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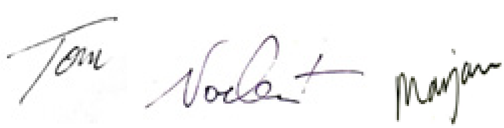
Human innovation can come in many forms: disruptive, stepwise, iterative, slowly evolving, singular or none of the above. Many things can drive it: necessity, happenstance, ambition, raw creative spirit. Innovation in the world of nature carries risks, of course, so that optimization, rather than maximization of any one trait, is often achieved over a long span of time, with inherent controls of reward and punishment for each incremental test version; an "eventual" if not "sudden", death playoff, if you will. The evolution of ideas, like the body parts of beetles, does not evolve in a vacuum, but is formed within an environmental context. Studying the *conditions* that encourage the introduction of novel but successful ideas is a fascinating area of inquiry for anyone with an interest in bio-inspired design.

In this issue we take a look at the some of the most demanding living conditions in the world in "Going to Extremes" the first of a two part series on extremophiles. We also highlight Virgilio Martenez-Velez, a wildly innovative designer from Peru who studies vertical ecotones and uses the sustenance produced as his medium. Heidi Fischer, in her ongoing series, follows biologist Chris Smith as he seeks to unravel the shared conditions of the Joshua Tree and a small pollinating moth that may have led to new species on the grand path of evolution. Finally, we interview three men who have made bio-inspired innovation and its study their vocations. Jan Knippers is the highly regarded German engineer working at the pioneering edge of lightweight organic structural form. Tim McGee is the founder of LikoLab, a multi-dexterous and biologically inspired consulting firm. Vytas Sunspiral is an entrepreneurial researcher working across disciplines to blend biologics, artificial intelligence and robotics into new paradigms for useful devices. Innovators all, they may give you an idea of the conditions they have created for bringing new ideas to our world. Happy reading! ×



Tom McKeag, Norbert Hoeller and Marjan Eggermont

A globular dandelion siphonophore

Photo: NOAA Photo Library, 2015 | Flickr cc

Article

Going to Extremes

Tom McKeag

vol 3 | 2017 **Article** Going to Extremes **Author:** Tom McKeag

Going to Extremes

Part one of two parts: extraordinary organisms

Biomimics have several ways in which to study living organisms for clues to solving their problems. They might look to compare functional success across ecosystems, or they might study the variations and range of success of single mechanisms. They might investigate convergence, where the same solutions have evolved in genetically distinct species. They might study all-round survivors, or, alternately, specialty champions, in say, speed or strength or endurance. One path to insight is to study those organisms that can really take it; live and reproduce under the most demanding conditions. These are the extremophiles. They exist all over planet Earth, have been here a lot longer than we have, and have much to teach us about how to thrive under adversity.

Acid

The Rio Tinto River flows in deep red hues from the Sierra Morena mountain range 95 km south-southwest to the Bay of Cadiz on the Atlantic. It is from an embayment of this very river that Columbus set sail in 1492, to discover a small tip of another world on the other side of the ocean. His voyage was as tied to the red color of the river as its geographical location. The river is red because of iron, and that iron is associated with the mining that brought forth the wealth that helped launch the great age of European maritime discovery.

The Iberian Pyrite Belt is one of the richest sulfide deposits in the world and strikes a 250 km east/west swath across southwest Spain and parts of Portugal. Within it is an ore deposit rich in iron, copper, zinc, gold, lead, arsenic and silver. The Rio Tinto has been mined since around 3,000 BCE, and scholars believe that this was the birthplace of the Copper and Bronze Ages. Iberians and Tartessans from the region first worked the pits, and then Phoenicians and Romans, lured across the Mediterranean by the rumor of riches. Some of the first Roman coins were minted from metals found here. Later, Visigoths, then Moors, Spanish and English all worked the mines up until circa 1998. As a result, the river holds the dubious distinction of being the longest continually polluted watercourse in the world and one of the worst.

This is also the world's most acidic river, made from water with a pH range from 1.7-2.5. This is more acid than lemon juice, which contains 5-6% citric acid and typically has a pH of between 2 and 3. You would not want to mix the waters of Rio Tinto for your lemonade, however, unless you desired a toxic cocktail of heavy metals and a draught comparable to sulfuric acid (around a pH of 2.0).

Despite this toxicity, life seems to not only exist here, but to thrive. Over 1300 forms of life have been collected and include bacteria, dia-

Rio Tinto | Photo: BigMaxPower(BMP), 2009 | Flickr cc

Euglena (middle) and *Aphanothece* [1 cm = 20 µm] | Photo: Proyecto Agua, 2010 | Flickr cc toms, yeast, fungi, algae and protists. The fact that a wide diversity of the more structurally complex *Eukaryotes* thrive here has fascinated scientists and upended the common belief that extreme environments only support *Eubacteria* and *Archaea*.

This trophic system is based fundamentally on the bacteria, and there is evidence that they are not only thriving in the river's extreme environment, but are creating it and causing its red color. The chemical structures currently being formed in the river are similar to the structures in bioformations found in ancient terraces of the river that predate mining. In other words, iron-loving microorganisms here have been creating acidic fluvial conditions by their metabolic activity for thousands of years.

These are so-called chemolithotrophic organisms; ones that feed on the chemicals from rocks. Iron-oxidizing and sulfur-oxidizing bacteria like *Euglena mutabilis* and *Thiobacillus ferrooxidans* have been making the river red for thousands of years. The Phoenicians called it "the river of fire". Bacteria with more discriminating palates restricted to iron, like *Leptospirillum ferrooxidans*, are voracious eaters and can skeletonize steel plate in a matter of a dozen years. Other bacteria appear to dine on the natural troves of metal sulfides, creating the sulfuric acid that, when mixed with the oxidized iron, cultures heavy metals in solution.

This environment is so unique and unlike what typically supports life on earth that scientists have used the area as a study zone for learning more about our terrestrial past and what may be our extraterrestrial future. The conditions here might be comparable to the Proterozoic (between 2.5 billion to 600 million years ago) where a mix of aerobic and anaerobic organisms co-existed and influenced their physiochemical surroundings. It might also be our closest model for the environment on Mars.

The Iberian Pyrite Belt was formed in an ancient hydrothermal system associated with basaltic volcanism. The presence of volcanoes and surface ice on Mars suggests a similar regime. Mars also has a lot of iron and sulfite, the components for sulfides like those at Rio Tinto, and basaltic volcanism appears to have been widespread on the Red Planet.

NASA scientists have drilled below the surface of Rio Tinto for core samples in order to assay organisms that do not get their energy from the sun, but from chemicals like iron and sulfur, the chemoautotrophs. This work has been conducted through the Mars Analog Research and Technology Experiment (MARTE), and has served as both an exploration of life in the Rio Tinto area, and a testbed for sampling techniques and technologies for the exploration of Mars. If life is to be found there it will probably exist underground and might use some of the survival techniques found in what the Moors called "the River of Sulfuric Acid".

Alkaline

Over 3600 km west from where Columbus made landfall in the Bahamas is a unique place of equally harsh natural wonders in the landlocked center of the continent he thought was Asia. Yellowstone National Park in the states of Wyoming, Montana and Idaho, USA, has been shaped by relatively recent seismic activity that

Grand Prismatic Spring Colors - Yellowstone National Park | Photo: brewbooks, 2016 | Flickr cc

has created highly alkaline hot springs. Many species of thermophilic bacteria, producing bright yellows and oranges, as well as viruses and diatoms exist where water temperatures may routinely reach 30-85 degrees C and pH values hover typically between 6 and 9.

Salt

685 km southwest of Yellowstone is another alkaline geographic feature; this one is also hypersaline. Mono Lake, in the state of California, lies to the east of the Sierra Nevada range. It is one of the most alkaline and saline lakes in the United States and it is also quite old; around 760,000 years. The unusual water chemistry contains carbonates, chlorides and sulfates, and average salinity is measured at 81 grams per liter, or about three times saltier than typical seawater. The salt is mainly sodium chloride, but also comprises sodium sulfate, and carbonate. The lake is 80 times more alkaline than seawater, with a pH of 10 and contains unusually high concentrations of borate and potassium.

Salt lakes typically exhibit other daunting challenges to life: extreme temperature swings, anoxic conditions, and wet/dry cycles. As in many extreme environments, the lake's conditions have favored a less diverse population dominated by a few species; multiplied unchecked by aquatic competition or predation. The fascinating array of creatures in this ecological niche includes around 5 trillion brine shrimp, *Artemia monica*, alkali flies, *Ephydra hians*, autotrophic algae and bacteria that form extensive gelatinous mats.

A. monica is endemic to this lake, but the genus is found worldwide wherever terrestrial water bodies have high salt, as much as 250 grams per liter or 250%. While 30-35% is optimal physiologically for the shrimp, 60-80% is the level where they escape aquatic predators unequipped to survive in the salt. While neither shrimp nor the flies (who spend most of their life in water as larvae) have to worry about being gulped down by fish, they do have to mind the skies above. Mono Lake is a haven for thousands of migratory

Alkali Flies

Photo: The Wandering Herpetologist, 2012 | Flickr cc

***Artemia monica* | brine shrimp**

Photo: djpmapleferryman, 2008 | Flickr cc

Tufa Towers Mono Lake | Photo: mo1229, 2016 | Flickr cc

Mono Lake

Photo: John Getchel Photography, 2013 | Flickr cc

birds drawn to the abundance and to the safety of the lake's two islands. As many as 800,000 have been recorded in a single day.

Within their one-year life cycle, brine shrimp have evolved two critical advantages. When oxygen is low or salt high, days short or temperatures wildly variable, *Artemia* secrete a rigid noncellular shell to protect themselves. The female crustacean will also lay her eggs or cysts with a protective chorion coating that allows them to remain in cryptobiosis for two years, withstanding extreme cold (-190 degrees C) and heat (105 degrees C) for short periods of time as well as no oxygen. The chorion has two distinct layers, an outer compact cortical layer composed of chitin, lipoprotein, hematin, and some metal elements and an inner alveolar layer. All of this is overlain by a supra cortical layer, a three-layer composite of fibers sandwiched between cuticulin membranes. This cyst shell plays an important role in resistance to UV irradiation, large temperature differences, osmotic pressure, dryness, and organic solution stresses. The combination of the protective shell and the ability to lapse into diapause or physiological dormancy has enabled the shrimp's evolutionary survival for some 400 million years.

Cold

The Southern Ocean surrounding Antarctica is at once the most challenging marine environment on Earth and the richest. The uninterrupted waters south of 65 degrees south latitude move in the Antarctic Circumpolar Current, the strongest current system in the world, moving great masses of water one hundred times the volume of all the world's rivers, ever eastward in a complete circle. The strongest average winds in the world blow here and water temperatures range from -2 to 10 degrees C. Seawater, because of the presence of salt, stays liquid at lower temperatures than fresh and so is intensely cold. In winter, all coastal waters not raked by high offshore winds freeze outward to the 55 or 65-degree south latitude.

These waters present extreme survival challenges to animals, but also rich rewards. The displacement of water and the differential between Antarctic and sub-Antarctic waters brings dense and salty water from the rich benthic zone depths and with it phytoplankton. Copepods and Antarctic krill feed on the plankton and from them an entire food web is supported that includes fish, squid, whales, seals, penguins and tens of millions of migratory birds.

Among the animals that feed on the krill are the five families of notothenioid fish. They are psychrophiles or "cold lovers", experts in coldwater living. They represent over 90 percent of the fish biomass of the region. They have survived by a race to the bottom with the seawater itself. As the water's freezing point has been lowered by salts, the fish have evolved a blood that stays liquid to even lower temperatures (-2.5 degrees C) by a combination of antifreeze proteins and normal body salts. These proteins bind to and inhibit growth of ice crystals within body fluids through an absorption-inhibition process. The proteins attach to small ice crystals, stemming their growth. The fish live with small ice crystals in their blood that do not hamper their physiology.

Heat

The same kind of hydrothermal activity that NASA researchers are hypothesizing about for Mars and Jupiter's moon Europa happens here on earth, and some of the hottest spots on the planet occur under the ocean in deep sea vents. This is where magma from below the earth's crust wells up near the surface at edges of the tectonic plates. Seawater percolates down through these cracks, is superheated by the hot magma and reemerges to form the vents, chimney-like formations of accreted material.

An ocean hydrothermal vent might occur 7,000 m deep in perpetual darkness and in 2,000 times the pressure we feel at the ocean's surface. The 350 degree C fluids are hot enough to melt lead and spew toxic chemicals into near-freezing seawater in great billowing plumes of either black (iron sulfides) or white (barium, calcium and silicon). Interestingly, although the fluids are extremely hot, they do not boil: the pressure is too great for the liquid to turn to a gas.

Despite these violent extremes a complex and robust ecosystem thrives. First discovered in 1977, near the Galapagos Islands, these communities are every bit as fascinating as the landed communities made famous by Darwin. Unlike terrestrial communities and those in the sunlit surface waters above, this trophic system is energized not by photosynthesis from sunlight, but by other means. The *Archaea* bacteria and microbes forming the base of this system have evolved chemosynthetic, rather than photosynthetic, processes. They create organic matter by using oxygen in seawater to oxidize hydrogen sulfide, methane and other chemicals found in the vent fluids. Clams, mussels, snails

Copepod | Photo: Labut, 2005 | Flickr cc

Riftia tubeworm colony, Galapagos | Photo: NOAA Okeanos Explorer Program, Galapagos Rift Expedition, 2011 | Wikimedia Commons

A globular dandelion siphonophore | Photo: NOAA Photo Library, 2015 | Flickr cc and shrimp feed on the microbes and in turn are eaten by fish and other predators. There is also mutualism occurring here, as creatures like red-tipped tubeworms, white crabs, dandelion siphonophores and shrimp host the microbes on or in their bodies in exchange for the nutrients produced by them.

The discovery of these lush living communities in these other-worldly conditions has completely changed the theory of how life may have formed on earth. These *Archaea* are thought to be the oldest forms of life on Earth. Life as we know it may have started in these extreme and violent conditions: in complete darkness, under tremendous pressure, in a superheated bath of toxic chemicals.

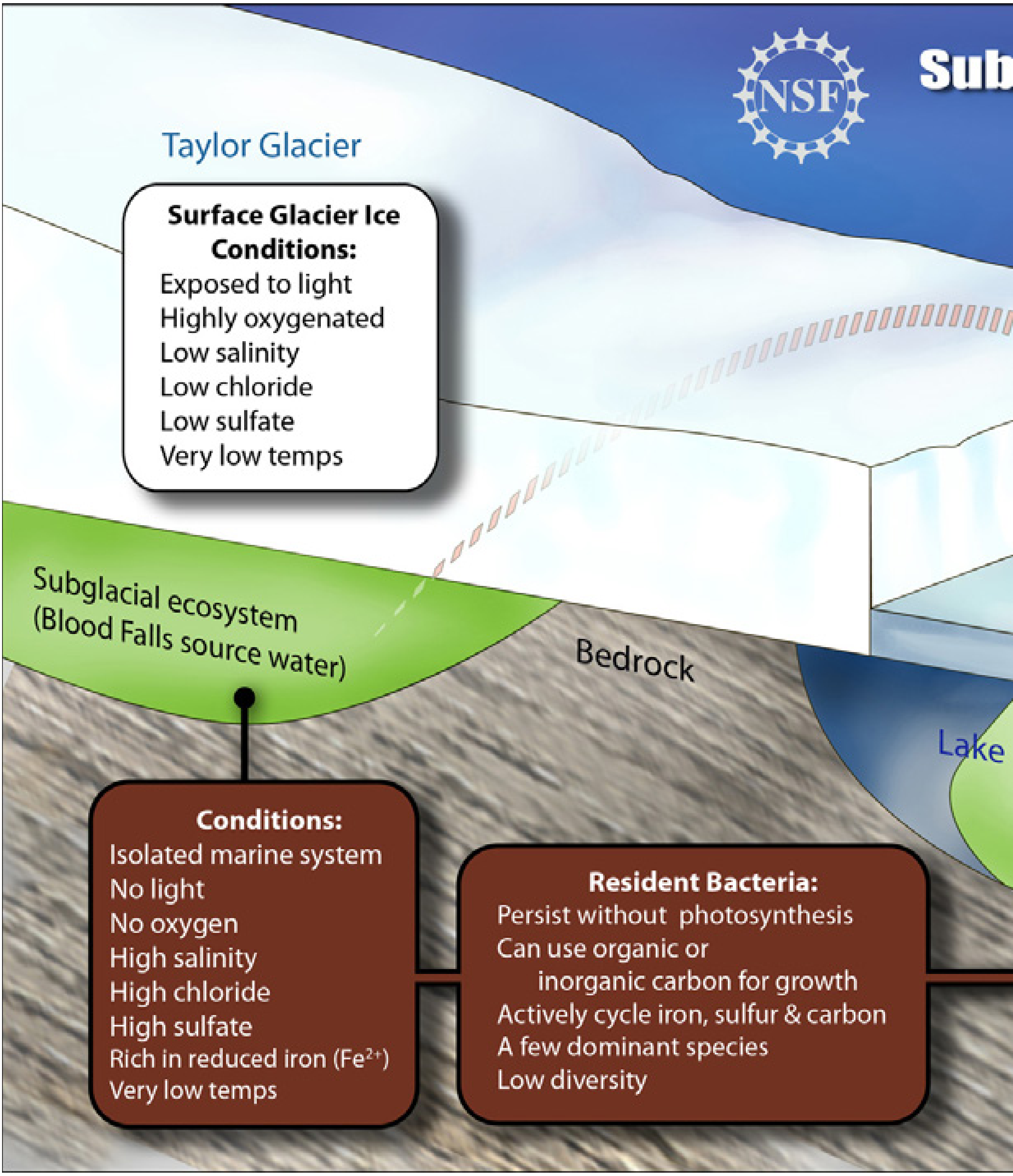
Dryness

The McMurdo Dry Valleys in Antarctica are just that. Located in southern Victoria Land, west of McMurdo Sound, they comprise about 4800 square kilometers of icesheet-free desert, the driest on the planet. Average temperatures here are -20 degrees C, and annual precipitation in the Wright Valley, for instance, averages less than 100 mm (3.9 inches) water equivalent per year. The valleys are sandblasted by strong, katabatic winds averaging 50 kilometers per hour. Cold dense air pulled down from East Antarctic Ice Sheet heats up as it descends and dries everything in its path, sometimes reaching speeds up to 320 kilometers per hour. Because of this lack of water, the ability to dry out, suspend activity, and resume life when moisture returns is a distinct advantage.

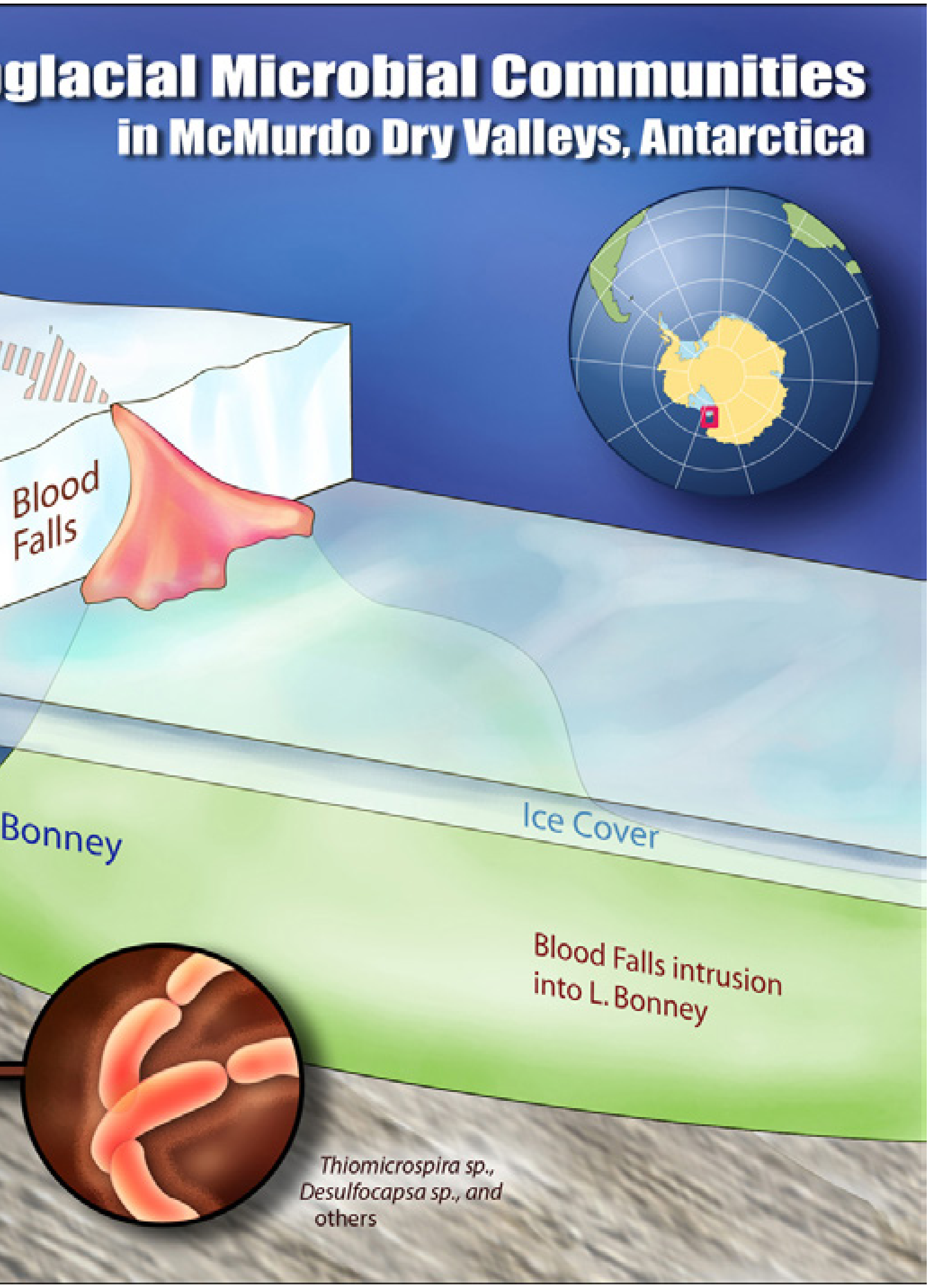
In some places, glacier melt during summer provides the surficial soil moisture that makes the desert organisms spring to life: rotifers, tardigrades, famous for their cryptobiosis, and nematodes. The well-known Blood Falls of the Taylor Glacier, red from iron oxides, is an example. Also in these dry gravelly soils are, *Acidobacteria* and *Actinobacteria*, including *Deinococcus* and *Rubrobacter*, desiccation tolerant super-survivors. In much of these soils there do not appear to be the autotrophs that typically form the base of an ecosystem, those organisms that are the first to start the energy transfer by creating it themselves from either the sun (photoautotrophs) or chemicals (chemoautotrophs).

Most of the life of this place lives not in soil but in rock: endoliths and chasmoliths, dwellers within and between stone. A few millimeters below the rock surface they find higher, more stable temperatures, some protection from the intense UV radiation, and more retained moisture. They appear to be distributed in two distinct layers, a top 2 mm layer dominated by a lichen comprising the fungus *Texosporium sancti-jacobi*, and the alga *Trebouxia jamesii*. Below the 2 mm level the cyanobacteria *Chroococcidiopsis* dominates.

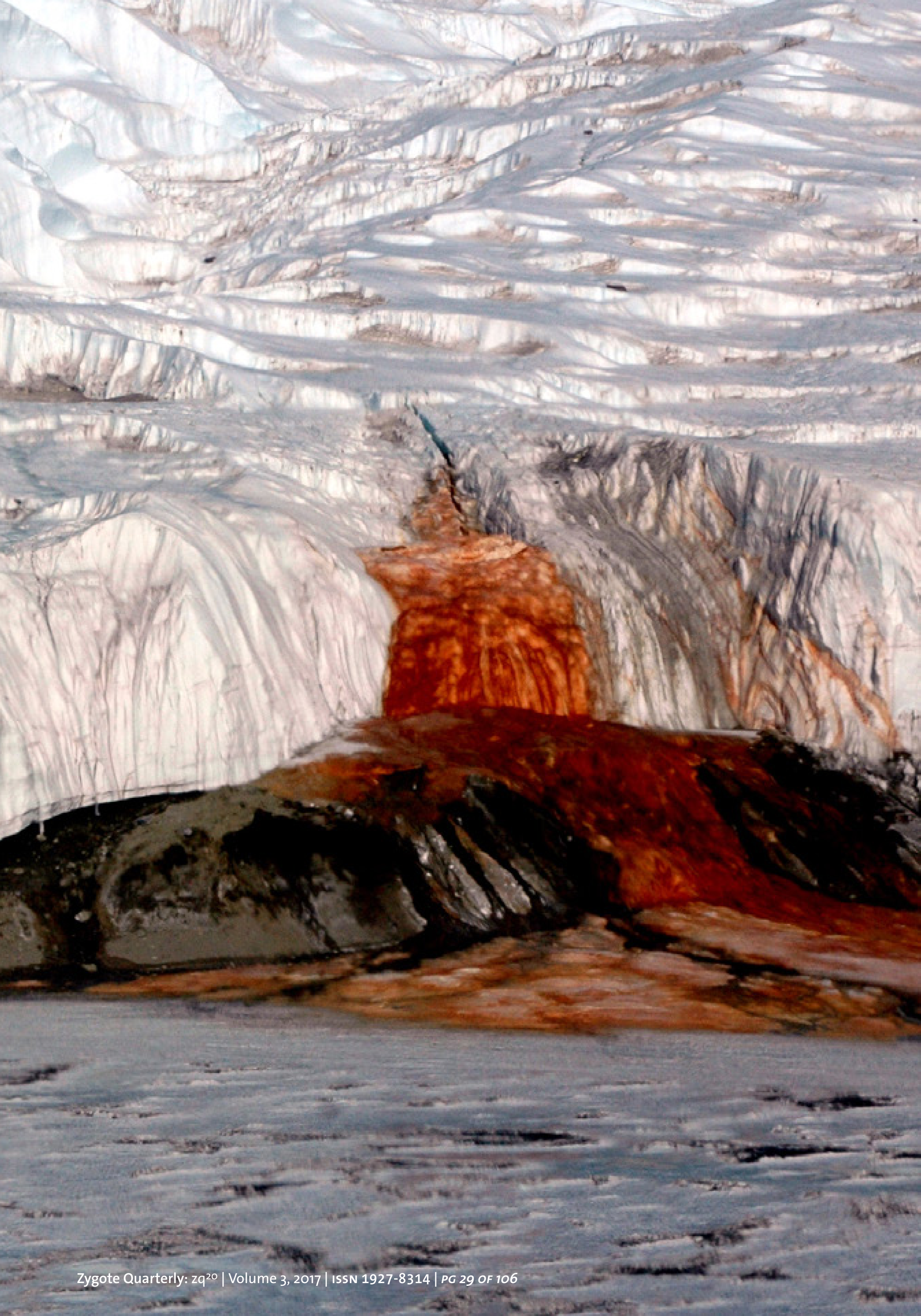
Chroococcidiopsis is as resistant to radiation damage as *Deinococcus radiodurans*. The *D. radiodurans* bacteria are found everywhere, but their ability to survive is anything but common. They can withstand radiation 1,000 of times more deadly than humans can resist (3 million rads). Their secret for success lies in their ability to repair DNA damaged by radiation, toxicity or accident. They can repair up to 500 breaks in their DNA nucleotide and replace the damaged chromosomes.

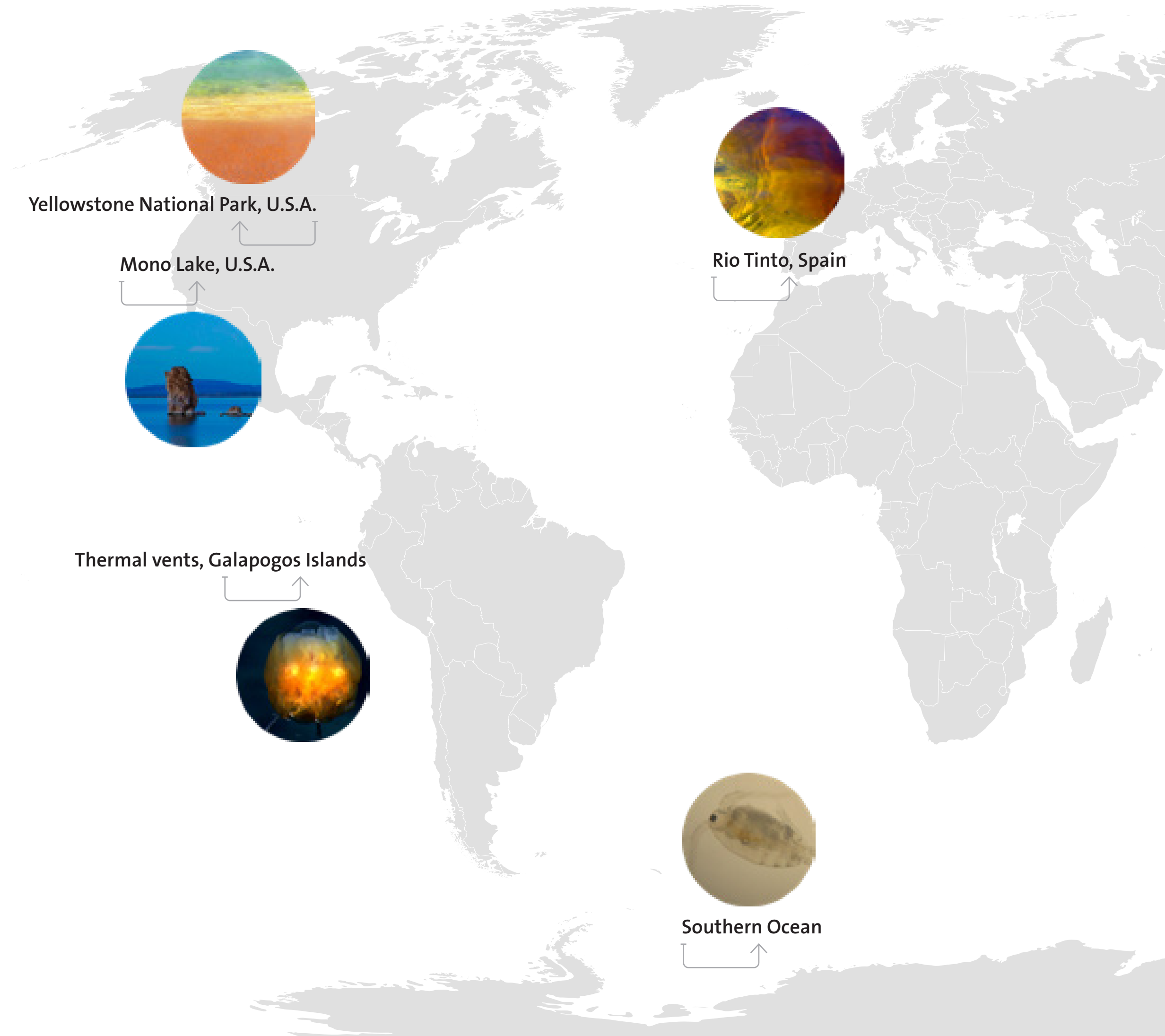


A schematic cross-section of Blood Falls showing how subglacial microbial communities have survived in cold, darkness and absence of oxygen for a million years in McMurdo Dry Valleys, Antarctica.
Photo: Zina Deretsky / US National Science foundation (NSF), 2009 | Wikimedia Commons


glacial Microbial Communities
in McMurdo Dry Valleys, Antarctica
Blood
Falls
Bonney
Ice Cover
Blood Falls intrusion
into L. Bonney
Thiomicrospira sp.,
Desulfocapsa sp., and
others

Blood Falls seeps from the end of the Taylor Glacier into Lake Bonney. The tent at left provides a sense of scale for just how big the phenomenon is. Scientists believe a buried saltwater reservoir is partly responsible for the discoloration, which is a form of reduced iron. | Photo: National Science Foundation/Peter Rejcek, 2006 | Flickr cc





World map

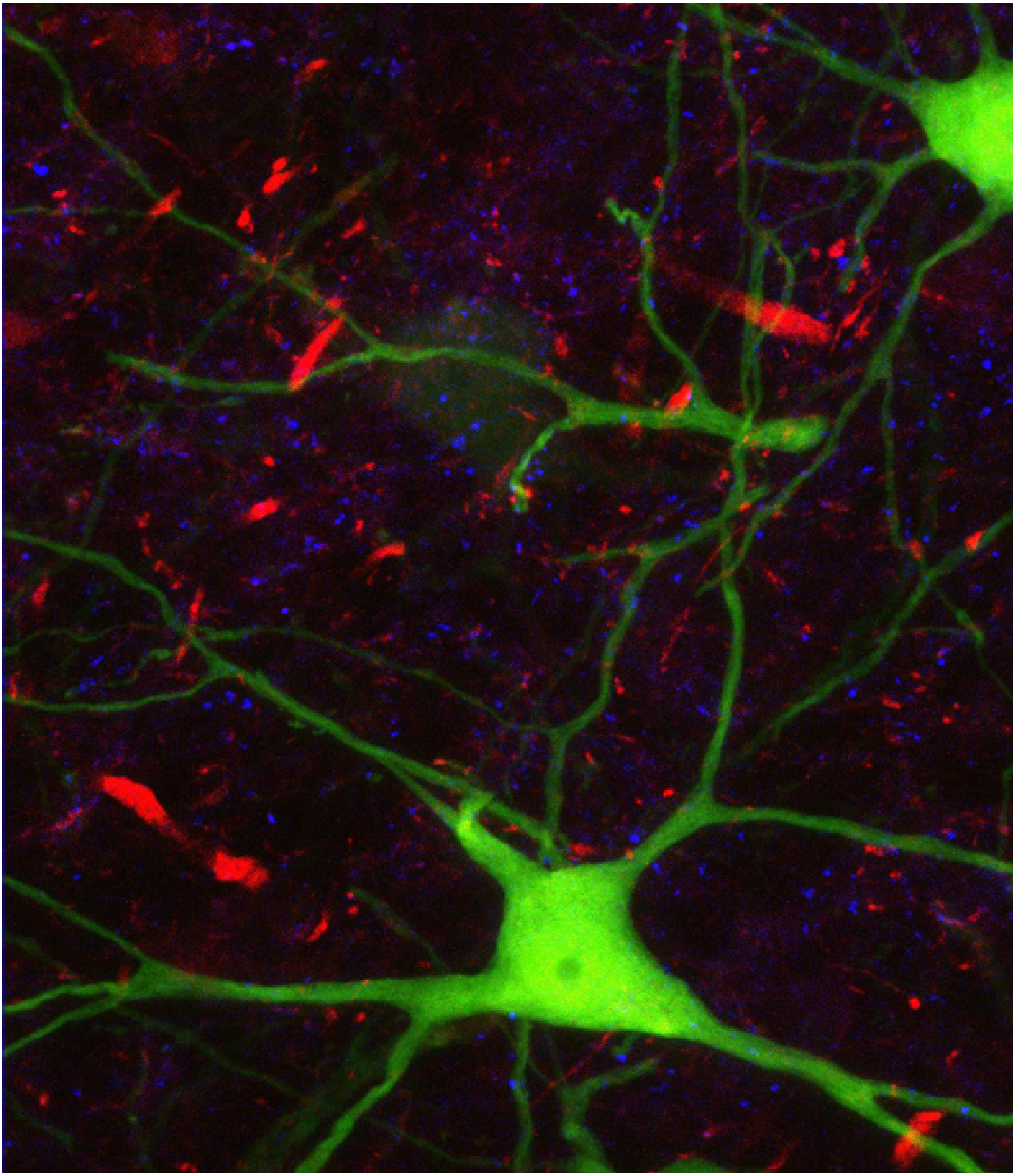
Image: McZusatz/DEMIS Mapserver, 2013 | Wikimedia Commons

Those living in the cracks of rocks are of a similar mix of various lichens and cyanobacteria. There are also cyanobacteria that live in translucent stone, the hypoliths, and squeeze all they can out of the little light that comes their way, less than 0.1% of incident light.

As at the Rio Tinto, scientists have been surprised at the diversity of life and the wide variety of mechanisms for survival. The three lithic communities studied include representatives from 19 phyla and 2 domains. Equally surprising is that those two domains do not include the *Archaea*, the typically assumed stars of extreme environments.

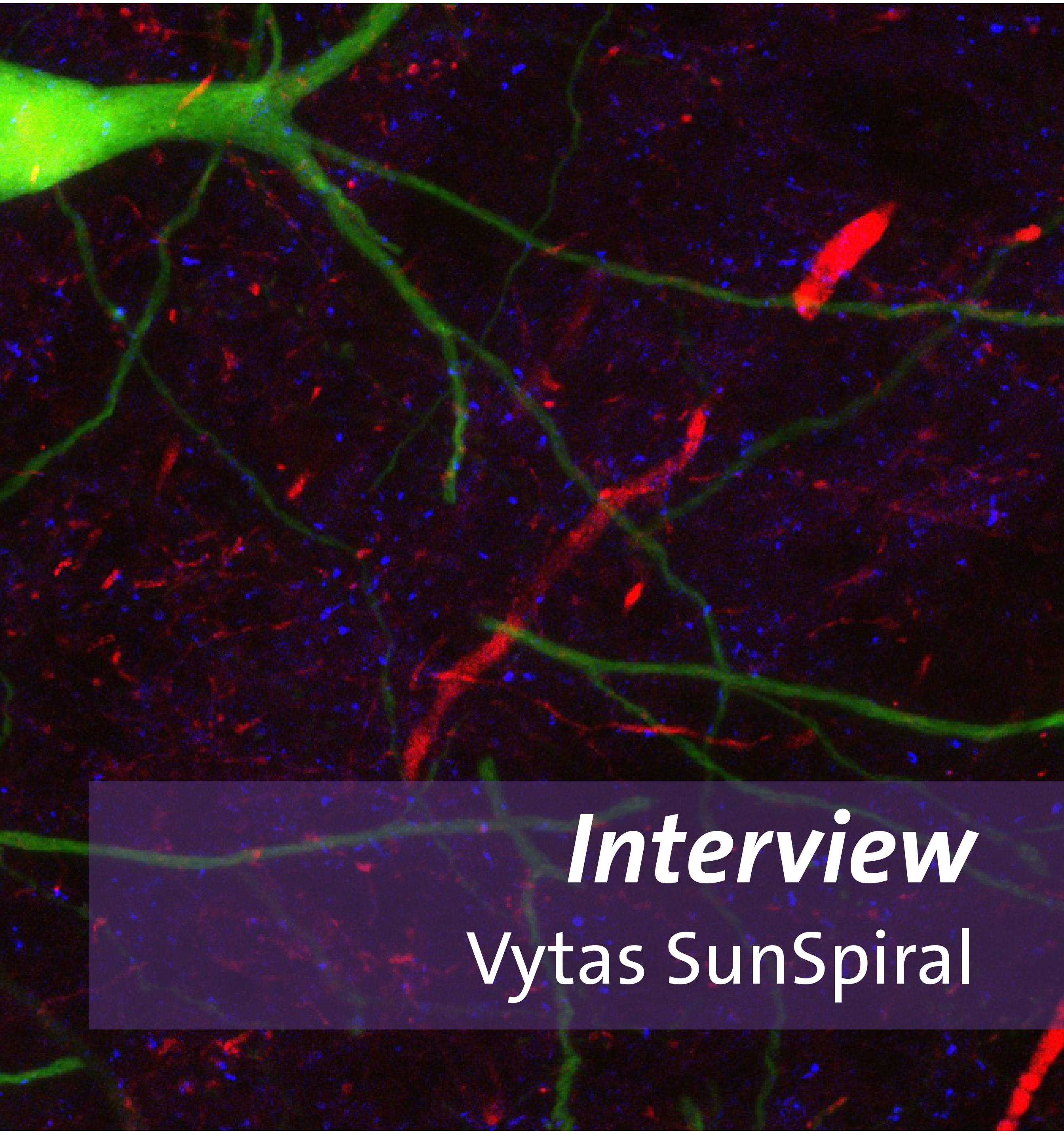
All around our globe, life persists despite conditions that seem insurmountable. The discoveries of new biological phenomena in unexpected places are providing clues to solving problems in many different fields. They are also revealing a wondrous richness in the biota that inhabit our planet, and testing long held assumptions about where and how life is possible. ×

Scanning electron micrograph of cyanobacterial sheath material, holding sand grains together, x 100.
Photo: USGS Canyonlands Research Station | soilcrust.org



Mouse brain, confocal microscopy

Photo: ZEISS Microscopy, 2014 | Flickr cc



Interview

Vytas SunSpiral

vol 3 | 2017 **People:** Interview **Author:** Vytas SunSpiral

Vytas SunSpiral is an entrepreneurial researcher moving fluidly between leading startups and building research labs to explore cutting edge robotic and AI technologies. He is a Fellow of the NASA Innovative Advanced Concepts (NIAC) program, and founded the Dynamic Tensegrity Robotics Lab (DTRL) within the Intelligent Robotics Group at NASA Ames Research Center. His research spans a multi-disciplinary fusion of robotics, physiology, AI, mechatronics, and neuroscience, with the goal of understanding human intelligence via the foundational role that motion plays in our evolution. This quest led to a fundamental new approach to robotics that has the potential to reinvent how we explore the solar system. He is an author of more than 50 journal and conference articles and was a contributing author of the 2013 Roadmap for US Robotics. Over the last 20 years he has also been the Founder, CTO, and Advisor to multiple startups, including Mobot, which sold the world's first commercially available autonomous tour guide robots. Vytas holds a Masters in Computer Science and a BA in Symbolic Systems from Stanford University. Vytas recently left NASA and is now the Director of Advanced Technologies at Zymergen Inc, where robotics and AI are enabling new approaches to engineering biology from the DNA up. This fusion of biology and technology is increasing the yields for industrial fermentation processes, and is enabling the discovery of novel materials which cannot be synthesized with existing engineering methods.

Vytas SunSpiral

How did you get started in robotics?

While in high school, I became fascinated with how we think and how intelligence works. Later I attended the interdisciplinary Symbolic Systems program at Stanford University that combined philosophy, computer science, psychology, and computational linguistics. Noam Chomsky and his ideas of the decomposition of language and the structure of language were popular but did not seem to reflect how I learned languages through immersion. It felt as though we were imposing our structure on the natural system we were studying, rather than understanding how language works in practice.

Artificial Intelligence at the time emphasized symbol manipulation. A 'tree' would be broken down into the component elements, but again this did not reflect how I *experienced* a tree. I concluded that intelligence came through experience and interaction – being embodied in the world. I became interested in robotics as an example of 'embodied machine intelligence', particularly robots that built a picture of their world through exploring it.

What else influenced your thinking about robotics?

I have always been interested in 'being in my body', through yoga, dancing, and martial arts. All that fun also resulted in some injuries which led me to holistic therapists and how they understood the body. For example, rather than recommending rest, they applied active manipulation in one part of the body that influenced the functioning of other parts. I began to appreciate the body as a complex, tensile network that worked holistically to redistribute forces. This integrative approach was dramatically different from the simplified engineering models of robots that dealt with single axial rotation.

The eureka moment came while attending a 2007 Bodyworlds exhibit (http://www.bodyworlds.com) displaying human bodies preserved through Plastination. I realized that connective tissue was acting as a 'whole body' harness which could only be understood us-

First SUPERball prototype in front of the NASA Ames Wind Tunnel. Many fundamental design and control insights were gained with this version.

Photo courtesy of Vytas SunSpiral

ing a distributed approach. In contrast, robotics typically involved numerous sensors that fed information to a central processing unit that in turn controlled discrete actuators. Such an approach breaks down as the degrees of freedom increased beyond seven due to the computational complexity. The human body with hundreds of muscles is based on a different model involving local sensing and control combined with the tensile network of connective tissue that links the distributed components. As shown by extensive research into decerebrated animals, complex motion is possible without any form of central control.

What are the major challenges facing bio-inspired design?

We interpret the world through the filters of what we already understand, using existing knowledge to make sense of the river of information that we live in. The challenge is that we often use engineering paradigms when we try to understand biology, even though these paradigms do not accurately reflect the underlying biological principles. The reductionist approach involving mechanistic deconstruction can allow us to apply mathematical and analytical methods that we are familiar with in new situations, but may also prevent us from fully understanding the complexity of biological systems, and even increasingly complex technical systems.

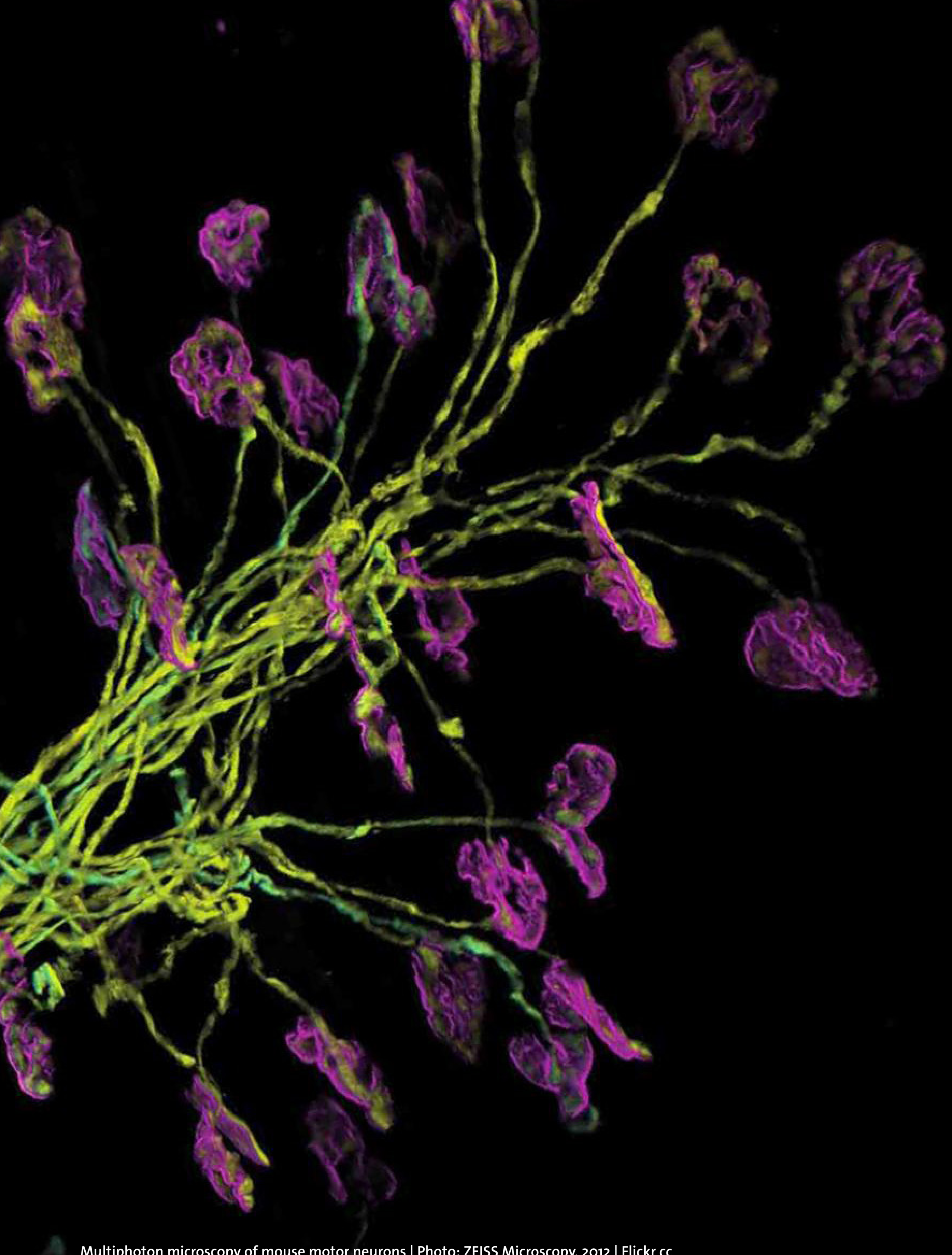
The tools and devices available in engineering do not map perfectly to biology. Muscle groups are not comparable to mechanical actuators – they are aggregates of thousands of muscle fibers that act independently, delivering complex ranges of motion. Soft robotics is an interesting area of research that is beginning to address these issues.

How have you overcome these challenges?

The first step is realizing that we are applying preconceptions and filters to everything we study. The next step is building something based on our current knowledge, comparing the results to how natural systems work, then updating the filters and associated underlying assumptions. Being inspired by biology and developing an engineering solution is only half the journey – we need to honestly ask how our technical system compares to the natural system, and use that knowledge to increase our understanding of *both* systems. The different perspectives of therapists and engineers and the obvious differences in how the human body performs compared to our robots drove me to explore this gap and why it arises.

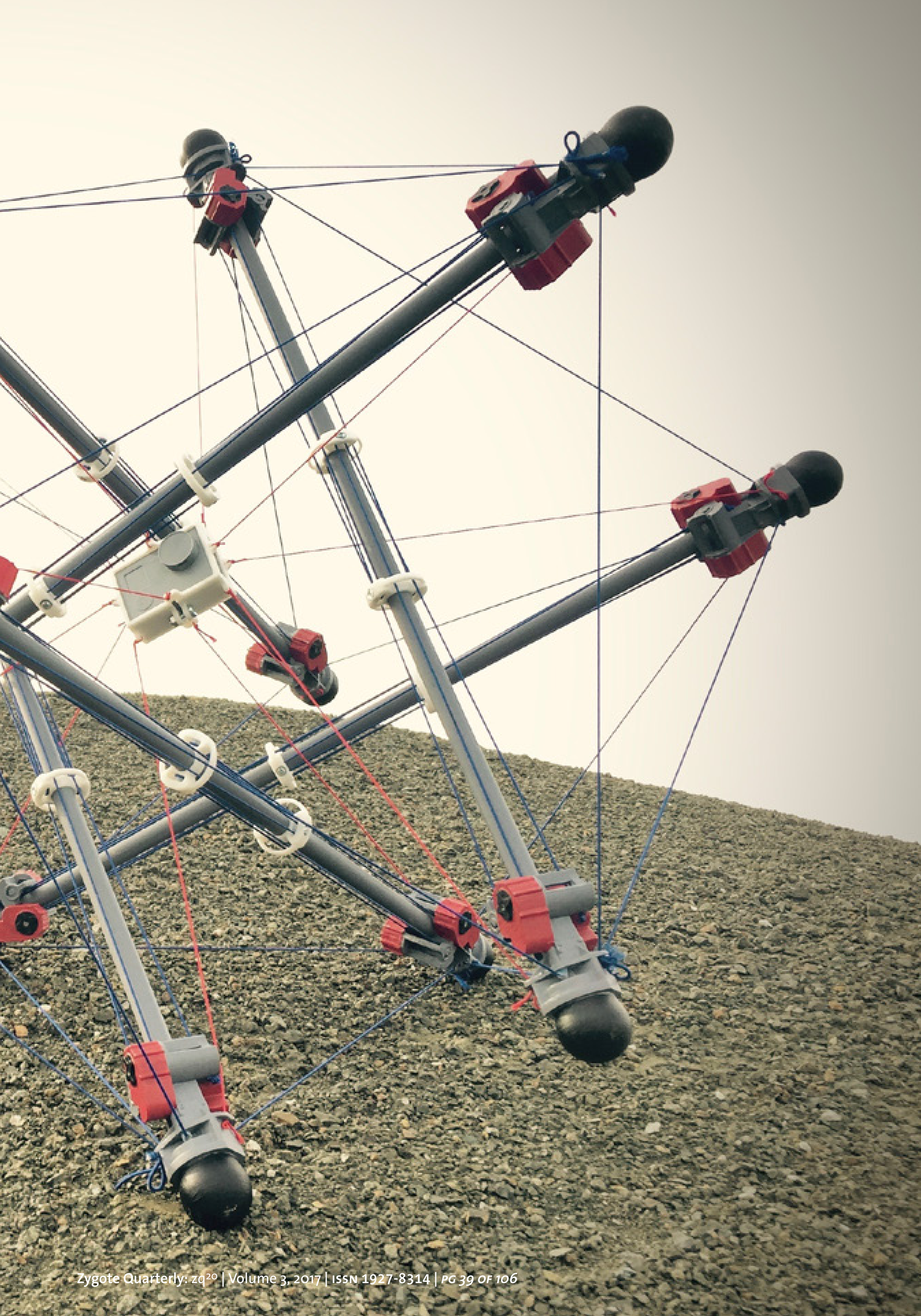
My core interest is understanding the human experience, using robotics as a mirror to increase my understanding of how the body and mind are integrated, and how the body works as a tensile system with distributed and decentralized control. I use the analogy of having biology and engineering ‘fun-house’ mirrors facing each other, creating an infinite creative space.

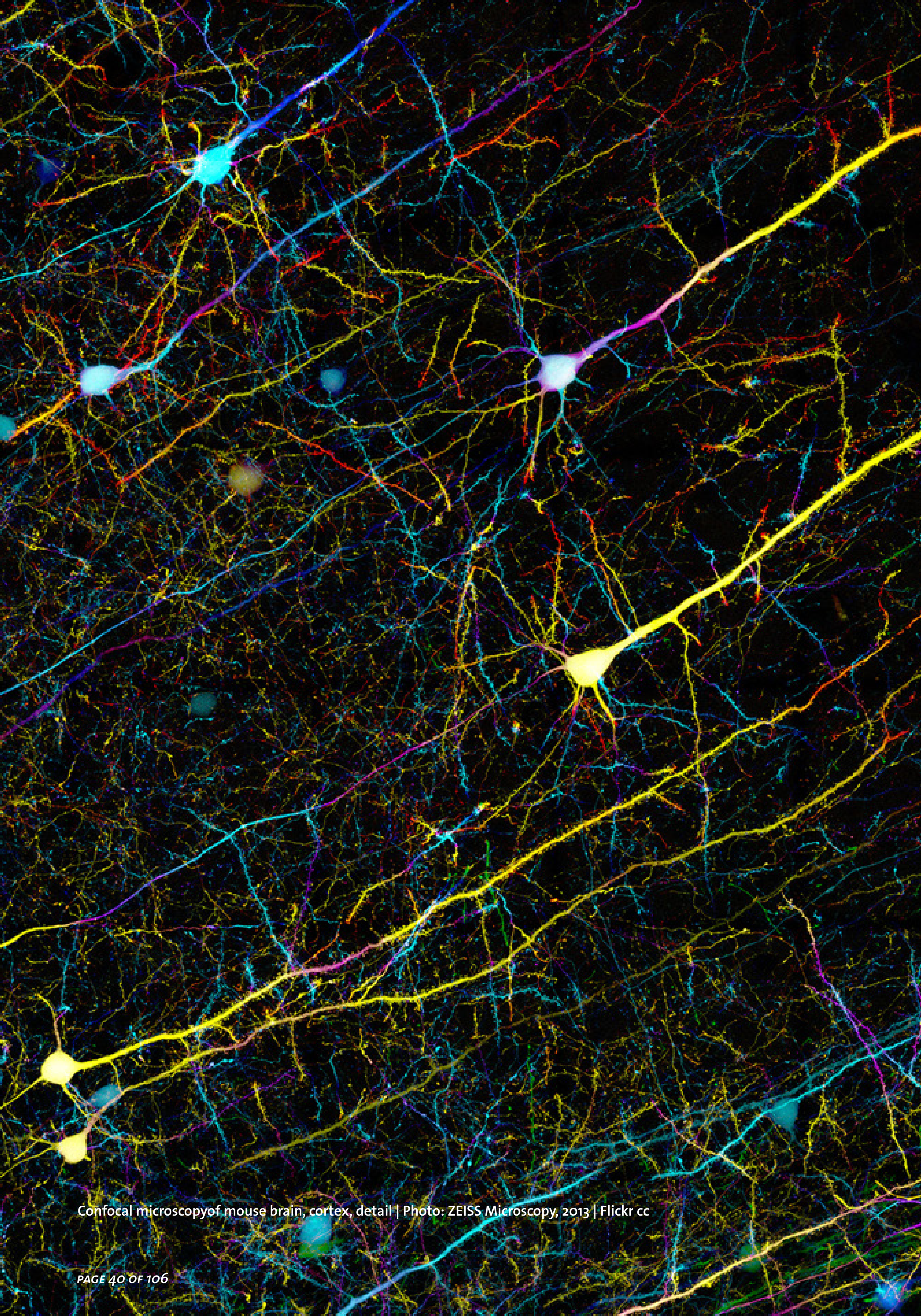
I avoid ‘toy problems’ that over-simplify complexity. Life must be reliable and pragmatic, and robots also need to survive in the complex, messy world. I have been fortunate to work on solving pragmatic problems for NASA although at times the engineering challenges make it difficult to ‘loop back’ to the biology.



Multiphoton microscopy of mouse motor neurons | Photo: ZEISS Microscopy, 2012 | Flickr cc

Scaled model of SUPERball V2. The full version is currently being manufactured, and will be capable of rolling off the roof of a building and landing safely and rolling to science targets. | Image courtesy of Vytas SunSpiral





Confocal microscopyof mouse brain, cortex, detail | Photo: ZEISS Microscopy, 2013 | Flickr cc

I often hear concerns that we lack the engineering capabilities required to implement solutions inspired by biology. It is worth remembering that we are seeing the result of incremental evolution that often started with simple and imperfect forms. Instead of waiting for the engineering capabilities to be perfected, work with what you have and incorporate feedback loops to mimic evolution.

How has your work developed?

After I graduated from Stanford, I helped launch my first start-up, Mobot Inc., where we made fully autonomous socially-interactive robots for museums, which required diving into physical aspects including electrical and mechanical engineering. Like many start-ups without a solid business plan, it eventually folded. After about a year and a half of adventuring and traveling, I joined NASA Ames Research Center in Mountain View. As I got deeper into robotics, machine learning, and state tracking algorithms, I began to feel that I was getting far from my roots of understanding humans: the interrelationship of our experience, how our bodies work, and intelligence. At the time, I was working on a four-meter-tall, six-legged walking robot called ATHLETE. The size of the robot allowed large internal lever-arms to magnify and accumulate forces at joints, which caused significant strain on its components as well as our models and algorithms, reinforcing my belief that biology had much to teach us about reliable and robust mechanisms.

Tensegrity principles have been used to design deployable structures – my interest is the redistribution of forces enabling direct engagement with the environment. Adrian Agogino and I were brainstorming with a tensegrity toy that easily survived rough landings. Tensegrity principles combined with my insights of the human body led to robots with physical priorities that had not been explored before.

Our explorations led to the Super Ball Bot, composed of rods without rigid connections but instead cables that collectively absorbed and distributed loads. It can land safely on a planet without complex landing systems like airbags, then roll across varied terrain by modifying its shape. The Super Ball displayed non-linear characteristics and could not be modelled using traditional methods. Rather than a central control system, we used adaptive machine learning and Central Pattern Generators inspired by neuroscience.

What allows you to make your ideas real?

I start by defining a vision and then determining what actions I can implement now that will help move toward that vision. I do not wait for the perfect plan – even if it exists, it will rarely survive contact with reality. I constantly look for learning opportunities that provide useful insights and capabilities.

I build and nurture an extensive network of collaborators who are leaders in fields related to what I am working on. I also rely on my local team who bring expertise and skills that I lack, and often deliver results quite different from what I expected.

What insights have you developed?

Math has limited our design space. For example, the math required to model flexible or compliant materials in design is really hard. Nature is not limited by mathematical models – it can use physical properties of materials that are non-linear. Natural systems handle the resultant complexity and unpredictability through distributed and emergent control systems that are compliant, resilient, and adaptable.

How has robotics changed you?

This is a hard question to answer, since I've been working with robots since I was in college, it is hard to separate the natural process of learning and growing from the impact of being in the field of robotics. Certainly, one important impact has been helping me be technically well rounded. While I started in AI, robotics encompasses all the branches of technology – including a wide range of algorithms (vision, localization, mapping, optimization, machine learning, etc.), mechanical design, electrical engineering, network management, user interfaces, and even material science. Good solutions require an integration of these many fields and more, so that has kept me learning and broadening my knowledge base throughout life.

What key messages do you have for the practice of bio-inspired design?

Biology is not always the best way to solve every problem. Ultimately both disciplines need to work together, which requires mutual respect. Both biology and engineering have addressed problems that the other discipline has not. Search for meaningful problems where biology can provide novel answers.

We all tend to play it safe, focusing on building expertise and staying within our comfort zone. Taking risks can be stressful but also exciting when we create learning opportunities at the intersection of biology and engineering.

Requirements are important but can inhibit creative/radical innovation. Search for key principles in biological systems, apply them to solve real problems, compare the results to your vision, and constantly strive to close the gaps. ×

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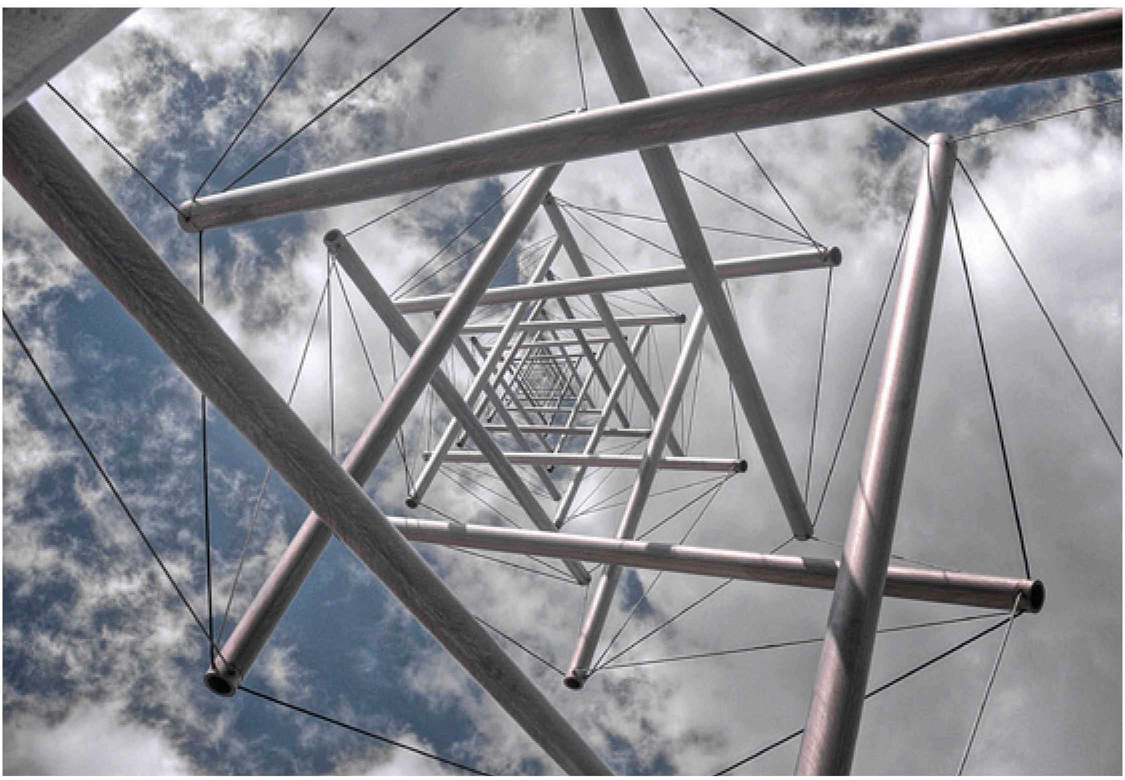


Tensegrity | Kenneth Snelson's Needle Tower

Photo: shonk, 2013 | Flickr cc

Harvest and Collection (detail) - Cosecha y recolección

Photography Central Restaurante

Portfolio
Central Restaurante
Virgilio Martinez

Peruvian chef Virgilio Martínez-Vélez chooses to approach the diversity of our ingredients in a manner similar to that used by the peoples of the Andes in pre-Hispanic times: through vertical ecological monitoring. According to this alternative way of understanding the geography, land is perceived not as a horizontal plane but rather vertically, so that it takes advantage of all that the flora and fauna are able to deliver according to the particularities of each ecological system. As a result of the dramatic fluctuations in the Andean terrain in a relatively small radius of 100 kilometres (for many farmers this is not a difficult hike), there is direct access to the country's products from various altitudes ranging from the coast to the Amazon.

Motivated by an insatiable curiosity and interest in conveying the complexity of their land, Virgilio is passionate about travelling and investigating ingredients that can bring undocumented and yet even more wealth to the local cuisine. He does so, through a number of areas: ocean, lower Andes, extreme altitude, and high and low jungles. He also has an interdisciplinary team that complements each new "discovery" in a necessary context that seeks to transcend the strictly culinary and penetrate nutritional, biological and anthropological aspects.

Virgilio Martínez-Vélez with his wife, Pía León, Central's chef de cuisine

Photography Central Restaurante

Could you tell us about how you are inspired by nature?

In many ways, biodiversity is key for us, we live in one of the most biodiverse places on earth where different microclimates coexist and provides us products, connection, and wisdom.

Seeing the world in altitudes help us to understand nature, in the way that we explore our territory going up and down, from the sea, to the Andes, and to the jungle.

What kind of techniques do you use for your work? Can you talk more about the approach you use?

We are open to different techniques no matter where are they from, modern and traditional are both part of our repertoire.

Can you tell us more about the Mater project?

Several Peruvian products are becoming increasingly known to the public due to their inclusion on the menus of Central Restaurante and Senzo, whose gastronomic offerings are influenced by the creative culinary process of Virgilio Martinez: the linking of the cultural and biological diversity of Peru with a culinary experience. In this search, Virgilio Martinez and a group of researchers travel to the countryside and compile the histories of these products, but above all, the histories of the life which give meaning to the inseparable union of the diversity of our land and Peruvian gastronomy. In this way, Mater was born, with the goal of sharing valuable information about Peruvian products with chefs and the public in general – now not only interested in good eating, but also in the knowledge of the origin of those local ingredients included on the menus. It seeks, in this way, to contribute meaning to the task of our producers and their knowledge, which form the base of our diversity.

Mater is the foundation of all we do, the soul of our work in a way. We register ingredients, traditions and methods in their origin, it allows us to understand our territory, our people, and mostly gives us the consistency for the future.

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

Travelling my territory, talking to people, and deep conversations about food are always important.

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

Mater Iniciativa labs, both in Peru, one in Lima and the other in Moray, on top of the mountains. For more on this initiative please see http://www.materiniciativa.com/en/ ×

Virgilio Martinez

Photography Jimena Agois

Virgilio Martínez-Vélez | Photography Daniel Silva

Andean Plateau - Altiplano y Ceja | Photography Central Restaurante

Colors of Amazonia - Colores de Amazonía | Photography Central Restaurante

Tree Skins - Pieles de Árbol | Photography Central Restaurante

Diversity of Corn - Diversidad de Maíz | Photography Central Restaurante

River Cotton - Algodón de Río | Photography Central Restaurante

Extreme Stems - Tallos Extremos | Photography Central Restaurante

Marine Soil - Suelo de Mar | Photography Central Restaurante

Extreme Altitude - Altura Extrema | Photography Central Restaurante

Virgilio Martínez-Vélez | Photography Jimena Agois

Jungle Scales - Escama de Selva | Photography Central Restaurante

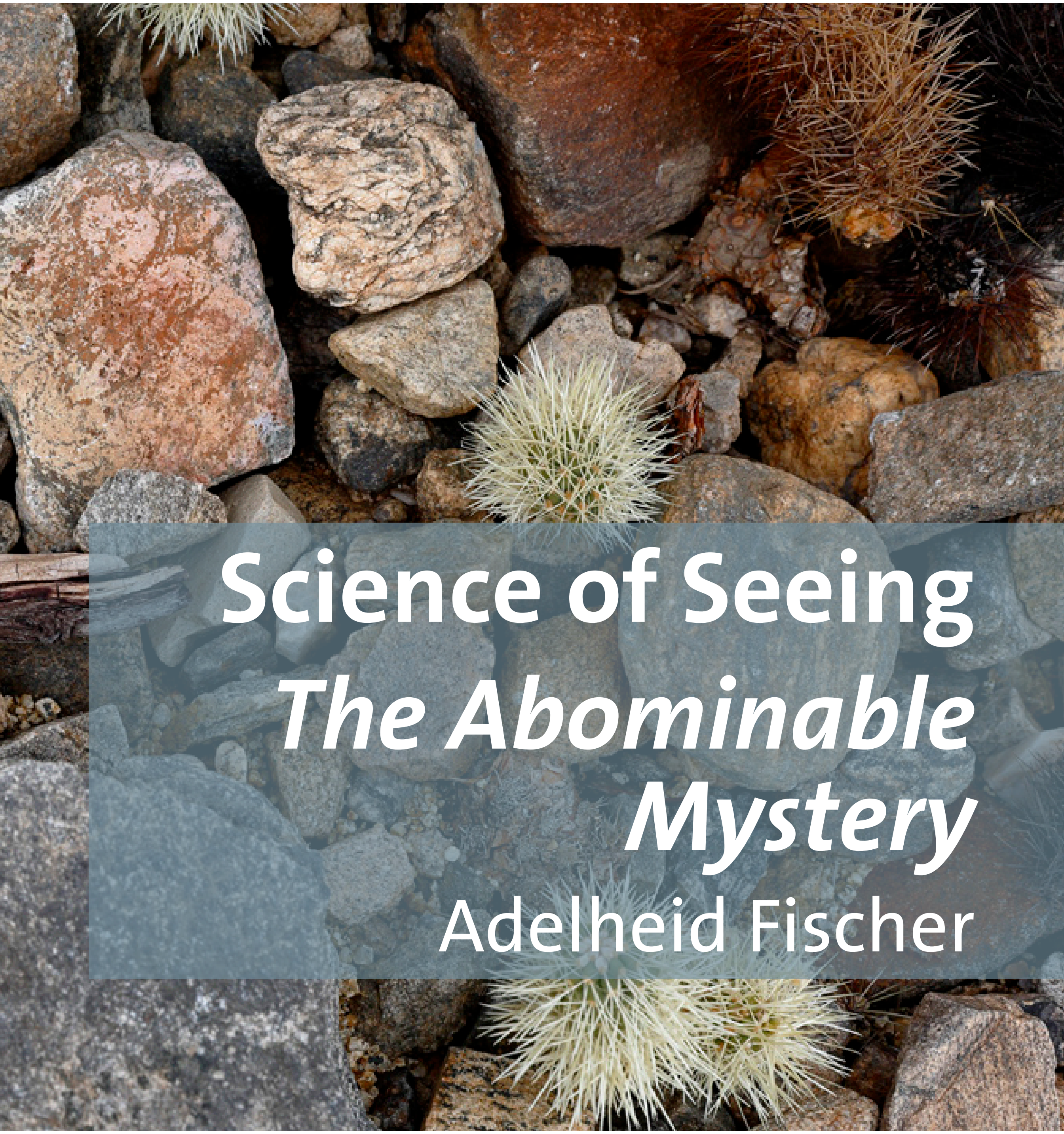
Low Andes Mountains - Cordillera Baja | Photography Central Restaurante

Close Fishing - Pesca de Cercanía | Photography Central Restaurante

Harvest and Collection - Cosecha y recolección | Photography Central Restaurante

Joshua Tree National Park

Photo: Ed Dunens, 2017 | Flickr cc



Science of Seeing

The Abominable Mystery

Adelheid Fischer

The Abominable Mystery

This past March I found myself in the remote Nevada desert several hours north of Las Vegas. To paraphrase an observation by the writer Gretel Ehrlich (unfortunately, one that too often comes to mind when I am on a solo road trip): I wasn't lost. I just didn't know where I was for a while.

I was searching for a gravel spur off U.S. 93 called Delamar Road where biologist Chris Smith and his field crew had set up base camp. For nearly fifteen years, Smith, a professor at Willamette University, has ventured into the remote corners of the desert Southwest to study the pollination biology of *Tegeticula* moths and giant yuccas, known as Joshua trees. As I began passing one unmarked gravel road after another, I discovered, much to my chagrin, that just because a road in Nevada bears a name on a map doesn't mean that a corresponding sign has been planted in the ground. Rangeland stretched from horizon to horizon with nary a cow or house in sight. Even more disconcerting was the fact that I seemed to be headed into the wrong ecological province for Joshua trees. The Mojave Desert, the main range of Joshua trees, began grading into the sagebrush ocean of the Great Basin Desert. My only recourse was to point the car in the direction of north toward a spot on the map marked *Joshua Trees* that was printed in an italic script so faint that it looked like a cartographical mirage. No, not Joshua Tree *City*, or Joshua Tree *Park* or Joshua Tree *Road*. Just *Joshua Trees*. It was like finding a generalized designation on a map for *Bluestem Prairie* in Kansas or *Redwoods* in California or *Bald Cypress* in Louisiana. In a sea of sagebrush, where best to find a Joshua tree researcher than in a place marked *Joshua Trees* on a map?

Then suddenly they appeared. The land gave way to an almost imperceptible rise out of what looked like an ancient low-lying playa. There on the slightly higher ground in the distance was the telltale sign of Joshua trees: a roughening of dark-green bristles on the landscape that, as I got closer, turned into a forest of spiked plants. A peek-a-boo, "now you see 'em, now you don't" kind of forest. "That's just how Joshua trees are," said Smith when I met up with him in his camp. It was located exactly where I had hoped to find him: smack dab in the heart of the cartographical mirage. On a range map Joshua trees are scattered in discrete clusters across parts of California, Arizona and Nevada. You can travel tens of miles without spotting a single plant and then, boom, wander into a thick shag of them as far as the eye can see. So magical is the abrupt appearance of these yuccas that Smith even has a recurring dream in which he stumbles across an undiscovered population of Joshua trees in his soggy home ground of the Pacific Northwest.

To be sure, not everyone has used the word *magical* to describe Joshua trees; the American explorer John C. Fremont encountered these tree-form yuccas on his travels in the American West in 1844. He described their tall trunks and crooked, upraised arms, their sword-shaped, razor-sharp leaves that from a distance resemble a sheath of loose bird feathers as a "stiff and un-

Joshua Tree National Park| Photo: Christopher Michel;, 2014 | Flickr cc graceful form [that] makes them to the traveler the most repulsive tree in the vegetable kingdom."

But Fremont is the exception rather than the rule. In 1936 the desert botanist Susan McKelvey declared in unabashed wonder that "one would not be surprised to see a huge prehistoric monster standing by and feeding upon the fruit." McKelvey wasn't the only one who was forced to raid her imagination to find a suitable description for the fantastical forms of Joshua trees. It is said that the children's book author and illustrator Dr. Seuss used them as a model in his 1971 book *The Lorax* for his much-beloved Truffula Trees, a mythical species of gangly plants crowned with a cartoonish mop of leaves.

By far the most enthusiastic fan of yucca plants, however, was none other than Charles Darwin. I thought of Darwin as I ventured into the field with Smith the day after my arrival in camp. Surely he would have given both his firstborn and his eye teeth to have stood beside Smith as he clipped flowers from the zig-zaggy branches of Joshua trees in search of their resident pollinating moths. Ninety percent of all land plants are pollinated by insects, Smith points out, including the dozens of species of yucca plants that cover a range from Guatemala north to Alberta, Canada. Most of these yuccas rely on their own particular species of moth for pollination. But yucca moths take the act of fertilization to a whole new level, as the great American entomologist Charles Valentine Riley described in a news-breaking account in 1873.

There are two words that describe the process of pollination by yucca moths: deliberate and methodical, a "far-cry from the almost accidental nature by which honey bees pollinate flowers," Smith observes. The story goes something like this. Following cues that are mysterious to scientists, adult moths time the emergence from their underground chambers to coincide with the spring blooming of yucca flowers. The male and female moths, which on Joshua trees are active during the day, stick close to the plants as they conduct their reproductive rites. When the mated female is ready to lay her eggs, she will visit the stamen of a yucca flower to scrape pollen from the anthers. She shapes the sticky pollen into a ball and uses a unique tentacle-like structure attached to her external mouth parts to grasp the pollen as she embarks on her egg-laying mission. The moth visits yucca after yucca, using a sharp tip at the end of her abdomen to pierce the pistil, or female part of the flower, and deposit several eggs on the ovules, or undeveloped female germ cells.

Before flying off, however, the female moths make sure that their progeny will be well provisioned with food. Crawling to the top of the pistil, they deposit pollen onto the flower's stigma, triggering fertilization and the subsequent production of seeds that will feed the developing larvae. Each blossom is marked with a pheromone, an olfactory stop sign that discourages other moths from laying their own eggs. Darwin was so taken by reading Riley's account of this intentional act of pollination that in an 1874 letter to his dear friend and colleague Joseph Dalton Hooker, director of the Royal Botanical Gardens, Kew, he rhapsodized that the win-win transaction between yuccas and their moths was the "most wonderful case of fertilisation ever published."

A female yucca moth (*Tegeticula synthetica*) pollinating a Joshua flower | Photo: Christopher Smith©, 2014

Joshua Tree National Park| Photo: Ed Dunens, 2017 | Flickr cc

Clearly, Smith thinks so too. Despite the fact that he has examined thousands of blooms over the years, Smith pauses with me to marvel over their improbable beauty. In desert environments, where plants are so parsimonious with moisture that most of their parts are leathery, spiny, dry or sandpapery, Joshua tree flowers seem almost recklessly profligate. Sprouting from the plants' branch tips are dense, artichoke-like flower heads that have the size and heft of a small, ripe cantaloupe. Each one contains tens of luscious, ivory-colored flowerets that are so thick and smooth to the touch that they seem to have been cast of wax. You might expect that such extravagant blooms would emit a pleasing, exotic fragrance but their odor is slightly rank and medicinal, reminding me of the industrial wax that was used to polish the floors of my convent grade school. Nonetheless, Smith points out that the flower parts are edible. He prunes away the petals of one floweret and offers me the vase-shaped ovary to taste. It is as crunchy and moist as a raw potato and tastes faintly like grass. So nutritious are these blooms that ranchers have reported to Smith that their cattle grow fat feeding on Joshua tree blossoms in the spring.

But there was a second, even more amazing surprise in store. As he peeled away the flowerets of one especially large head of blossoms, Smith spied a female moth diving for cover and quickly captured her in a clear plastic vial. This is the yucca moth, I gasped, the star of the pollination story that caused Charles Darwin to speak in exclamation points? Fluttering in the tube was a khaki-grey moth with silvery wings little more than the size of a cucumber seed.

Looks, however, are deceiving when it comes to Joshua tree moths. Smith strongly suspects that these drab, unimpressive insects wield an influence on Joshua trees that far exceeds their tiny proportions--and vice versa. Together the yuccas and their pollinating moths may be star players in an unfolding coevolutionary drama whose outcome is nothing less than the creation of new species on earth. And when it comes to coevolution, few stories are more classic than the one about the giant Joshua trees and its diminutive partner.

Interest in the evolutionary history of Joshua trees dates back to the work of early 20th-century field botanists who noted that populations in the western reaches of the plants' range, largely in eastern California and Nevada, had a dramatically different architecture than those in the eastern half of their range, mostly in Arizona. Western varieties of Joshua trees, known as *Yucca brevifolia brevifolia*, feature tall stems that are topped by an asymmetrical crown of branches. On the other hand, the branches of the more easterly variety, *Yucca brevifolia jaegeriana*, begin sprouting far lower to the ground in a more shrublike fashion. *Jaegeriana* also has shorter leaves than *Brevifolia*.

But things didn't get really interesting until recent years when scientists took a closer look at the *Tegeticula* moths that pollinate Joshua trees. They discovered that the body size of pollinating moths in the western part of Joshua tree's range were larger overall than those in the eastern part. Even more intriguing was the finding that the western moths had longer ovipositors than their fellow eastern moths. In subsequent tests, researchers declared that the differences between the moths were not simply morpholog-

Joshua Tree (*Yucca brevifolia*) panicle | Photo: Takwish, 2008 | Wikimedia Commons ical but genetic as well and in 2003 divided them into two separate species: *Tegeticula antithetica* in the east and *Tegeticula synthetica* in the west.

Scientists also began to look more closely at the differences between the two varieties of Joshua trees as well. They hypothesized that the two varieties took separate evolutionary paths after their range was bisected some five million years ago by an inundation from the Sea of Cortez known as the Bouse Embayment. They pointed to similar genetic differences in easterly and westerly populations of animals ranging from desert tortoises and spiders to snakes.

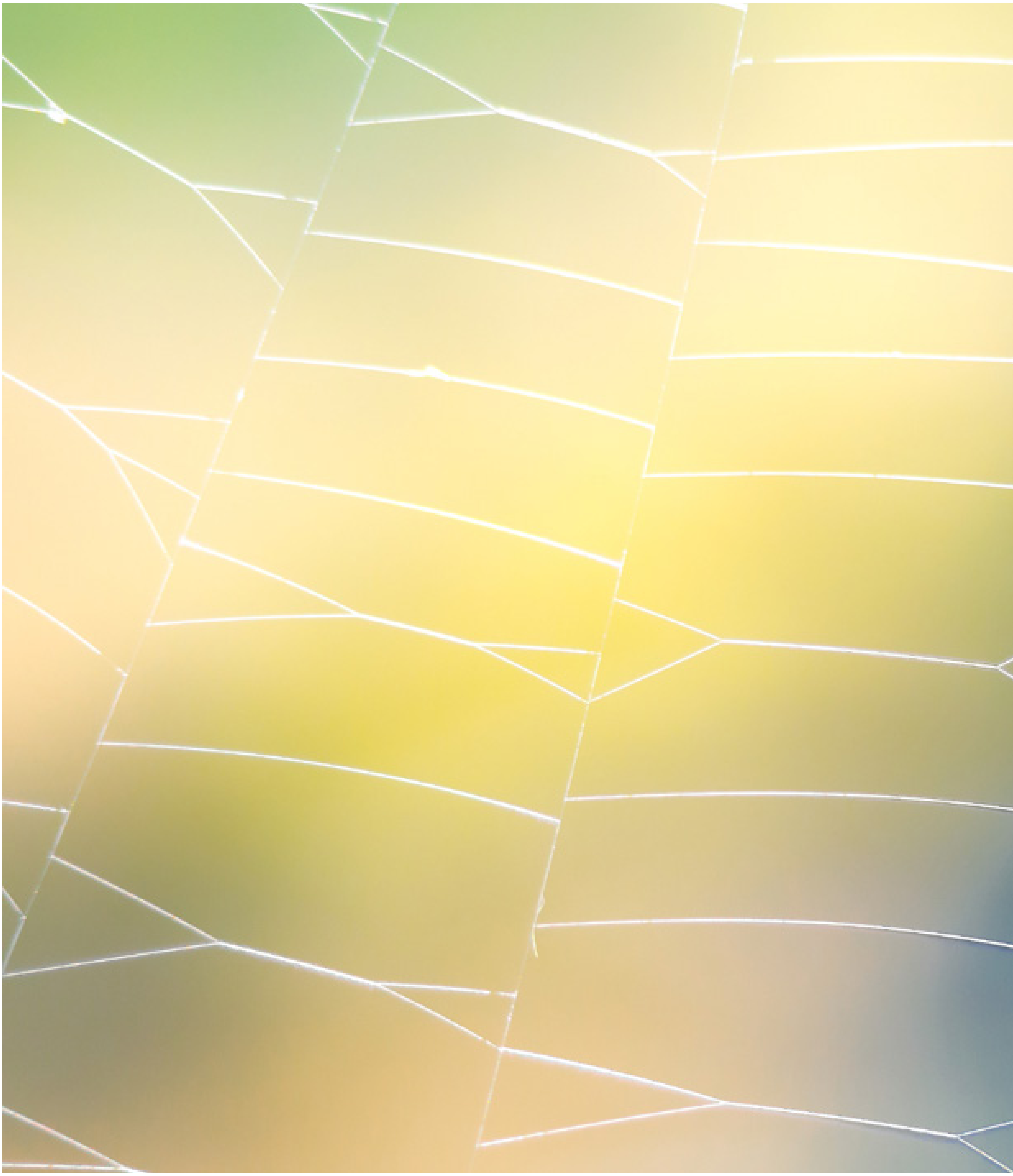
Subsequent genetic tests revealed, however, that the two varieties of yucca had diverged from a common ancestor prior to the incursion by the Bouse Embayment. “I got excited when I saw that the Bouse Embayment was not causing speciation [the formation of new species],” Smith recalls. The revelation prompted Smith to take another look at the pollination biology of yuccas and moths and begin investigations of a long-standing and tantalizing idea in evolutionary biology instead: that pollinators can drive plant diversification and, therefore, the formation of new species. Making a hard-and-shut case for the idea, however, “has turned out to be really hard. People have tended to get contradictory results in both theoretical and empirical research,” Smith observes.

Instead of looking at the pronounced differences in the architecture of the two yucca varieties, Smith began by focusing his attention on analyzing the structure of the flowers. A close examination of plant parts revealed that the length of the style (the tube through which the female yucca moth inserts her ovipositor in the process of laying eggs) was shorter by almost half in *Jaegeriana* than in *Brevifolia*. Then he measured the ovipositors of the two species of yucca moths and discovered that “amazingly, the length of the stylar canal in each tree variety matches exactly the body length of their respective pollinators,” Smith writes. These differences have important implications for the reproduction of both yucca varieties. In Nevada’s Tikaboo Valley, an unusual site where *Jaegeriana* and *Brevifolia* grow side by side, Smith and his colleagues have conducted experiments showing that the two species of moths visit both yucca varieties. However, their reproductive success is severely diminished or fails outright when one species carries out pollination in the Joshua tree to which it is not best adapted.

With each experiment in the great outdoor laboratory of the Mojave Desert, Smith and his colleagues are getting one step closer to solving one of the scientific conundrums that would vex Darwin until the day he died and continue to puzzle evolutionary biologists to this day: the sudden appearance and explosion of flowering plants that occurred during the Mesozoic at a time when flowerless plants such as pine trees, ferns, mosses and horsetails had dominated the fossil record for millions of years before them. Darwin, like other scientists of his time, speculated that the rise in insect diversity around the same time played an important role in catalyzing the diversity of flowering plants. Studying the pollination biology of Joshua trees and their moths might provide the smoking gun demonstrating coevolution at work in the process by which “plants affect the fitness of the insect, that these same insects affect the fitness of the plant, and that together these have caused the formation of new species," Smith writes. As yet, he hasn't definitively solved what Darwin called the "abominable mystery", but with each field season, he's one step closer. ×

Two female yucca moths (*Tegeticula synthetica*) on a Joshua flower

Photo: Tad (Will Cole)©, 2015



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Photography Seth GaleWyrick | unwhirl.com

Interview
Tim McGee

Timothy R. McGee is the founder of LikoLab, a biological insights studio on Bainbridge Island, WA. At LikoLab, Tim helps people create positive impact for themselves, their organizations, and the world by using cutting edge design research, foresight, and sustainability principles to guide projects towards more valuable, and broadly beneficial outcomes. Tim has helped teams develop new materials, manufacturing processes, innovation routines, business strategies, and digital applications. Tim delights in the challenges of new projects and industries, and has worked in aerospace, automotive, architecture, urban planning, healthcare, high-tech, fashion, textiles, consumer goods, and retail.

Tim is also the co-founder of Biomimicry New England, a non-profit that works to establish nature and natural systems as an important resource for education and innovation in New England. Prior to LikoLab Tim spent time at IDEO (a global design firm) and Biomimicry 3.8 (a global biomimicry consulting firm) building on the interaction between biology and design. Tim regularly facilitates workshops on design research, biomimicry, and is also currently an adjunct professor at MCAD teaching Foundations of Sustainable Design. Tim holds a BA in Biology from Colby College, and a MS in Biochemistry and Molecular Biology from the University of California Santa Barbara. When not in the studio Tim is with his family hunting the woods for edible mushrooms, fiddling with camera equipment, or dipping his toes in the ocean.

Tim McGee

Photo courtesy of Tim McGee

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

It's tough to feel the edges of an idea. Sitting on a small island in the Salish Sea, I can say that what I see is that bio-inspired design seems to be growing and blurring. One of the reasons I started the podcast 'Life-Centered' (https://itunes.apple.com/us/podcast/life-centered-podcast-likolab/id1154841365?mt=2) was to understand and grow awareness of the incredible diversity of people working in the field. From artists like Betsy Hinze, who take people on a magical journey through art and food to learn about place, to global policy and business leaders like Tariq Al Olaimy who speak about adding nature as a partner at the United Nations. We talk to business leaders like Buero Co-founder Ben Kneppers whose system perspective and deep empathy for the problems of the Chilean fishing industry led him to create a process to remove ocean waste, and create a new circular product. Or Asheen Phansey who works as an intrapreneur within Dassault Systemes that literally helps make the objects we use every day.

I think that the ideas, process and tools of looking to nature are continuing to adapt and evolve

untitled | Photography Kathy Zarsky | unwhirl.com

untitled | Photography Tim McGee | unwhirl.com

in different fields. Chemists are increasingly able to find a link to biology for inspiration. Designers are asking questions based on biological insights. Strategists and Marketing professionals are rethinking how they tell stories and implement new system based on nature's complex adaptive examples. There are architects and urban planners asking how we can re-wild, and reconnect with place to make our cities healthy for us and the environment. And I think most impressively we have seen students of all ages find biomimicry one of the most exciting and engaging ways to learn and develop. I think more people are realizing the true power of bio-inspired design isn't necessarily in finding inspiration, but helping all of us ask better questions.

What do you see as the biggest challenges?

I would like to see dramatic increases in access to funding and organizations dedicated to collective and clear impact. When it comes to funding, the opportunities that exist in bio-inspired design are often so disruptive they fall off the map of typical innovation pathways. There have recently been a few venture firms like OS Fund that seek to fund companies that change how our society operates, and of course government programs like DARPA exist, but their fluency in bio-inspired design tends to fall short of the deep technological impact that looking to nature can really have. Fundamentally, they rely on more traditional strategies of technological or human centered innovation to make decisions of funding rather than a more comprehensive pathway that considers the broad impact of these technologies on our local and global systems. The Biomimicry Institute's efforts have been fascinating to watch, and my hope is that we can increase the community's ability to obtain increased funding and execute on designs and projects that have real economic, human, and environmental impact.

By what criteria should we judge the work?

One of the most exciting developments in the past few years is the emergence of the International Living Future Institute's new Living Product Certification. For the first time, we see a comprehensive system through which products can grow, evolve, and learn how to be generous within the biosphere. I would love to see this program continue to capture more industries, technologies and markets. But to put it simply, I would ask three big questions. How many people does it help? How does it help them? How does it help the systems those people are in? If we can start to answer those questions for the things we make, I think we will be in a better position moving forward.

What are you working on right now?

I'm in a bit of a transition point in my career where I'm looking at where I can have the most impact. I'm deeply interested in helping people imagine different future possibilities. Nature is much more weird and wonderful than we can imagine, and I have been exploring how I can be a better mentor to others (rather than instructor or consultant) to help teams get deeper results faster. This has meant literally being a mentor to biomimicry teams through the Biomimicry Student Challenge, but also working with companies to help them achieve Living Product Cer-

untitled | Photography Tim McGee | unwhirl.com

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tification, or use living organisms and systems as a foresight tool. I'm also exploring how I can share and develop tools that the community can use to grow and develop for free, so that all of us can make high quality products, faster. Two of my most recent projects in this avenue are the podcast 'Life-Centered', where I get to interview and explore topics in depth with leaders in the field, and 'unwhirl.com' (http://www.unwhirl.com/) which is a website where folks in the bio-inspired design community can share their bio-inspired, functional photographs or illustrations free of attribution or charge.

What is the last book you enjoyed?

I just finished reading *How to Raise a Wild Child* by Scott Sampson, and it left me with several new ways to think about biophilia, and the long-term vision of bio-inspired design. Scott approaches the field from the deep perspective of a paleontologist and as a result we see he has carefully uncovered how we can approach mentoring the young or young at heart to help foster a connection and love for the natural world. I think the lessons, resources, and thinking in the book can help parents, but is also sage advice for anyone looking to work with others to learn from nature.

What's your favorite motto or quotation?

"Against the assault of laughter, nothing can stand." - Mark Twain

What is your idea of perfect happiness?

Wool socks & a fresh pot of coffee

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

I want to be a wondersmith when I grow up. The only wondersmith I know is Betsy Hinze (http://www.betsyhinze.com/), who appeared on our podcast. Her ability to weave together an experience for people that is deeply rooted to place is magic to me, and I think we all need to create a little more magic in the world. ×

Elytra Pavilion in Weil am Rhein inspired by research on beetle elytra by Achim Menges with Moritz Dörstelmann; Jan Knippers; Thomas Auer.

Photography Julien Lanoo

Interview
Jan Knippers

Authors:
Jan Knippers and Mauricio Soto Rubio

Jan Knippers specializes in lightweight structures for roofs and façades, as well as the use of innovative materials such as glass-fiber reinforced polymers. He is also partner and co-founder of Knippers Helbig Advanced Engineering with offices in Stuttgart, New York City (since 2009) and Berlin (since 2014). The focus of their work is on efficient structural design for international and architecturally demanding projects. Since 2000 Jan Knippers is head of the Institute for Building Structures and Structural Design (ITKE at the faculty for architecture and urban design at the University of Stuttgart and involved in many research projects on fiber based materials and biomimetics in architecture. As such, he is speaker of the Collaborative Research Centre 'Biological Design and Integrative Structures' funded by the German Research Foundation (DFG) and author of numerous publications such as the 'Construction Manual for Polymers and Membranes'. Jan Knippers completed his studies of civil engineering at the Technical University of Berlin in 1992 with the award of a PhD.

What is your best definition of biomimicry?

For me, the study and analysis of biological role models is a line of research parallel to my work on advanced building structures. The aim here is not the linear and direct transfer from biology to engineering, which would be a quite naïve way of understanding biomimicry in the realm of building construction, but rather the comparison of design and construction principles in nature and in architecture. The idea is to deepen my own approch to engineering by investigating structures and systems outside of existing paradigms of architecture and engineering. My aim is to find inspiration for building structures of improved efficiency and performance.

Jan Knippers

Photography Knippers Helbig

How have you developed your interest in this area?

My primary interest is how computational fabrication methods enable novel building structures. Computational fabrication allows for local differentiation of geometrical features as well as mechanical and chemical properties. Local adaption may be considered as the main feature of all natural constructions. My hope is therefore to find directions for development and research on building structures through investigation of natural constructions.

What are your impressions of the current state of the discipline?

During the last decades, major advantages in biomimetic research were achieved in the field of surfaces, for example self-cleaning, dirt-repellent and anti-bacterial coatings. In the realm of large-scale architectural constructions, the discourse on biomimetics stays usually on a very superficial level, i.e. the adaption of visual and aesthetic appearance and not the underlying

Compliant shading system ‘flectofin’ | Photography Julian Lienhard

Thematic Pavilion EXPO 2012 Yeosu, South Korea By Soma Architecture and Knippers Helbig. | Photography Knippers Helbig

Bird of Paradise Flower (Strelitzia Reginae) as Inspiration for compliant facade System Flectofin

Photography Roslou Koorts

working principles. The scientific foundation of architecture is in general low. This is true in particular for the so-called biomorphic architecture. What is still missing is a conceptual foundation of biomimetics as a scientific discipline in the realm of architecture and building construction.

What do you see as the biggest challenges?

The biggest challenge of biomimetic research for architecture is scaling up, not only in terms of size, but also in terms of loading and life span. Architectural constructions are in most cases not only much larger than biological role models, they also have to carry much higher loads and the expected life span is usually much longer. In addition, architectural constructions require a very high safety levels and low deformations compared to most natural constructions.

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

We need fabrication techniques that allow for local differentiation of material properties as well as of geometrical features of its components on the large scale of building construction, for example the on-site robotic fabrication processes of fiber composite structures we are currently working on.

By what criteria should we judge the work?

Evolution in biology follows guiding principles that have the potential of pushing architecture and building technologies towards a more sustainable direction: the efficient utilization of scarce natural resources and their efficient conversion into physical elements. All processes in nature are essentially based on the use of solar energy in various forms. Living beings are part of large energy and material cycles in the bio- and geosphere. All 'waste' is used in a cascade-like manner by other organisms.

These are general principles that are also pursued in today's architecture and building construction industry. Whether these ecological properties can be transferred via a bio-inspired design process to architecture and building construction is the key criteria to evaluate biomimetic research.

From the projects you have completed, which one is your favorite? Why?

My favorite is the 'Thematic Pavilion' at the EXPO 2010 in Yeosu, Korea, as it is one of the very rare examples that illustrate how fundamental research in biomimetics can lead to new architectural applications on a large scale. The design of the compliant kinetic facade made of fibre reinforced composites is inspired by research on plant movements, mainly the bird of paradise flower.

What are you working on right now?

We continue to work on fibre-composites as most natural constructions consist of fibers such as cellulose, chitin or collagen with directed properties embedded in a matrix.

A variety of examples such as bone or wood adjust to the existing loading conditions by adaptive and anisotropic growth. Anisotropy leads to

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highly efficient structures and to the most efficient usage of natural resources. Even partly contradicting requirements, such as high stiffness or high toughness to avoid crack propagation, can be fulfilled through adapted orientation of the various fiber layers and the embedding matrix material. We continue to work on the development of fabrication techniques that capture this potential.

Biomimicry/bio-inspired design is by nature a multidisciplinary discipline. How do you manage collaboration between specialists in your institution?

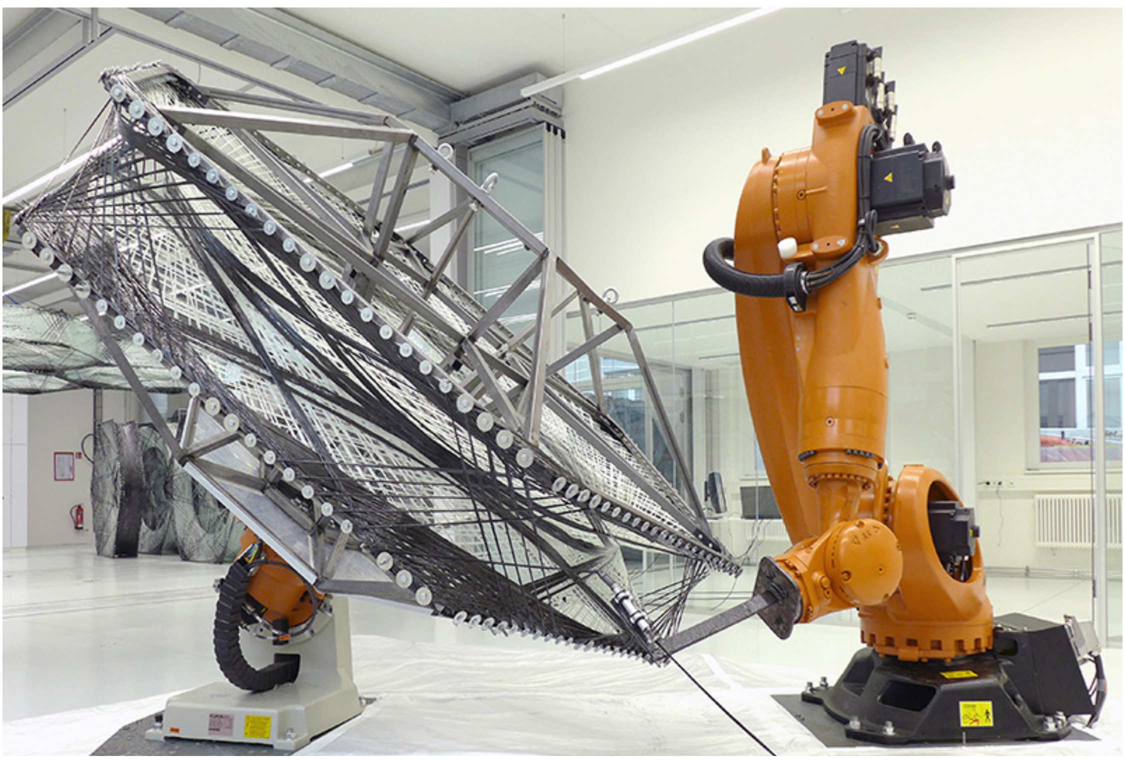
We established a collaborative framework for previously isolated activities by founding the Collaborative Research Centre 'Biological Design and Integrative Structures', funded by the German National Science Fundation DFG. We have

Elytra of Ground Beetle and Flying Beetle
Image by ICD/ITKE University of Stuttgart

regular meetings and joint publications that foster communication between the different disciplines.

Recent technological advances have changed the way we study bio-organisms and apply this knowledge in our designs. How has the work of the ITKE at the University of Stuttgart responded to this change?

During the last decades, fundamental steps towards digital technologies have been made in all fields of science and technology. In biology, new analytical methods such as computed tomography imaging have been introduced. In architecture and building construction, computational design, simulation and fabrication are omnipresent today. This means more than just a deeper insight into biological systems or better tools for design and construction of more complex building structures. The 'digital model' provides a common basis for the exchange of knowledge across the disciplines and enables direct communication between widely separated fields of science. In this sense, simulation technologies become increasingly relevant as they provide both a scientific approach to the quantitative analysis of the form-structure function relation-



Robotic arm fabricating component of the Elytra Pavilion

Photography Knippers Helbig

Elytra Pavilion in Weil am Rhein inspired by research on beetle elytra by Achim Menges with Moritz Dörstelmann; Jan Knippers; Thomas Auer.
Photography Julien Lenoo

ships of biological role models and a platform for the abstraction of their structural and functional principles and their implementation in architecture. The transfer of data and the organization of the flow of information in both directions, from biology to technology but also vice-versa, has become the main aspect of research.

After the work of Frei Otto, there seem to be a long-standing interest in the area of biomimicry at the University of Stuttgart. How do you see your own work fitting within this tradition?

For Frei Otto, 'lightness' was the overarching paradigm that connected his widely separated fields of research. A 'lightweight structure' in the sense of a 'material-efficient' system was seen equivalent to an energy-saving, environmentally friendly and cost-effective design. In addition, lightweight structures were perceived as social relevant because they added value and followed timeless design principles. In general, 'lightness' was seen as the governing criterion guiding architecture and technology into a sustainable future. This perspective was shared by many architects and engineers at the end of the 20th century, but only a very few postulated it as radically as Frei Otto.

Today, the awareness of the multiple networked and barely controllable mutual dependencies of our globalized world is becoming increasingly prevalent. This requires the reconsideration of inherited paradigms, including those in architecture. A lightweight structure made of non-recyclable and primary-energy-intense materials, requiring non-local fabrication processes does not necessarily contribute to sustainable development. Thus, the work of Frei Otto might be conceived as the endpoint of a century-long search for efficiency. Even though his lightweight systems still offer the potential for further optimization from an engineering perspective, the challenges of our time are different: How can we mediate between the ever more complex and often conflicting social and ecological requirements that our built environment has to fulfil.

One could conclude that biological systems have the potential to compromise between partially conflicting requirements and to adapt to non-steady environmental conditions. Therefore, they might guide future development in architecture and technology. From that perspective, Frei Otto's concept of design processes driven by natural laws is even more valid than ever.

Nevertheless, the increasing challenges for our built environment require their extension towards the integration of a multitude of design criteria beyond 'lightness' and the mediation between them. The technical means for this are provided by the fundamental progress in computational technologies. ×

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