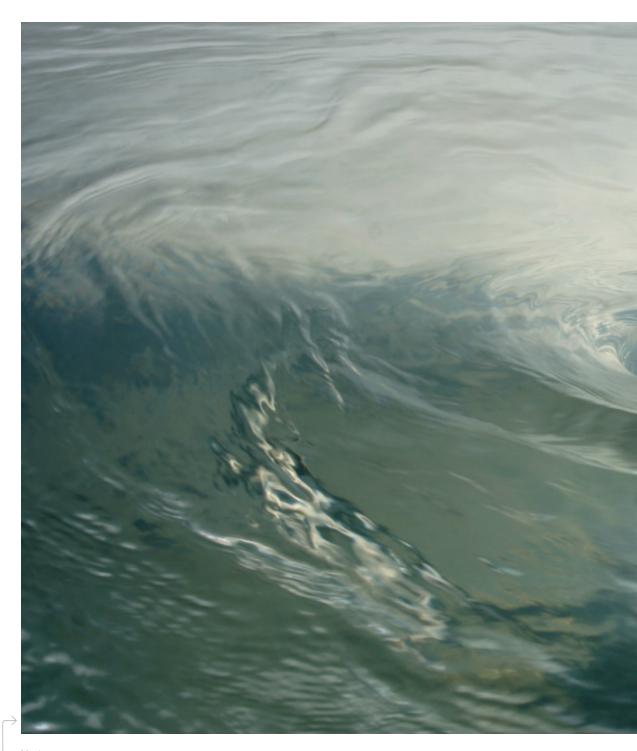
Photo: Axel Rouvin, 2006 | Flickr cc



Arizona Cactus, with Ant

Photo: steve luscher, 2010 | Flickr cc





Vortex

Photo: ahisgett, 2007 | Flickr cc



**People:** Interview **Author:** Jay Harman

## Interview with Jay Harman

A serial entrepreneur and inventor, Jay Harman has taken a hands-on approach to his lifelong fascination with natural fluid systems. In the process, he has grown successful companies that design innovative products, ranging from prize-winning watercraft, to a non-invasive technology for measuring blood glucose, to his most recent companies, PAX Scientific (http://paxscientific.com/) and its subsidiaries.

The culmination of Jay's work in natural flow has been the development of the PAX Streamlining Principle (http://paxscientific.com/tech.html), a guideline for translating nature's extraordinary efficiencies into industrial applications. PAX designs more efficient industrial equipment, including fans, mixers, pumps, refrigeration equipment, and distillation systems, based on Jay's revolutionary concepts. Jay's goal is to show manufacturing industries that more efficient equipment is profitable for both shareholders and the environment.

Jay serves as the CEO of PAX Scientific, Inc. and PAX Pure, Inc., as well as serving on the boards of PAX Water Technologies, Inc. and PAX Mixer, Inc. Jay is also actively developing a new non-profit, Nature of Hope, with its mission focused on biomimicry education.

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

I think our profession is in a post-embryonic phase, having really started as a recognizable profession such a short time ago. Many of us really didn't see a lot of uptake until the last several years. I think now we're on the cusp of a tidal wave.

What do you see as the biggest challenges?

In my experience, the three greatest challenges that I have found can be summed up as:

- needing to Cross the Divide or translation issues between scientists and businesspeople
- turning the Ship of industry which has far greater inertia than anyone can imagine
- the need to Plan for Patience, because the men and women that I have studied and learned from in the bio-inspired space recognize that we are planting forests, not growing crops of tomatoes

It's a long, slow process to get to the market with viable products, but it is worth the effort and the road is getting easier each year. Businesses and governments are finally waking up to the tremendous benefits offered by learning from nature, and the dedicated professionals who have been diligently working behind the scenes for years are beginning to get more attention. Overall, however, there still needs to be more ex-



Pax Rotor

Photo: ©Pax Scientific, all rights reserved

**People:** Interview

Author: Jay Harman

amples of people and companies profiting from the application of bio-inspired design to really kick the biomimicry revolution into full gear, and that usually means money. In the world of power and politics, profits speak loudly.

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

Education, education, education. My conclusion after years of being in the field is that this is a generational issue, which needs to be supported in schools at all levels, in order to fully bloom in coming years.

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

I grew up in nature — born and raised near the ocean in Australia, I worked in Fisheries and Wildlife protection for the government before starting a series of businesses that seek to apply nature's Streamlining Principle to improve the performance and sustainability of industrial equipment.

What is your best definition of what we do?

We learn from nature's design and problemsolving genius.

By what criteria should we judge the work?

If by criteria we are saying success and application of nature's design genius, it would be

through uptake by both industry and government regulation, which is mostly motivated by dollar values.

What are you working on right now?

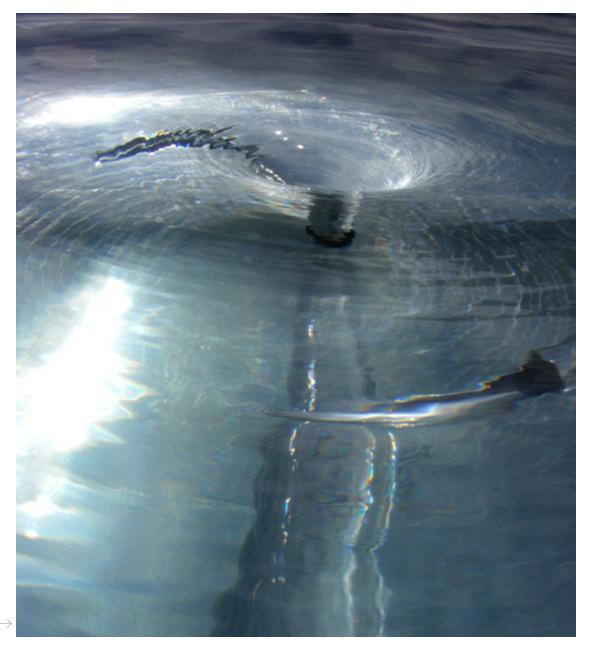
PAX has several subsidiaries that apply nature's streamlining principle (of least effort for most impact in fluid flow) to a variety of industries. We have designed fans, mixers, air-conditioning systems, boats, and even an atmospheric technology that might break through layers of smog to dissipate them in mega-cities such as Beijing. Our latest subsidiary is PAX Pure, which is developing a novel, bio-inspired water purification and desalination technology.

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

There are so many new inquiries in progress that it's impossible to list them all. John Warner's work in green chemistry is particularly exciting, and he's not alone – there's a rapidly growing groundswell in the material and chemical sciences. It certainly has China's attention, with over a dozen institutes for green chemistry alone. It may prove to be the country with the fastest uptake, not just in the chemistry-related domains, but across the board.

What is your favorite biomimetic work of all time?

To be honest, I'd have to admit that my own research into natural fluid flow, and the infinite



Vortex

Photo: Jo Jakeman, 2008 | Flickr cc

**People:** Interview **Author:** Jay Harman

ways it is expressed in all forms from tornados to erosion to seashells to plants to the human body, remains for me a great source of fascination.

What is your idea of perfect happiness?

A day spent in nature, diving on coral reefs.

### What is the last book you enjoyed?

I think Amory Lovin's *Reinventing Fire* is an important book – a "must have" for biomimics as well as political leaders.

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

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I'd probably be a farmer.

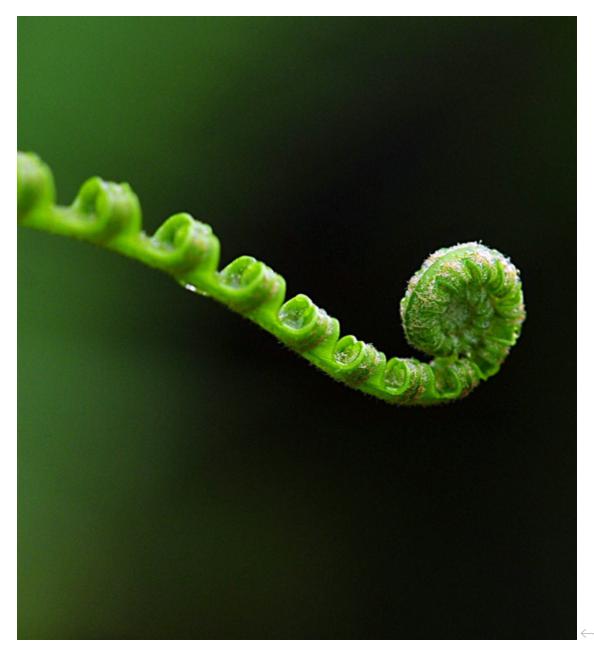
Who do you admire? Why...

Anyone with the courage and conviction to want to make a change in our troubled world.

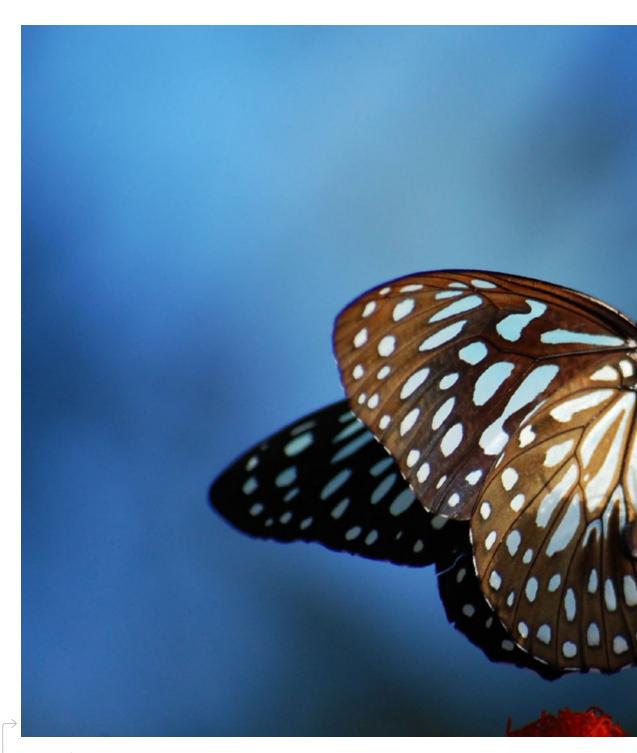
What's your favorite motto or quotation?

There's a quote often attributed to Goethe, which is actually by William Hutchinson Murray in 1951, which says it all:

"Until one is committed, there is hesitancy, the chance to draw back. Concerning all acts of initiative (and creation), there is one elementary truth, the ignorance of which kills countless ideas and splendid plans: that the moment one definitely commits oneself, then Providence moves too. All sorts of things occur to help one that would never otherwise have occurred. A whole stream of events issues from the decision, raising in one's favor all manner of unforeseen incidents and meetings and material assistance, which no man could have dreamed would have come his way. Whatever you can do, or dream you can do, begin it. Boldness has genius, power, and magic in it. Begin it now."



Spira uncoiling
Photo: spiderman (Frank), 2009 | Flickr cc



Blue Tiger | India

Photo: challiyan, 2007 | Flickr cc



**People:** Interview Author: Ashok K. Goel

### Interview with Ashok K. Goel

Ashok K. Goel is a Professor of Computer and Cognitive Science (http://www.cc.gatech.edu/aimosaic/ cogsci/) in the School of Interactive Computing at Georgia Institute of Technology in Atlanta. He is also Director of the School's Design & Intelligence Laboratory (http://www.dilab.gatech.edu), and a Co-Director of Georgia Tech's Center for Biologically Inspired Design. Born and brought up in India, Ashok immigrated to the U.S. for graduate studies. He conducts research into artificial intelligence and cognitive science, with a focus on computational modeling, design, and creativity. He is an Associate Editor of IEEE Intelligent Systems, AI for Engineering Design, Analysis and Manufacturing, and Advances in Cognitive Systems, and serves on the editorial boards of AI Magazine, Advanced Engineering Informatics, and Biologically Inspired Cognitive Architectures. He recently co-chaired two workshops on A Research Agenda for BioInspired Design (http://designengineeringlab.org/BID-workshop/ NSF\_BID\_Workshops.html) sponsored by the US National Science Foundation, and is presently co-editing a volume on Computational Methods and Tools for Biologically Inspired Design. His recent TEDx talk (http://www.youtube.com/watch?v=wiRDQ4hr9i8) summarizes some of his research on biologically inspired design..

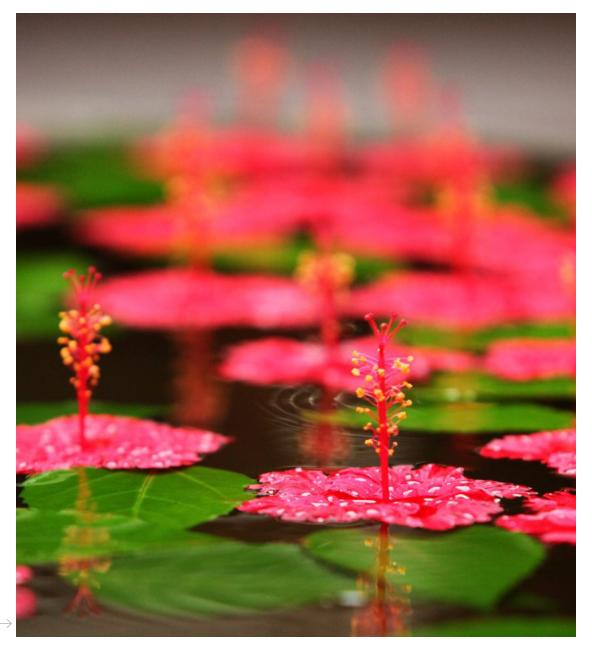
What are your impressions of the current state of biomimicry/bio-inspired design?

The growing movement of biologically inspired design is pulled by the need for sustainable design and development, and pushed by the desire

for design creativity and innovation. Unfortunately, we do not yet understand any of these big sounding phrases: we have yet to build a principled methodology for design creativity, or biologically inspired design, or sustainable design. It is interesting that we have made considerable progress in the natural sciences such as biology. Thus, there is a broad agreement among most biologists about many fundamental principles of biology. However, we have made relatively little progress in what Herbert Simon called the "sciences of the artificial," such as design, economics, management, sociology. Much of biologically inspired design in practice appears to be based on serendipity, and there is significant debate about even its most basic elements. Thus, perhaps the biggest question in biologically inspired design is how do we transform a promising paradigm into a scientific discipline.

What do you see as the biggest challenges?

I think we have three big challenges. I already have alluded to the first challenge. At present, there are not many successful case studies of goal-directed, problem-driven biologically inspired design in which a designer or a design team started with a design problem and then used one or more biological systems as analogies in addressing the problem. Thus, the first challenge is how do we collectively build a de-



Floating flowers | India

Photo: Tom Olliver, 2009 | Flickr cc

**People:** Interview

Author: Ashok K. Goel

sign methodology, and supporting practices, services and tools, for goal-directed, problem-driven biologically inspired design?

Secondly, industry and business by and large are not yet willing to accept biologically inspired design. This is because of several reasons, such as cultural inertia, risk and cost of a new design paradigm, and skepticism about biologically inspired design. Thus, the second challenge is how do we collectively persuade industry and business to adopt biologically inspired design as a fundamental design process.

Thirdly, parts of the popular media in general, and the popular science media in particular, are unnecessarily hyping up biologically inspired design. This leads first to high expectations, then to disappointment at unmet expectations, and next to skepticism about biologically inspired design. Thus, the third challenge is how do we collectively keep doing serious work on biologically inspired design without being distracted by all the noise and changing fashions.

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

I have been fortunate in having been a part of Georgia Tech's Center for Biologically Inspired Design (http://www.cbid.gatech.edu/). The Center has enabled me to collaborate with colleagues from biology and engineering, as well as to systematically study biologically inspired design in practice. I have also had the opportunity to co-organize two NSF-sponsored workshops on biologically inspired design. These workshops have allowed me to get acquainted with the work of several leading scientists and

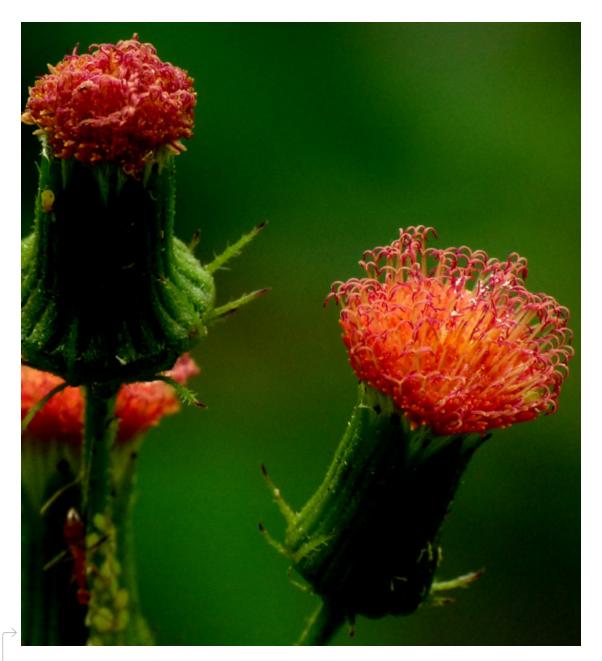
institutions engaged in biologically inspired design. Now I serve on the Boards of Biomimicry 3.8 Institute (http://biomimicry.net/about/biomimicry38/institute/) and BioInspired! (http://bioinspired.sinet.ca/), a bio-inspired design community of practice. These boards give me a broader perspective on the biologically inspired design movement as a whole.

### What are you working on right now?

For the last few months, in a project sponsored by the NSF we have been attempting to understand the problems faced by design practitioners, consultants and managers, and trying to relate our research on biologically inspired design to their tasks, problems and needs. We have interviewed more than seventy design professionals about biologically inspired design. My observations about the current state of biologically inspired design and the challenges the movement faces are based partly on our conversations with these design professionals. Another lesson I have learned from this exercise is that while it is critically important that as "academic scientists" we develop a principled methodology of biologically inspired design, it is useful if some of us also act as "public intellectuals" who promote the paradigm. I believe this is one of roles played by this magazine, Zygote Quarterly.

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

I started working on bio-inspired design in the early summer of 2006 for both professional and personal reasons. Professionally, since the mideighties I had been conducting research on artifi-



Thickhead, Fireweed (Crassocephalum crepidioides) | India

Photo: kadavoor, 2010 | Flickr cc

**People:** Interview Author: Ashok K. Goel

cial intelligence and cognitive science theories of design and creativity, such as analogical thinking and systems thinking. Because biologically inspired design is creative and entails both analogical thinking and systems thinking, it provides me an important arena for exploring and applying artificial intelligence and cognitive science techniques. From a more personal perspective, I am very concerned about environmental sustainability, but also quite excited about the potential of biologically inspired design to help address some aspects of sustainable design and development.

Thus, working on biologically inspired design allows me to imagine that I am promoting sustainability.

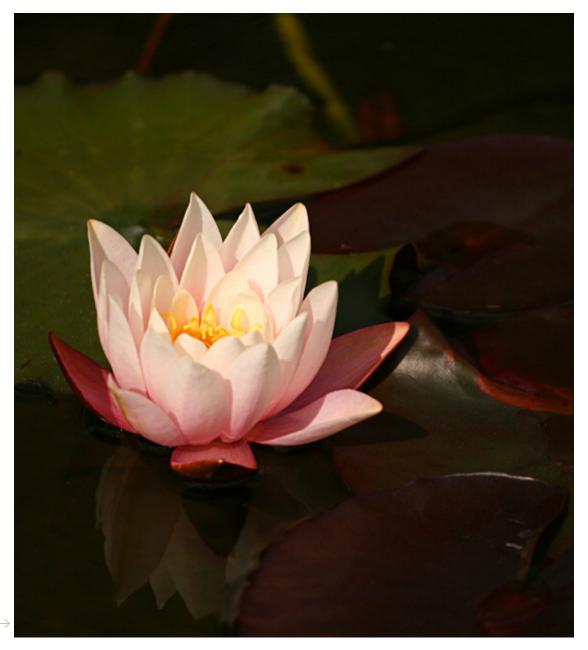
### Who do you admire? Why...

Buddha and Gandhi, for much the same reasons: both were men of peace, who gave up their worldly possessions, sought the path to truth, struggled for justice, and changed the world. I sometimes think that man makes God in his image. If this is true, then a God in Buddha's and Gandhi's images would be a God I could be happy with, at peace with.

### What is your idea of perfect happiness?

I am happiest and most peaceful when my two sons and I are together. However, since my older son has gone to college, this happens infrequently. Soon my younger son will go to college as well. I know that all this is a natural, normal part of life, but I do miss us being together. If not a scientist/designer/educator, who/what would you be?

Perhaps a social worker or a policy maker. I have always wanted to make a difference, to have an impact. Public policy and social work often make a difference to people's lives, have an impact on the world. Of course so do many other professions such as politics and business. Unfortunately, I am not very good at either politics or business. So I will settle for public policy and social work.

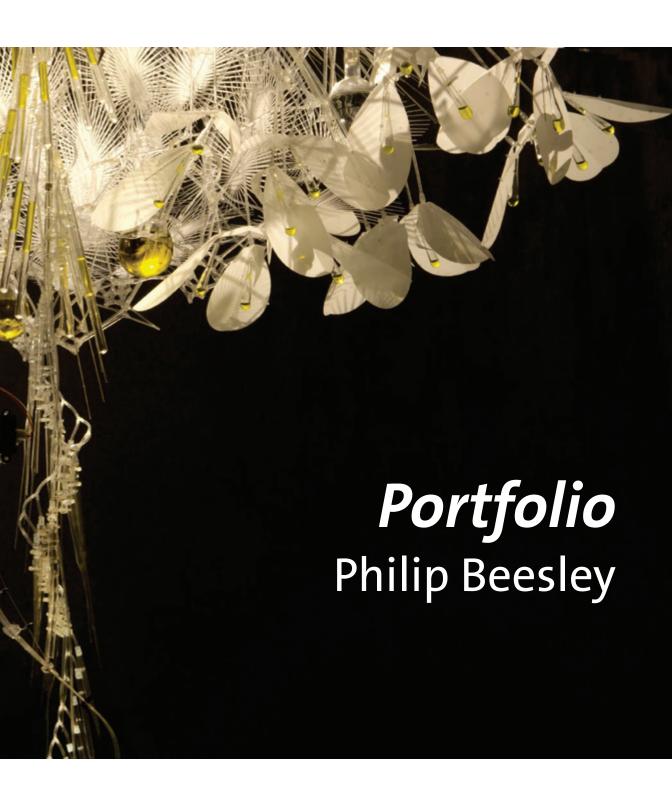


Lotus Flower

Photo: mirod, 2012 | Flickr cc



Hylozoic Series: Espacio | Fundacion Telefonica, Madrid, Spain, 2012 ©PBAI



Portfolio

Author: Philip Beesley

Philip Beesley is a professor in the School of Architecture at the University of Waterloo. A practitioner of architecture and digital media art, he was educated in visual art at Queen's University, in technology at Humber College, and in architecture at the University of Toronto. At Waterloo he serves as Director for the Integrated Group for Visualization, Design and Manufacturing, and as Director for Riverside Architectural Press. He also holds the position of Examiner at University College London.

Dedicated to expanding the role for the arts integrated within architecture, Beesley has worked in sculpture, next-generation digital media and cross-disciplinary experimental visual art for the past three decades. He has focused on public buildings accompanied by field-oriented sculpture and land-scape installations, exhibition and stage design. His experimental projects in the past several years have increasingly worked with immersive digitally fabricated lightweight "textile" structures, while the most recent generations of his work feature interactive kinetic systems that use dense arrays of microprocessors, sensors and actuator systems. These environments pursue distributed emotional consciousness and combine synthetic and near-living systems.

Beesley's principal collaborators include mechatronics engineer Rob Gorbet and synthetic biologist Rachel Armstrong. His work was selected to represent Canada at the 2010 Venice Biennale for Architecture, and he has been recognized by the Prix de Rome in Architecture, VIDA 11.0, FEIDAD, two Governor General's Awards and as a Katerva finalist.

Beesley's Toronto-based practice PBAI is an interdisciplinary design firm that integrates advanced digital visualization, industrial design, digital prototyping, and mechatronics engineering. Recent installations include The City Gallery (Wellington, New Zealand), The Dutch Electronic Art Festival (Rotterdam, Netherlands), Fundación Telefónica (Madrid, Spain), the Digitial Arts Festival (Taipei, Taiwan) and the 2012 Sydney Biennale, as well as permanent acquisitions for The Leonardo (Salt Lake City, USA) and Simons Department Store (Edmonton, Canada).

https://www.philipbeesleystudioinc.com

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

I will have to answer this as an architect/artist. I think there is an extraordinary, searching optimism that has influenced the profession in interesting and curious ways. It has produced innovation in near-market products, and allowed us to optimize energy use and materials in order to live more sustainably. It seems "natural", if you will forgive the phrase, to learn from the successful forms of nature. In my field of art and design, I appreciate the availability of addressable commercial tools. The open source movement, for example, has provided graphic software, like Grasshopper, with which a designer can integrate a fine-grain exploration into his iterative design process.

What do you see as the biggest challenges?

There is a curious absence of concern; by that I mean that there is not the kind of debate about nature-based design that we might have seen in the past.

There is always a danger that biomimicry will come to be associated, in a negative way, with a political movement. This would lead to uncritical review of the work.



Hylozoic Series: Vesica | The City Gallery, Wellington, New Zealand, 2012 | ©PBAI

Portfolio

Author: Philip Beesley

As the use of parametric tools becomes more common, this increases the chance of careless designs that have merely grown, like cancer, from the software program itself.

Having said this, I must say that I enjoy this turbulence.

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

In general, I am keen to see some input from cultural experts about this design phenomenon.

I also think that the concept of "ambivalence" could be useful. Two scenarios come to mind: juxtaposing the worry about nature with a championing of it, and combining the precision of science and engineering with unbridled fiction might create rich possibilities. The expressive involvement of futurists with the technical "foregrounding" of parametric designers, for example, could lead to potentially emergent designs. The danger is that, like the Moog Synthesizer in the world of music, a striking new paradigm could breed a new rigidity, a knee-jerk process that produces homogeneous outcomes by its adherents.

"Mortality" is a concept that I think the profession could explore in a way that pairs an embrace of nature with the idea of cutting against it. There are a lot of possibilities of working with this if done sensitively: degradation, exhaustion, for example; not in the sense of the drill sergeant, but along the lines of shedding and renewal.

By what criteria should we judge the work?

I think a work should be judged by its gravitas and the importance of its impact, and I think these can be quantified. Design should borrow some of the practices of science and engineering.

Should our work show more rigor?

Well, rigor is the first word in rigor mortis! In addition to gravitas, work needs a complementary component. A full-blooded emotional response to a project's possibilities belongs to this profession. The language of ethics and morality should be part of every professional's training.

What are you working on right now?

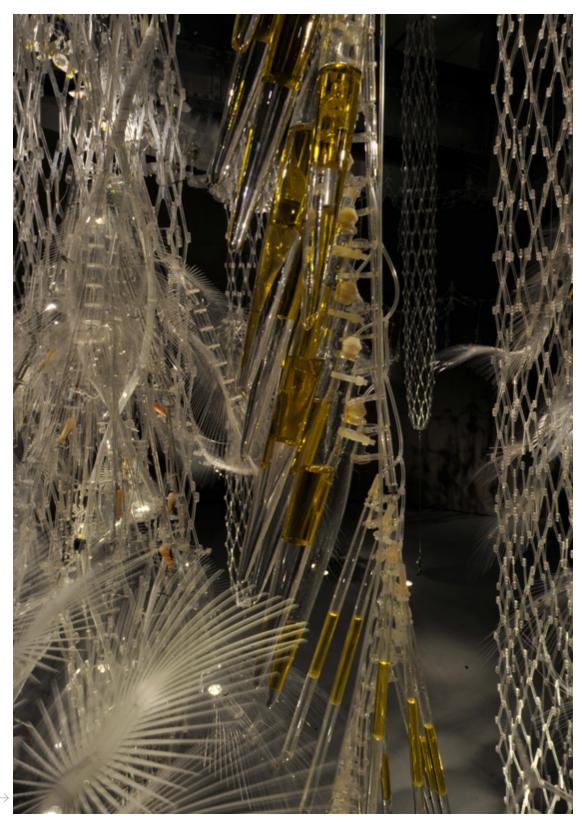
We are designing a permanent installation for the Simons Department Store in their new West Edmonton location. It is inspired by the Aurora Borealis.

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

My path to this field has been punctuated by several influential people:

A dialogue with Warren Seelig, textilist from Philadelphia, led me to Wilhelm Worringer, a German philosopher who wrote of abstraction and empathy. My collaboration with Warren led to the use of geotextiles as enhancements, spatial delineators.

Rachel Armstrong and a conversation at the Bartlett was important. Rachel introduced me to her work in protocell research and her multi-



Hylozoic Series: Espacio | Fundacion Telefonica, Madrid, Spain, 2012 | ©PBAI

**Portfolio** 

Author: Philip Beesley

disciplinary approach, the investigation of complex systems and the use of algorithms to reproduce them. It was from this exposure that I started to think of architecture as metabolism.

Michelle Addington, a Mechanical Engineer I met in Rome fifteen years ago has also been an influence.

Rupert Soar of Loughborough University is a mechanical engineer and knows about digital fabrication and was fascinated by cellular systems and termite mounds. He worked with oscillating accretions seen in the mounds and tinkered with energy, pressure and humidity gradients in order to achieve effects. This I thought could be linked to broader design, and also learned that small inputs could yield big impacts as seen in some of the beautiful chains he produced.

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

Iris van Herpen and her work of the last couple of years have intrigued me. Her dresses capture some remarkable qualities, a mix of the earthy grotesque of the grotto and ethereal nature of smoke and haloes.

By what biological concepts could you categorize your body of work?

Resilience

Metabolism

Maximum potency/interaction

Diffusive systems

Any last thoughts?

Fragility and vulnerability as virtues could change our design language. The metaphor that I would use is the snowflake versus the raindrop. The raindrop is our current reductionist model, the liquid drops from the sky and forms a perfect sphere. The snowflake, on the other hand, is also a valid model, for something formed from a release of energy, into a beautiful, expansive shape. Why not have an oscillation between both?

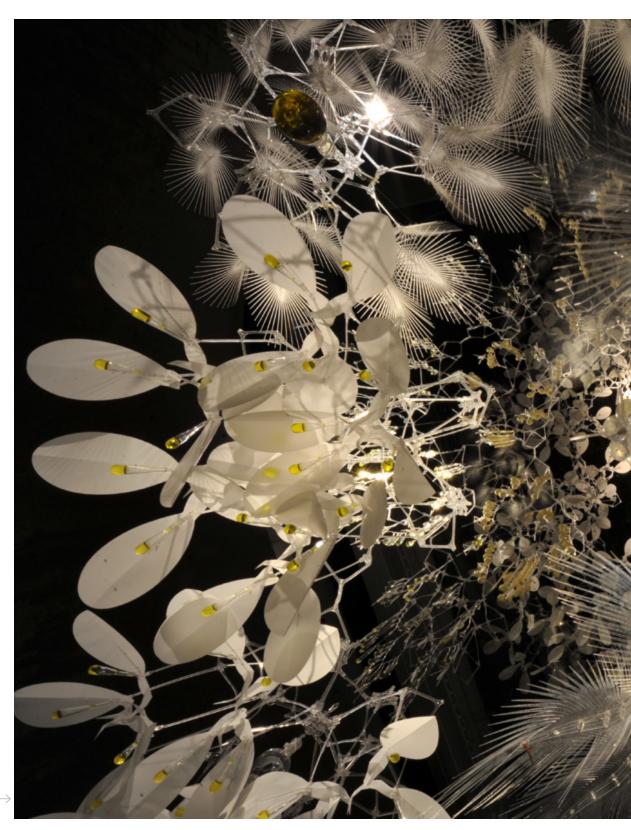


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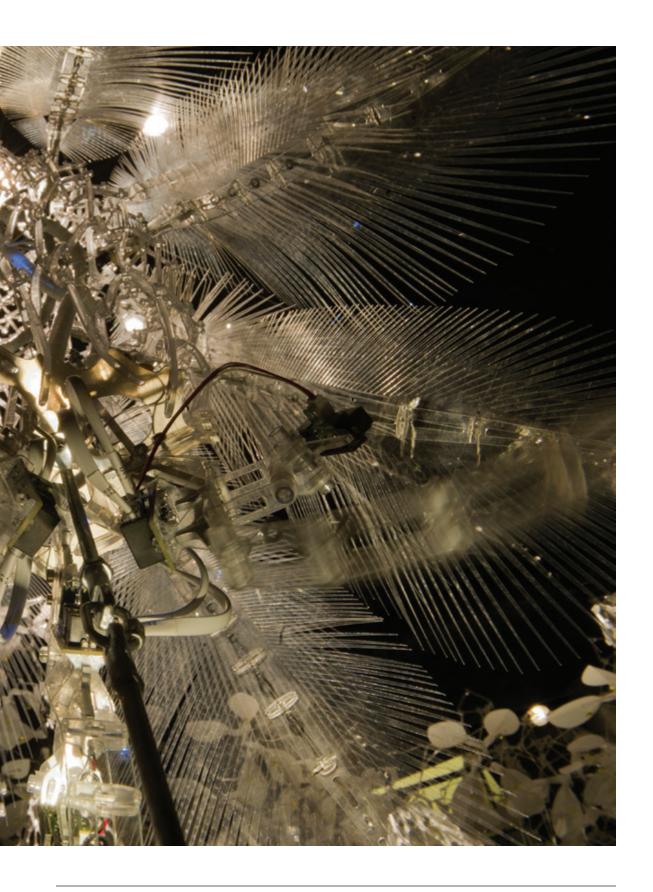


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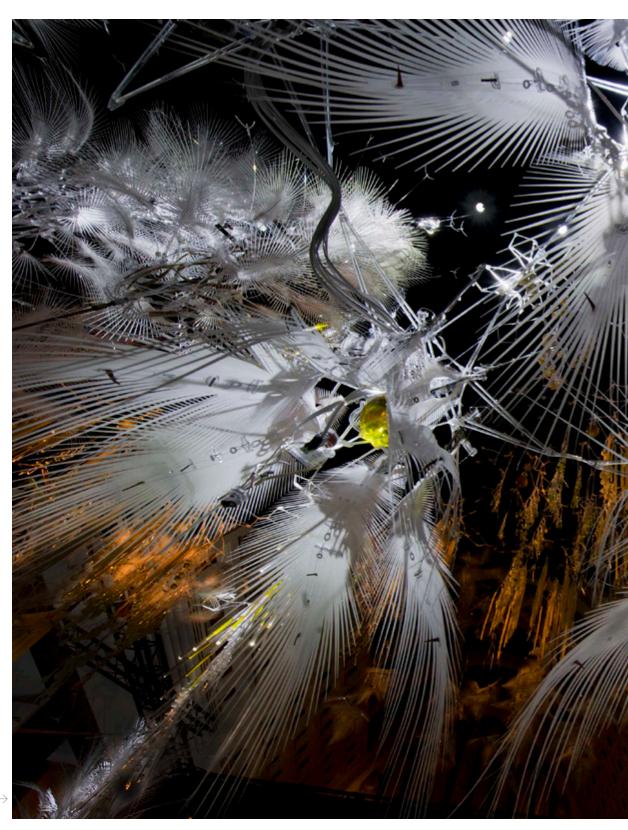
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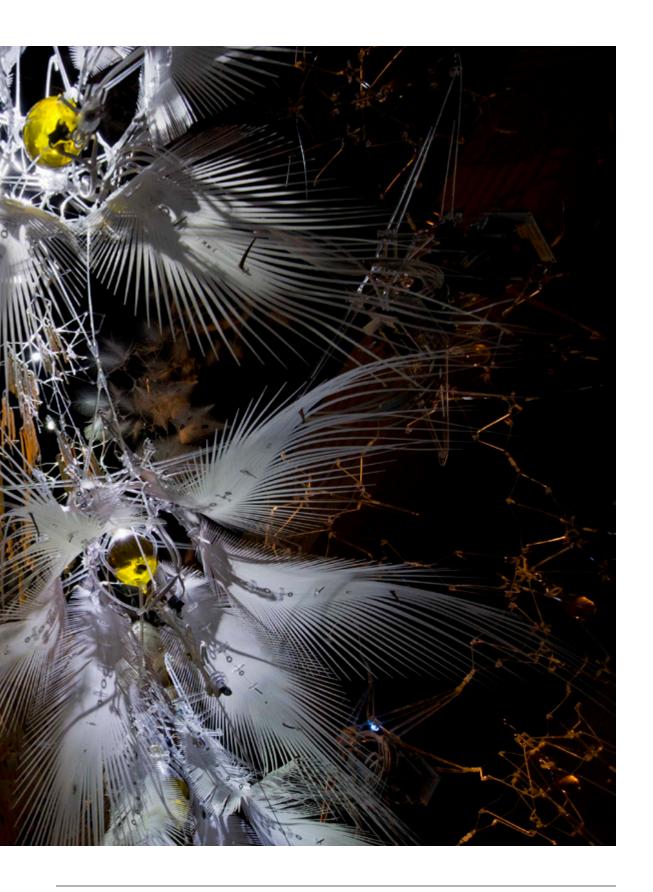


Protocell Field | Dutch Electronic Art Festival, 2012 | ©PBAI





Protocell Field | Dutch Electronic Art Festival, 2012 | ©PBAI





Hylozoic Series: Sibyl | 18th Sydney Biennale, Sydney, Australia, 2012 | ©PBAI



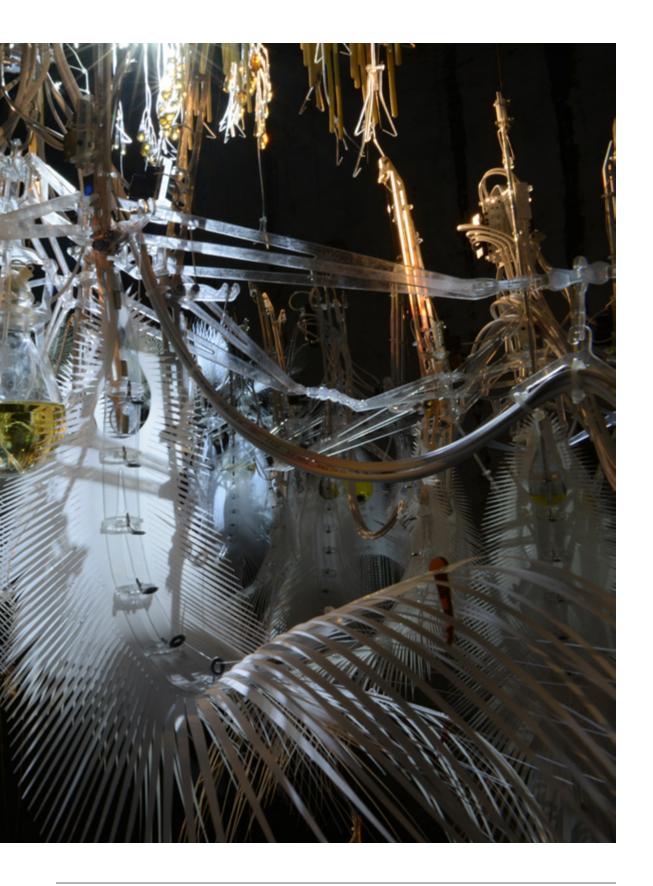


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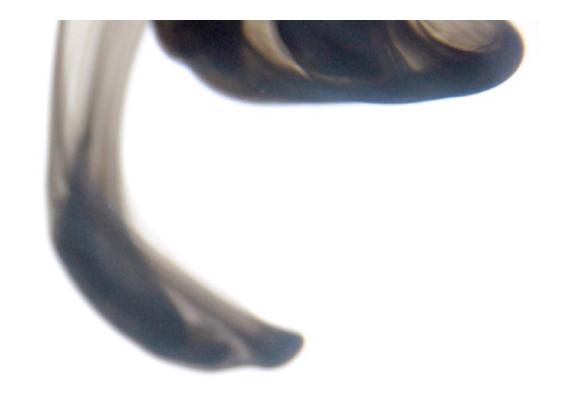
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Photo: árticotropical, 2009 | Flickr cc



Design in Nature
by Adrian Bejan and
J. Peder Zane
Reviewed by Tim McGee

winter 2012

Book review

**Author:** Tim McGee

## Design in Nature: How the Constructal Law Governs Evolution in Biology, Physics, Technology, and Social Organization

'Life is flow', is the Zen-like summation Adrian Bejan and J. Peder Zane propose as the main thesis of their book, *Design in Nature*. In the book the authors outline Bejan's principle organizing paradigm for our physical, biological, and social world, called "The Constructal Law". When writing about flow Bejan is not being poetic, he is telling us, literally, that life is a flow system and even more profoundly that life is not as distinct as we might expect. Life itself is a "plot twist in the larger story of mass and energy flows being shaped by the constructal law."

The book explores this seemingly strange world where animals are shaped to be 'like raindrops in a river basin'. Bejan uses an informal and personal storytelling narrative that elucidates the world and everything in it as a tapestry of flow systems which follow the constructal law. At times this approach interferes with the communication of the idea, but does provide a personal perspective in anticipation of the challenges to acceptance of his theory.

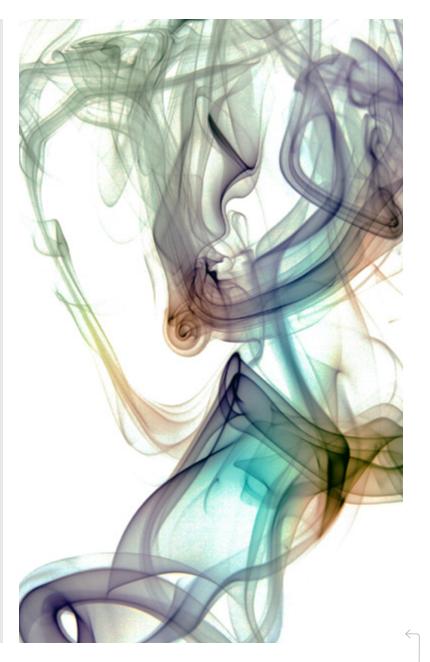
The constructal law is the idea that any flow system will evolve through time so that the design (the shape) of the flow system will change in order to allow better flow through the system.

Constructal law challenges some long held assumptions of the scientific community. Most poignantly for me is Bejan's exploration of evolution. In modern evolutionary theory evolution has no foresight. Evolution cannot "predict" the future. Biologists have focused on the mechanism of variation and selection, but Bejan points out that this is only part of the story. In a constructal view of the universe, evolution has a direction, a goal: to allow better flow through the system. Bejan insists that this is not a conceit, but a result of thermodynamics; all systems will evolve towards better flow or cease to exist.

Bejan tells us that the question 'Why do trees exist?' has a simple answer once we understand the flows of the system in question. Trees exist because they must: in order to facilitate the flow of water from the ground to the sky. Indeed,

What the author is proposing: A universal law that governs the formation and evolving shape of macroscopic forms, both living and nonliving, within our biosphere. This law is conceived as a basic, or first, principle of physics, in the same order as the Second Law of Thermodynamics. As such, it is purported to account for all design generation and evolution in nature. In 1996, Bejan defined it as the following: "For a finitesize system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed currents that flow through it."

The Laws of Thermodynamics: Thermodynamics is the branch of natural science concerned with heat and its relation to other forms of energy and work. It defines macroscopic variables (such as temperature, internal energy, entropy, and pressure) that describe average properties of material bodies and radiation, and explains how they are related and by what laws they change with time. Thermodynamics does not describe the microscopic constituents of matter, and its laws can be derived from statistical mechanics.



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Photo: nicholasjon, 2009 | Flickr cc

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Book Tim McGee

trees will always look like trees. If we set foot on an alien world that has had the same gravity, atmosphere, and flows of energy, that world would have evolved trees. The deterministic language and intention is what sets constructal theory apart. The constructal law doesn't just explain the structure of trees, it is a law that lets us understand why trees emerge, and predict how they will evolve in the future.

The organization of the book sets up an interesting sequence of case studies that build on the idea of the encompassing impact of the constructal law. Bejan explains how the law can predict the shape of a tree, but also the root, and the structure of the entire forest. Indeed the constructal law has predicted the global weather patterns that have emerged on Earth. From a biomimicry perspective this universal scalability of the law provides a unique bridge. It adds a layer of expected outcomes to what before might have been seen to be randomly emergent, and informs us of how our own design interventions can accommodate better flow.

Bejan doesn't stop with predicting the design of trees, but points out that all flow systems, including the flow of human culture and ideas, conform to the constructal law. Biologists have been crossing the divide between these fields since Charles Darwin. E.O. Wilson was doused, famously, with a pitcher of water for suggesting that evolution can help explain social behavior. Evolution, as a theory for unraveling some of humanities toughest questions, has been debated and expanded as a paradigm for the past 150 years. Bejan pushes this one step further, telling us that evolution is not just for biologists but is an expected outcome from a physics perspective. 'Where Darwin showed the links between bio-

logical creatures, the constructal law connects everything on the planet.' This universal result of flow systems means that questions in the humanities, when framed as flow systems will take on new dimensions, and will be able to be linked to the physical principles of flow.

What is often challenging about the book is the request for the reader to imagine flow systems and physics principles in his or her head. Some well developed visualizations and diagrams would, in this reader's analysis, go a long way to making the material more accessible to a wider audience. The book also, at times, seems to struggle to develop a compelling new language for expressing constructal law. Words such as vascularization, svelteness, better, complexity and even evolution are being explicitly defined by constructal law in ways that many readers might not find familiar.

The constructal law appears to offer a powerful toolkit for exploring any system, including the human condition. It is a passport for examining all subjects from a flow system perspective, elevating (or reducing, depending on your perspective) the conversation to thermodynamics and allowing us to predict the shape of things to come. Constructal law provides a predictive capacity to systems evolution, and suggests that, if you can understand what is flowing, you can predict how the system will evolve through time. Inherently, this has implications for how we can manage our own technology, culture, or organizations to accommodate this universal deterministic outcome, because as Bejan points out 'design evolution never ends'.

The First Law of Thermodynamics states that energy can be gained or lost in chemical processes, but it can't be created or destroyed. The Second Law states that energy inevitably dissipates, or moves from ordered structures toward entropy, and that this flow is irreversible.

The Constructal Law proposed by the author is based, in large measure, on the observed physical condition of thermodynamics as summarized in these two laws. The "imposed currents" referred to in the Constructal Law reference this energy flow, and shape the evolution of physical form through time.

Self-organization: Self-organization is a process where some form of global order or outcome arises out of the local interactions between the components of an initially disordered system. This process is spontaneous: it is not directed or controlled by any agent or subsystem inside or outside of the system; it may however, be determined by basic laws or processes. In this case, the flow of energy from higher to lower concentrations, for example, would be seen by the author as the engine for the continual selforganization and shape of biological forms which are morphing in accommodation of this flow.

Other References to Thermodynamics and Biological Evolution:

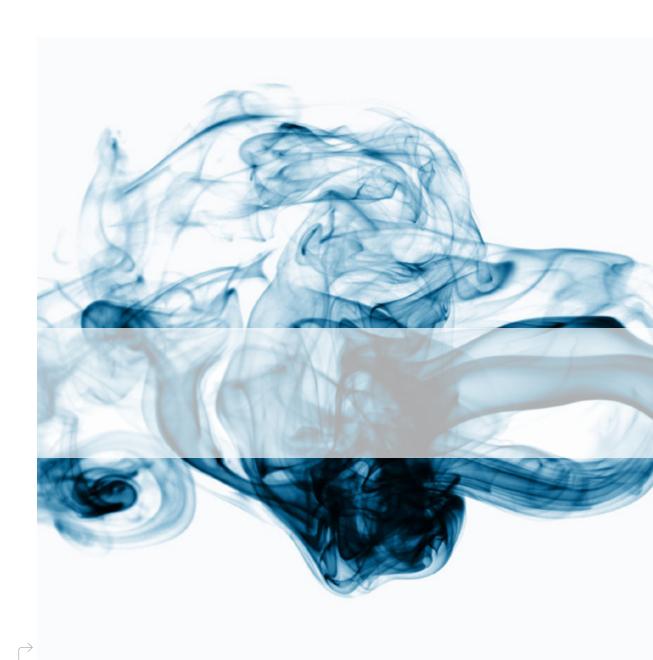
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Article: Book **Author:** Tim McGee



Water (explored)

Photo: johanlundahl, 2008 | Flickr cc

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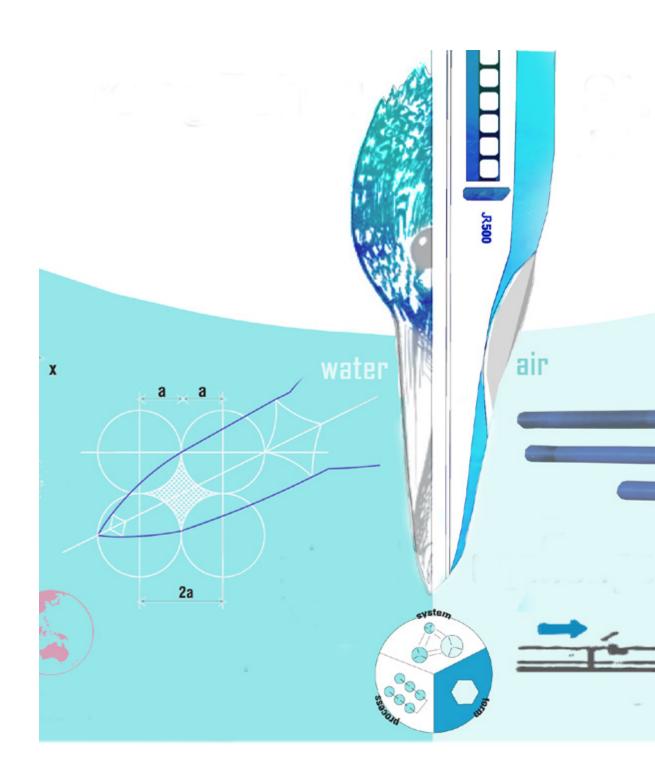
Other Reviews of "Design in Nature":

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http://www.openlettersmonthly. com/book-review-the-design-innature/

https://www.kirkusreviews.com/ book-reviews/adrian-bejan/design-in-nature/ Tim McGee is a Biologist and Designer in the Boston office of the international design firm Ideo. He worked previously as a Biologist and Strategist at Biomimicry 3.8, a combined consultancy and educational institute from which he received a Biomimicry Professional certification.

He received his MS in Biochemistry and Molecular Biology from the University of California, Santa Barbara. Tim is dedicated to integrating the fields of biology, design, engineering and business to create regenerative systems, products, and services that revitalize our relationship to the living world.



## InfoGraphic Raul de Villafranca et al.



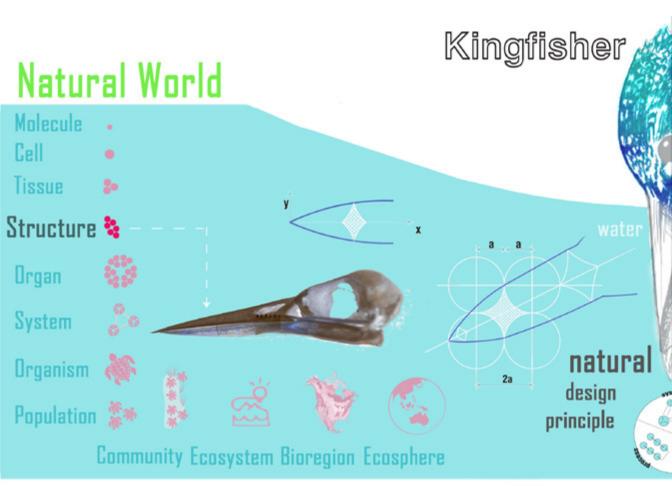


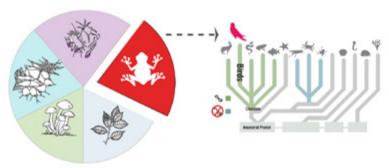
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