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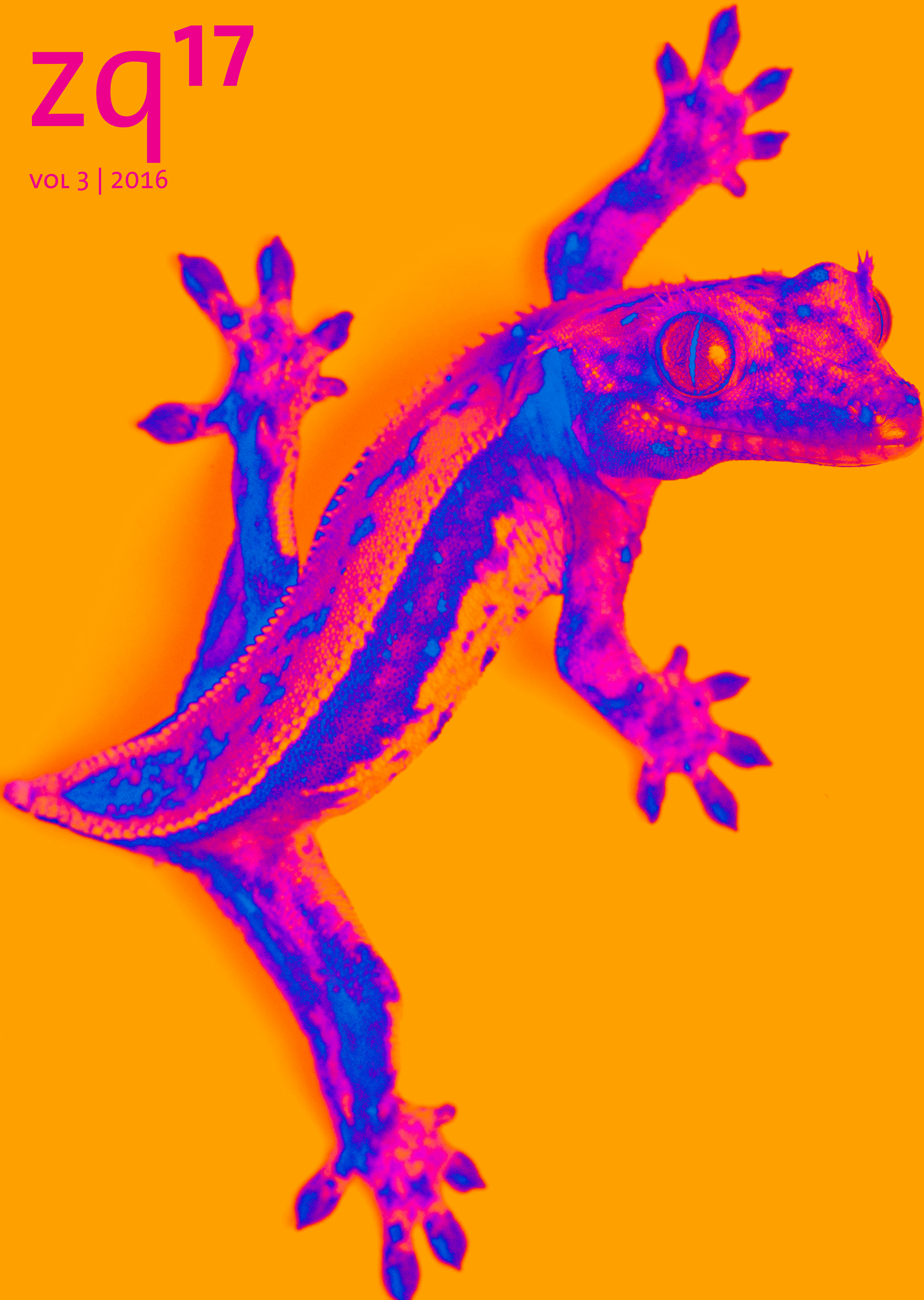

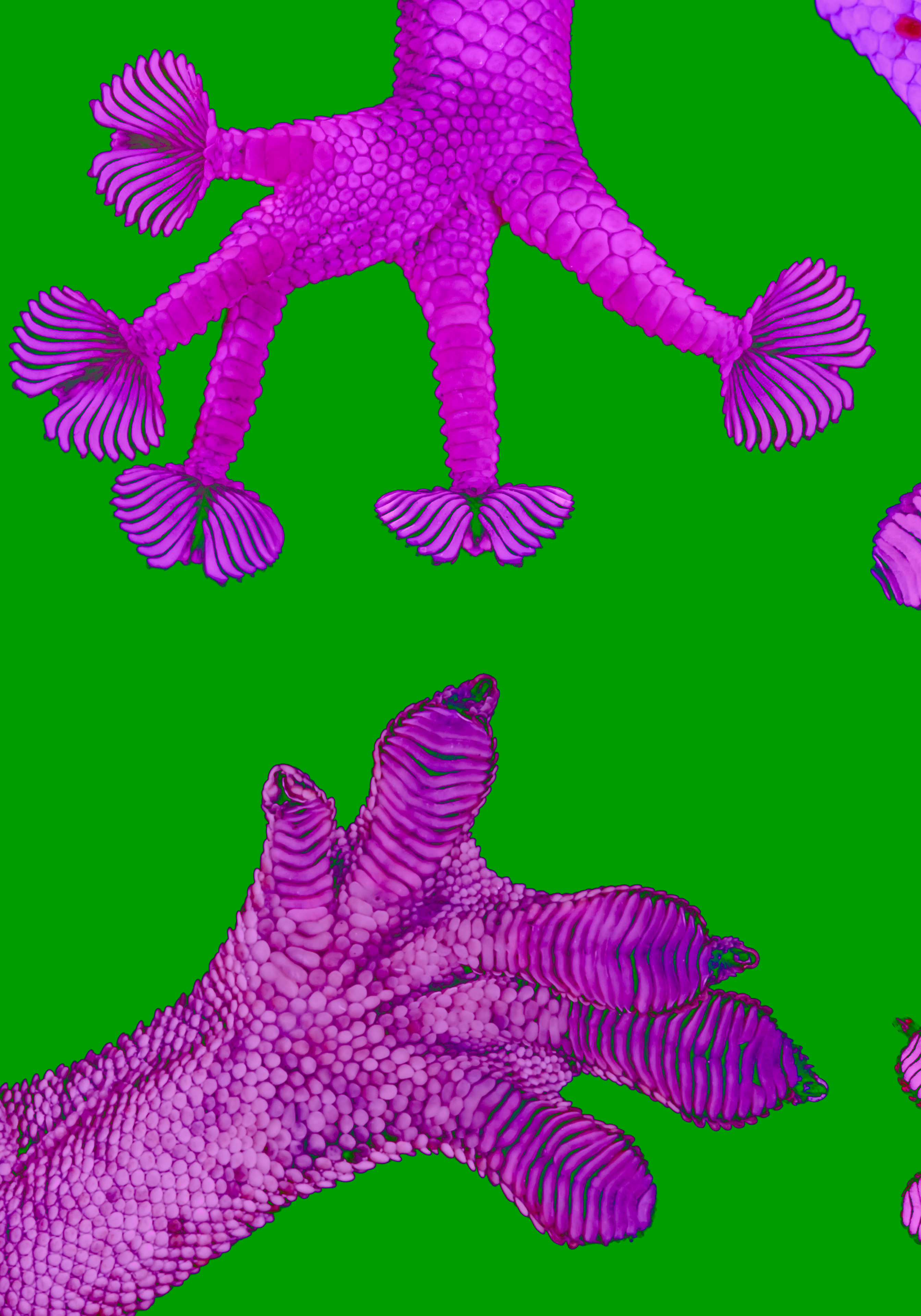

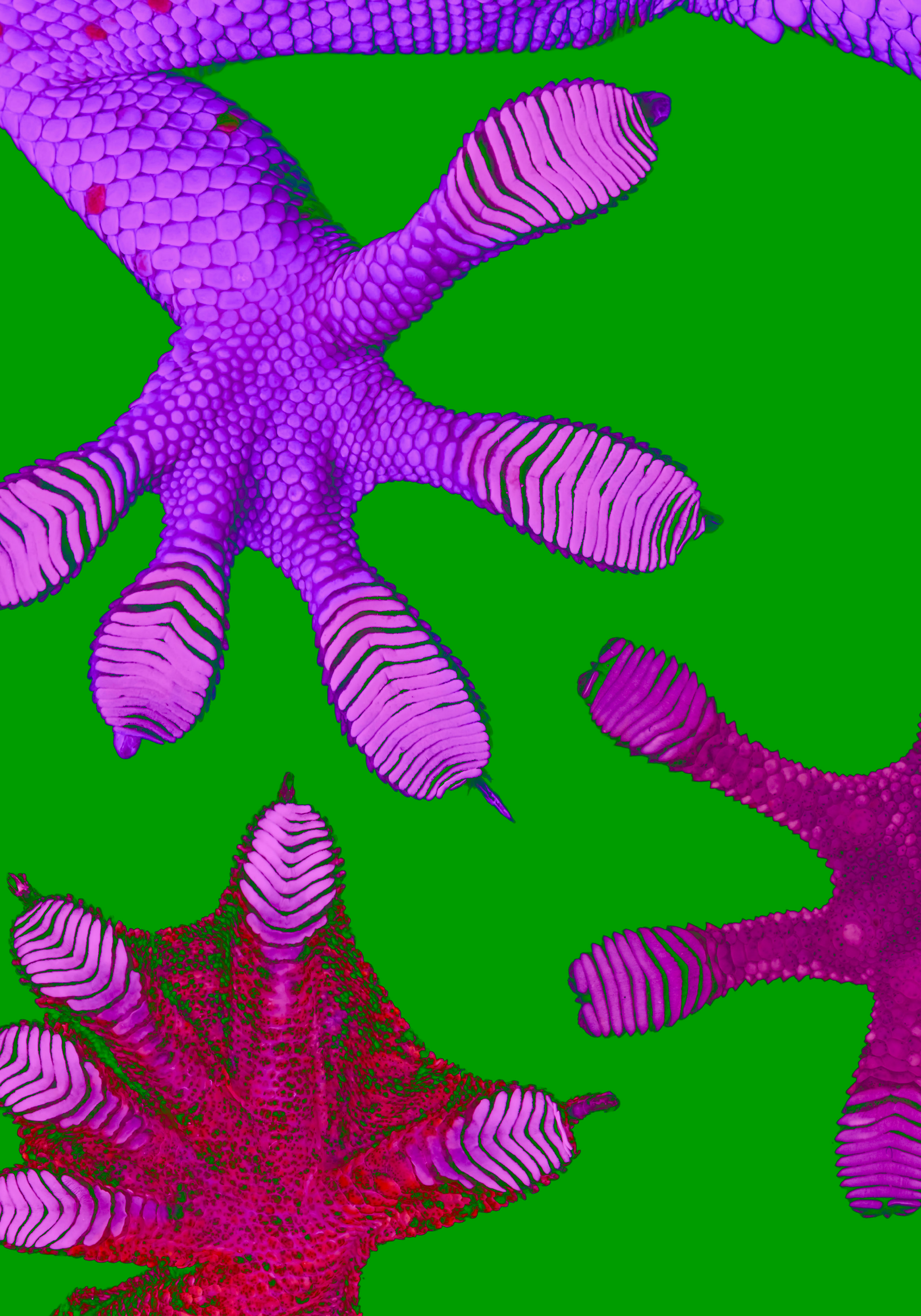

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Little Dragon (modified)

Photo: Kellar Autumn

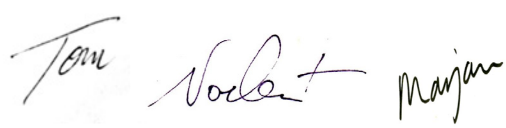
Editorial

"It is necessary to study not only parts and processes in isolation, but also to solve the decisive problems found in organization and order unifying them, resulting from dynamic interaction of parts, and making the behavior of the parts different when studied in isolation or within the whole…" Ludwig von Bertalanffy, *Perspectives of General Systems Theory*

"We can't impose our will on a system. We can listen to what the system tells us, and discover how its properties and our values can work together to bring forth something much better than could ever be produced by our will alone." Donella H. Meadows, *Thinking in Systems: A Primer*

We live in a world of systems and many of the most successful bioinspired problem-solvers have investigated the nested systems beyond and within their main focus of research. If a system, simply put, is a collection of components with interrelationships resulting in an identifiable outcome, then choosing where to look for inspiration or knowledge within the system becomes a critical choice for scientists or designers…and the details of that are not so simple.

Many of the articles in our current issue are, ultimately, about systems, large or small, whether the hierarchical structure of gecko feet or the regional infrastructure needed for sustainable settlement. We are pleased to highlight one of the world's leading experts in biomechanics and the discoverer of gecko adhesion, Kellar Autumn, by recounting his professional work and displaying his creative photography. Marc Weissburg and Daniel Wahl each write about the larger scale of industrial and infrastructure ecology, and how regenerative systems design can be framed at a regional scale. In our opinion section, Alyssa Stark makes the case for inclusion of biologists in the current mainstream of bioinspired design research and development, and Heidi Fischer, in her ongoing *Science of Seeing* series, delves into another sense, hearing. Let her take you out to the desert to listen! ×



Tom McKeag, Norbert Hoeller and Marjan Eggermont

Untitled

Photo: rophotosuk, 2012 | Flickr cc

Case Study

Sticking to the Chase: Kellar Autumn's Pursuit of Science

Tom McKeag

Sticking to the Chase: Kellar Autumn's Pursuit of Science

Eureka!

Kellar Autumn is afraid of spiders. He reveals this to me in a small Asian restaurant in Portland, Oregon, as a drizzle of summer rain strolls by outside. He explains that spiders, therefore, always get his attention, and if not for this, our knowledge of a few things scientific, and his 20-year career of investigation might have been very different.

Autumn is trim and tan, a martial artist, with a quick mind and easy speech, so his phobia seems out of place, especially after an hour listening to a fascinating explanation of his work. He is a professor in the Department of Biology at Lewis and Clark College and is recognized as the man who discovered how geckos stick to surfaces; a discovery that has led to an international industry of researchers seeking to perfect a universal application for this elegant mechanism.

Back in 1996, he was a postdoctoral fellow in Robert Full's lab at UC Berkeley. Autumn was working on a team with the iRobot company, funded by the ONR (Office of Naval Research, US Department of the Navy) to develop a legged climbing robot. The team had looked at many different ways for the robot to stick to surfaces, but no mechanism seemed to be completely satisfactory.

Autumn was on vacation with his wife Valeurie in Hawaii, and this work was on his mind. Alone in their room one night he watched uncomfortably as a large cane spider crawled about the ceiling. Suddenly a gecko appeared, scurried out onto the ceiling and deftly flipped the spider off after a brief battle. Kellar became intrigued by the mechanism that had allowed this reptile to so easily traverse the walls and ceilings of his lanai. He spent the next week poring over the literature about geckos, before forming his hypothesis of dry adhesion.

Getting to Work

At the time, researchers were not quite sure how these creatures did this: was it an adhesive? Suction cups? Capillary action? The gecko had fascinated naturalists for some time, all the way back to Aristotle, and quite a few modern theories had been afloat for over two centuries. Researchers in the 1960's, however, had a distinct advantage over their predecessors.

Their view of the structural details of the gecko foot was vastly superior thanks to the development of the electron microscope. This electronic device yields 1000 times finer resolution than an optical device. The scientific world, for the first time, saw that the gecko's foot pads were actually a complex array of hierarchically organized materials. Fringes or lamellae were populated

Gecko feet | Photo: Kellar Autumn

Crested gecko | Photo: Kellar Autumn

with bristles or setae and each seta was divided at the tip; each tip division having a tiny spatula shaped pad. However, the precise molecular mechanism of adhesion remained unclear.

Autumn believed that these nanoscale structures were enabling the gecko to stick to surfaces by van der Waals forces, weak molecular attraction, that, when aggregated over many tiny surface structures, could be sufficient to keep the gecko firmly planted, upside down, onto the ceiling of his Hawaiian bungalow.

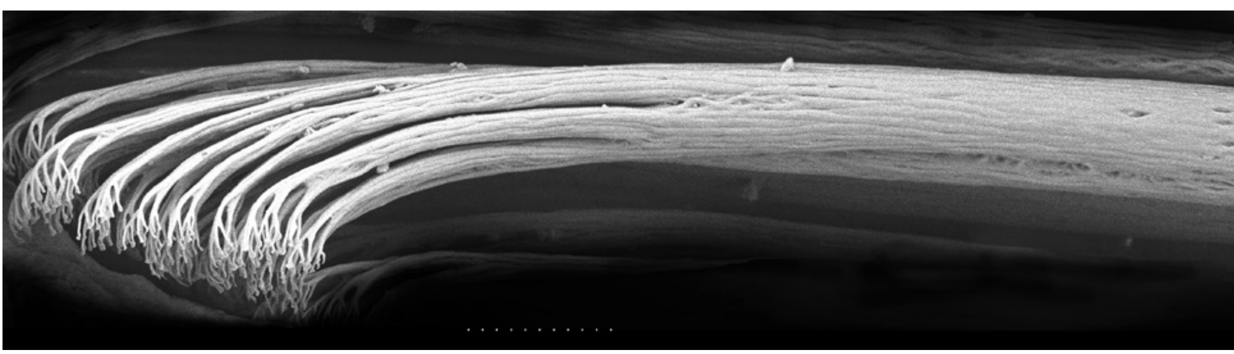
In 1997 the Full lab began its investigation of the gecko's adhesive action by using high-speed cameras and force meters to understand the dynamics of how geckos climb. This combination of the elements of time and force was an important approach for studying complex actions that take place in a fraction of a second.

By 1998, the team was also investigating the individual hair or seta on the foot of a tokay gecko. What was the mechanism of attachment at this scale? Just measuring this was a challenge as the setae are typically about 110 microns long and 4.2 microns in diameter. A human hair varies in diameter, but is typically 40-50 microns in diameter, or about ten times the width of the typical seta.

Despite weeks of painstaking work (particularly by Tonia Hseih, an undergraduate at Berkeley, now on the faculty at Temple University), the team could not get the single seta to stick to a metal insect pin, until it was discovered that it was the way that the seta was applied to the pin that mattered.

"We already had the dynamics data, but didn't realize they could help us make the single seta stick. It took us over a month to figure out that we needed to replicate the force pattern of a gecko foot to make the seta adhere.", says Autumn who in the same year moved from Berkeley to his current lab at Lewis and Clark.

The same geometry discovered for the foot applied to the individual setae: they must be preloaded and dragged at 30 degrees in order to grip. "Frictional Adhesion" was thus explained as a result of applying a load force at a particular angle. Since this force was directional or anisotropic, it increased the growing confidence that this was a material and geometry phenomenon.



Montage of 5 cryo-SEM images of a single seta of a tokay gecko (*Gekko gecko*).

Photo: Kellar Autumn

The early setbacks to attachment were, ironically, to be critical to a wider understanding of the attachment force, according to Autumn. The insights from them reinforced the early hypothesis. The adhesion could be replicated mechanically, the gecko was activating natural forces by manipulating the angle of attack, and the default mode for the foot was non-sticking.

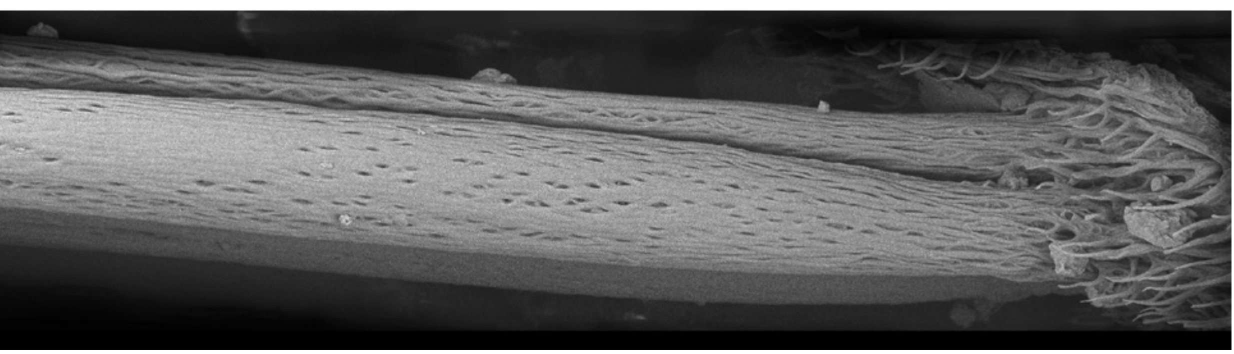
With these insights in hand, Autumn et al. published their now famous paper in the journal *Nature* in 2000. This article has been cited more than 1800 times since then. In it they proposed that van der Waals forces were the source of the adhesion, but also that placement by the animal was increasing the frictional sticking power of the material by 600 times, and allowing the creature to unstick easily by changing the angle of application (curling its toes backwards).

The Long Academic Debate

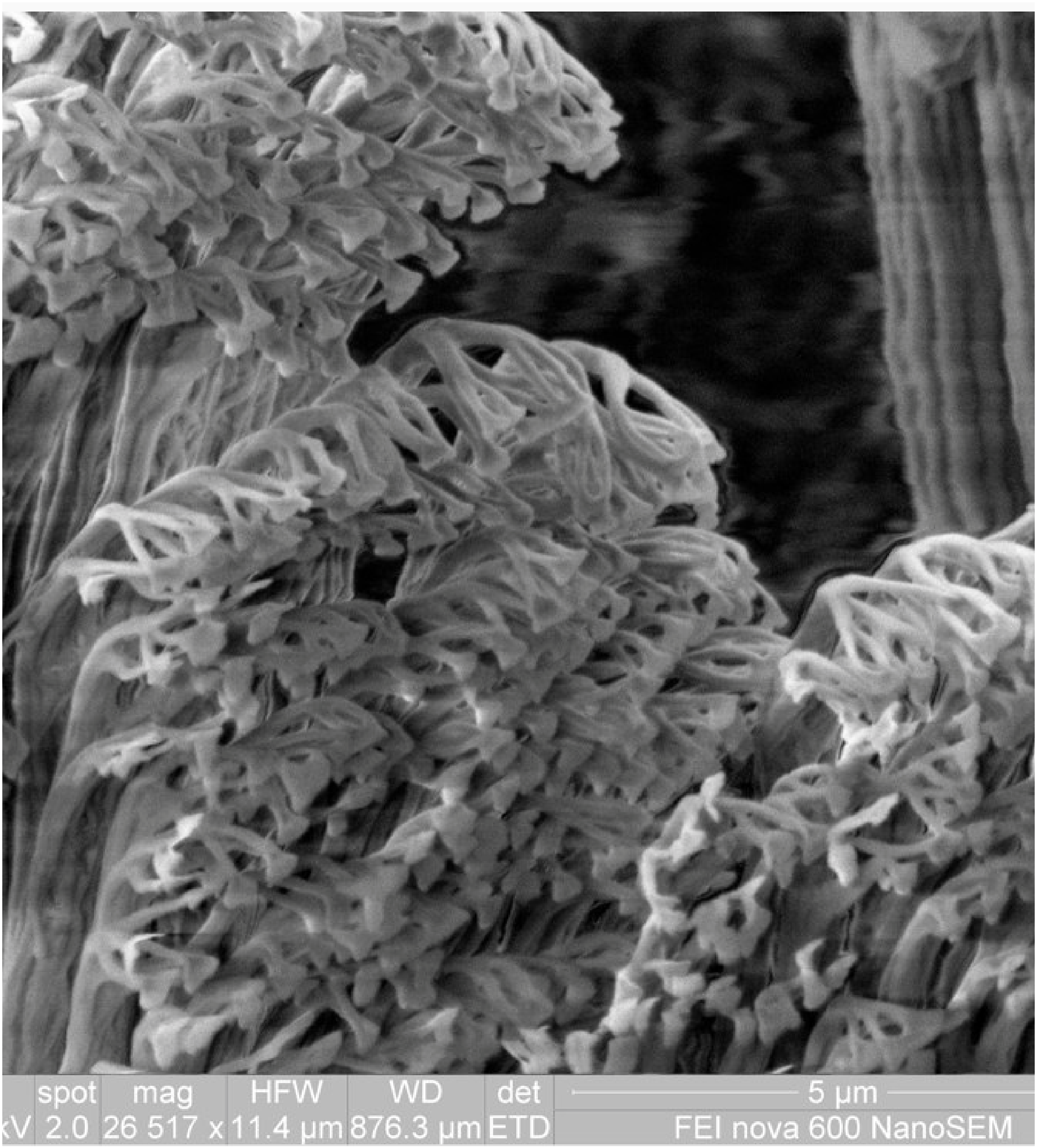
At the time this article sparked a vigorous debate amongst the biomechanical research community: what is the fundamental nature of this adhesion? Advocates for the force of capillary action as the source of the adhesion were unconvinced by the van der Waals proponents.

Two undergraduates in Autumn's new lab at Lewis & Clark College, Simon Sponberg (now on the faculty at the Georgia Institute of Technology) and Anne Peattie, performed a series of controlled experiments in which gecko feet and individual setae were placed on two substances, gallium arsenide (GaAs) and silicon dioxide (SiO2), to test whether capillary action could be dismissed as a cause of the adhesion.

The SiO2 was used as a control as the gecko foot would stick to this material due to either of the two candidate causes. The GaAs, however, is highly hydrophobic and so would reject any moisture serving as a medium for capillary action. The gecko foot stuck to the GaAs nonetheless and the researchers could make the claim that capillary action was not the cause. Moreover, Autumn was now convinced that geometry and physics were the main determinants of this adhesive force. This opened up a world of possibilities: conceivably, people could make a similarly functioning synthetic material.



Gecko toes | Photo: Graham and Sheila, 2010 | Flickr cc



SEM of gecko setae tips

Photo: Kellar Autumn

The team's work made the cover of the *Proceedings of the National Academies of Sciences* (PNAS) in 2002, and raised the profile of the lab.

"Now the target was on my back", says Autumn, recalling the mixed blessing of the national exposure and the ingrained professional skepticism of his fellow scientists.

Researchers began deeper investigations of both the structure and material makeup of the gecko feet, many wondering if they could refute Autumn's theory. Humidity still seemed to play a part in increased adhesion supporting the proponents of capillary action. Jonathan Puthoff, now on the faculty at California Polytechnic State University Pomona, and Autumn's graduate student, Mike Prowse, did extensive research on the environmental effects on the gecko foot mechanical properties, publishing with Autumn in the *Journal of Experimental Biology*, *Acta Biomaterialia*, and *Soft Matter* in the years 2010-2013.

What they demonstrated has put the controversy finally to rest. While increased relative humidity did make the gecko stick better, they showed that it was because the extra moisture increased the viscoelasticity of the setal keratin proteins comprising the foot hairs. The foot became more conforming in this more plastic state and therefore increased the dry adhesive properties. Capillary action was shown not to be the cause, particularly when the scientists measured the shear rate of the foot action, revealing that this rate was too high to allow capillary forces to commence. Thus, van der Waals force remains the only known mechanism of adhesion in geckos.

This Remarkable Creature

Over Thai street food, Autumn ticks off some of the fascinating functional properties of the gecko that he had written about in 2007:

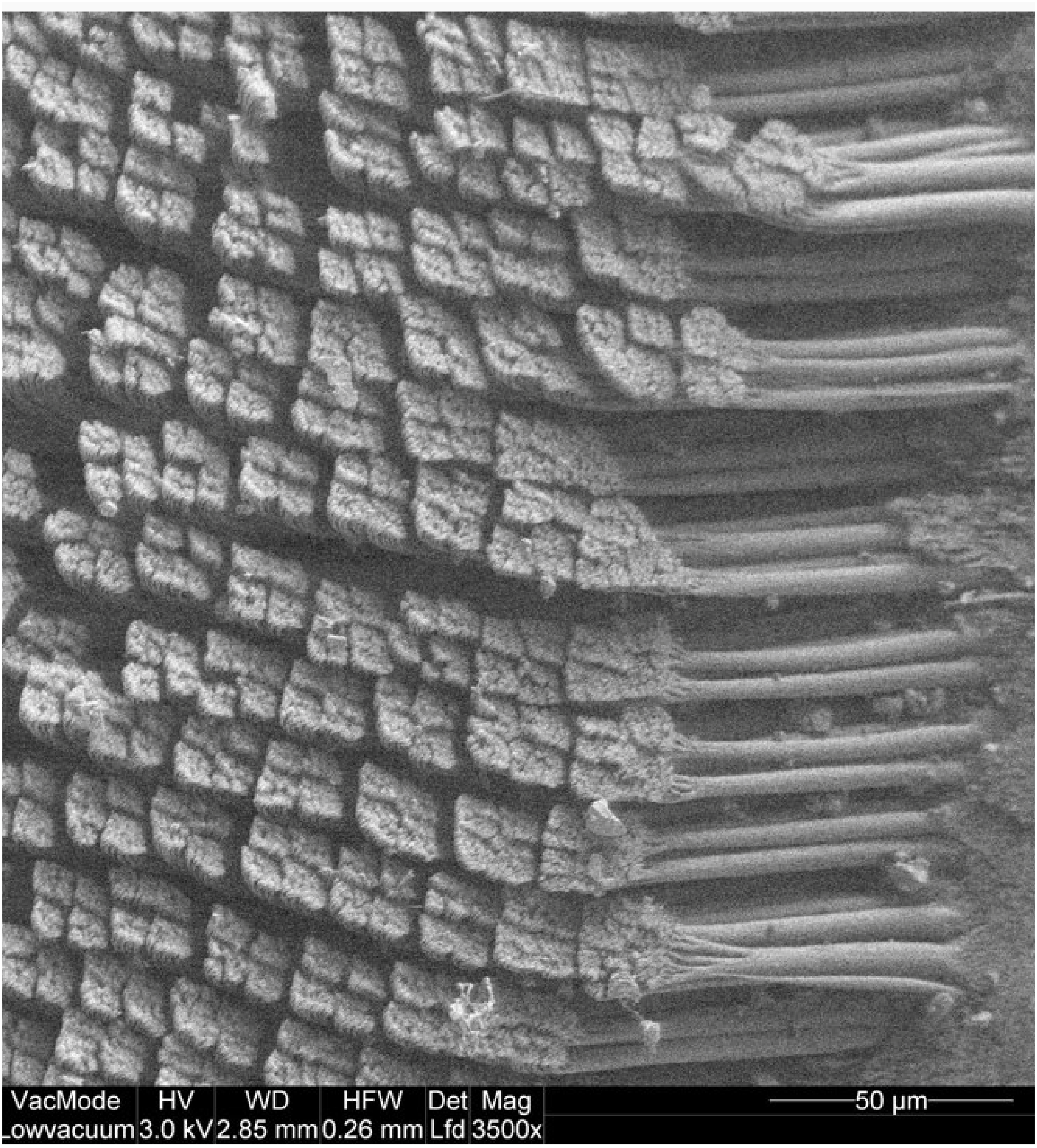
Anisotropic attachment: the directional nature of the loading and drag sequence needed for the adhesion, although seemingly limiting, means that the mechanism is controllable and tunable.

High pull off to preload ratio: geckos do not ponderously plant their feet unto a surface (high pre load). If they did, they would not be able to scurry about agilely. Instead they gently touch the surface, and then pull their feet inwards producing a resultant force with an angle less than 30 degrees, if it is a vertical or inverted surface. Interestingly, if geckos are running on level ground, they push their feet away from their body, preventing attachment of their adhesive.

Non-sticky default state and low detachment force: there are plenty of powerful adhesives available, but which ones can unstick easily and be used over and over again without losing their gripping power? This is one of the revolutionary attributes of this mechanism. The dry, unsticky nature of the material when it is not put to work is also of great value—and if a gecko was to touch its feet together, they would not stick to each other.

Material independence and rough surface compatibility: because the adhesion is caused by the *structure* of the material array and not by any particular chemical or substance, it has universal applications, and since it depends on

“Little Dragon” (Crested gecko) | Photo: Kellar Autumn



Scanning electron microscope image of gecko setae

Photo: Kellar Autumn

the natural attraction between any molecules, it can be applied to all surfaces whatever the texture.

Self- cleaning: Autumn's lab discovered that geckos also have a remarkable ability to keep their feet clean, since the keratin protein material of their feet is less attractive to dust particles than the surface they are treading on, and only a few nano-tips are attached to any single dirt particle. After several foot plants most of the dirt is deposited on the surface the gecko climbs over.

All of these properties contribute to a unique blend of attributes for a climbing or all surface device that is on the move. That, of course, is what the gecko is. Geckos have been quite successful. They comprise the most species-rich group of lizards, live worldwide and have developed this remarkable climbing mechanism in about 60% of the nearly 1500 species known to exist. Independent acquisition or loss of adhesive toepads in various lineages seems to have happened many times over the course of their nearly 160 million year existence.

Van der Waals forces, the attraction the lizard has taken advantage of, are very weak molecular forces, much weaker than covalent or ionic bonding. They are also effective only at short atomic distances, and are cumulative, so cannot be saturated. Because of this any mechanism employing these forces needs close contact with an adjoining surface and a large surface area to be effective...a very large surface area.

A square millimeter of gecko footpad typically contains about 14 thousand setae with a diameter of about 5 micrometers. Each seta terminates with between 100 and 1,000 spatulae approximately 0.2 micrometers long and 0.002 micrometers thick. At this scale, the spatula is smaller than the wavelength of visible light.

There is great power at this tiny scale, however, as the multitudinous structure accumulates the aggregate attractive force of proximate atoms. Each seta can resist 10 milligrams-force (100 microNewtons), equivalent to ten atmospheres of pull, and there are millions of them on the gecko's feet. It has been estimated that a typical 2.5 ounce lizard has the capacity to hold a weight of 133 kg (290 lbs.) aloft. The vicissitudes of life as a gecko may require an overdesigned capacity, for the typical animal can support its own weight with just one (highly fringed) toe.

Applications

This potential for a disruptive technology has not been lost on the veritable army of researchers who have become engaged in gecko research since the revelations of the Full laboratory days. Still, a truly biomimetic commercial version of gecko dry adhesion has been elusive, although synthetic gecko adhesive has been made by many different labs of many different materials.

When asked what the biggest hurdle to adoption and application of this mechanism to our built world is, Autumn quickly answers, "Scaling up. We know now how to test three-dimensional stress at interfaces, and we have a good idea of the best combinations of material properties and geometry for applications, but it is extremely expensive to create the machinery for manufacturing this material at scale. The main challenge is fitting these forms to the current methods and materials of manufacturing in order to mass produce them. There are plenty of labs around the world that now make dry adhesive in small, expensive batches."

Autumn recently estimated the cost of a single machine at $20 million, with fine-tuning and shakedown at another $20 million. While admitting that manufacturing cost estimates are not his field, he believes his order of magnitude is accurate for the kind of investment needed.

The payoff is potentially huge, however. This has led to hundreds of journal papers by laboratories across the globe, more than $30 million in U.S. federal grant funding and over 100 U.S. patents and patent applications.

Kellar Autumn, Robert Full, Tom Kenny (Stanford University), and Ron Fearing, an engineer at Berkeley, all shared the credit for one of the first: the 2004 US Patent # 6,737,160 "Adhesive Microstructure and Method of Forming Same."

In 2006, the Mark Cutkosky lab at Stanford went on to create the well-known Stickybot, a mechanical version of the gecko that can climb up glass walls. For this work the lab garnered *Time* magazine's recognition as one of the "Best inventions of 2006."

In June, 2014, working under the aegis of the DARPA Z-Man project, the Cutkosky lab demonstrated the utility of a gecko-inspired polymer in a climbing apparatus of two large paddles. It can support an over 200-pound man carrying a 50-pound load as he climbs up a 25-foot high wall of glass. DARPA (Defense Advanced Research Projects Agency) is an agency of the U.S. Department of Defense. The paddles are being developed for military use with the goal of developing a climbing field kit for urban warfare.

The nanoGriptech company of Pittsburg, Pennsylvania, a 2009, spinoff of the Carnegie-Mellon University research of mechanical engineering professor Mettin Sitti, has offered the first commercial, mass produced dry adhesive product based on the fibrillar adhesion of the gecko. Their products are made of polyurethane, have nano-scale pillars that mimic the gecko setae, and adhere in both the normal and shear directions.

The company offers three products, a friction tape, gripping material and fasteners, and demonstrates several possible applications, among them tighter fittings for prosthetics, better seals for protective gear, and more streamlined fittings for furniture, auto interiors and other removal coverings. Within the realm of robotics, where dry adhesion originally got its start, the market for robotic manufacturing, specifically in so called "put and take" operations, the repeatable, reversible and dry adhesive appears to have significant potential.

A Wider World of Fundamental Science

When asked what about his work that he was most pleased with, Autumn waxes enthusiastic. It is his ability, after so many years of interdisciplinary work, to share his findings with others and to inform other areas of science, particularly physics and material science.

"These fields, after all", he says, "helped me answer the questions that I was asking, and now it is a pleasure to be able to contribute to the

Fan toed gecko toe

Photo: Kellar Autumn

fundamental science in them". Indeed, at the 7th World Congress of Biomechanics in 2014, he gave a talk on this subject.

He uses rate-state friction theory as an example of how such basic science theory can be helped by the methods developed in investigating the tunable material properties of the gecko. He is currently collaborating with a wide range of colleagues, and cites his work with Nick Gravish, a former technician in his lab (now on the faculty at UC San Diego), and his former postdoc, Jon Puthoff (now on the faculty at California Polytechnic University, Pomona) on the relationship of shear rate to adhesion, his interest in the modeling of friction by Tristan Baumberger at the Paris Institute of Nanoscience, and the current work on earthquake modeling by geophysicist John Rundle at UC Davis.

In a recent Royal Society paper, Autumn speaks to the importance of interdisciplinary research when discussing the connection between investigating fibrillar versus bulk friction and its impact on friction theory in general. The combining of functional morphology and phylogenetic research is "... likely to lead to new insights ... also extrapolation for new approaches to bioinspired design, fabrication and application of GSA's (gecko-inspired synthetic adhesives)".

Autumn has some additional reflections on the pursuit of science that reveal both the professional and the person behind the decades of scientific effort. First is the importance of "mutualism" in which different professional passions and capabilities are brought to bear on a shared challenge. The model here is of deep and complementary expertise, rather than a shared generalism.

Finally, there is the tradition of mentors and he is deeply appreciative of his past apprenticeship under Dr. Robert J. Full of the Integrative Biology of UC Berkeley. Autumn goes on to speak of his warm relationship with his mentor, whom he talks with regularly, and Full's dedication to all his students "for life". Mentorship, he says, "... is at the foundation of academia. It is what unites us; it binds us all together." A review of Autumn's long list of academic papers and successful students reveals that he has paid it back – and forward – as his research continues to inform us about the fascinating world in which we live. ×

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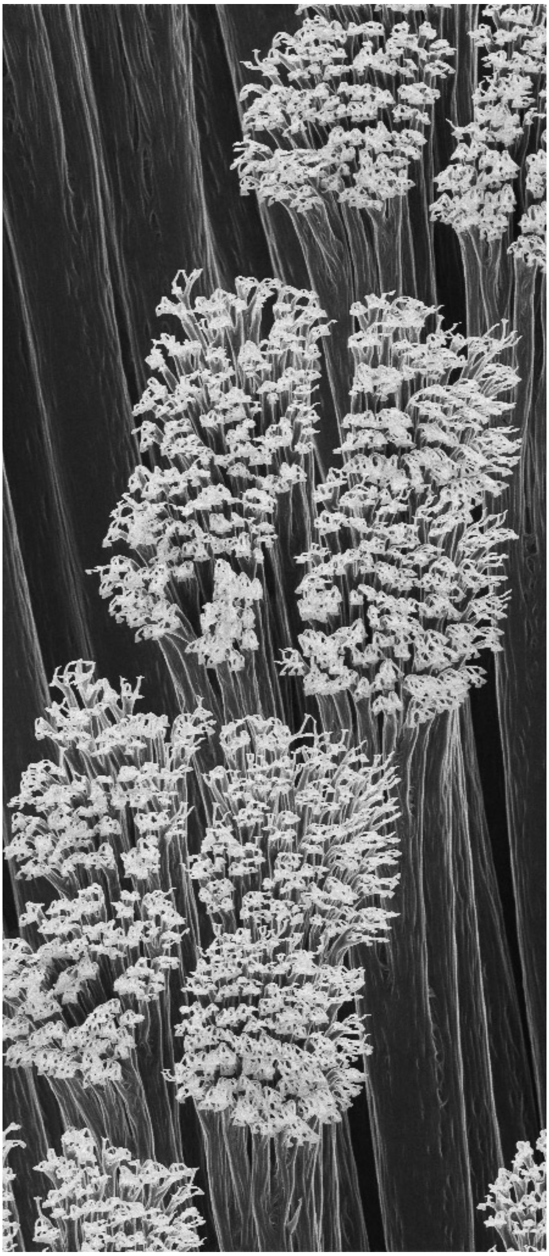

Helium ion microscope image of tokay gecko setae

Photo: Kellar Autumn

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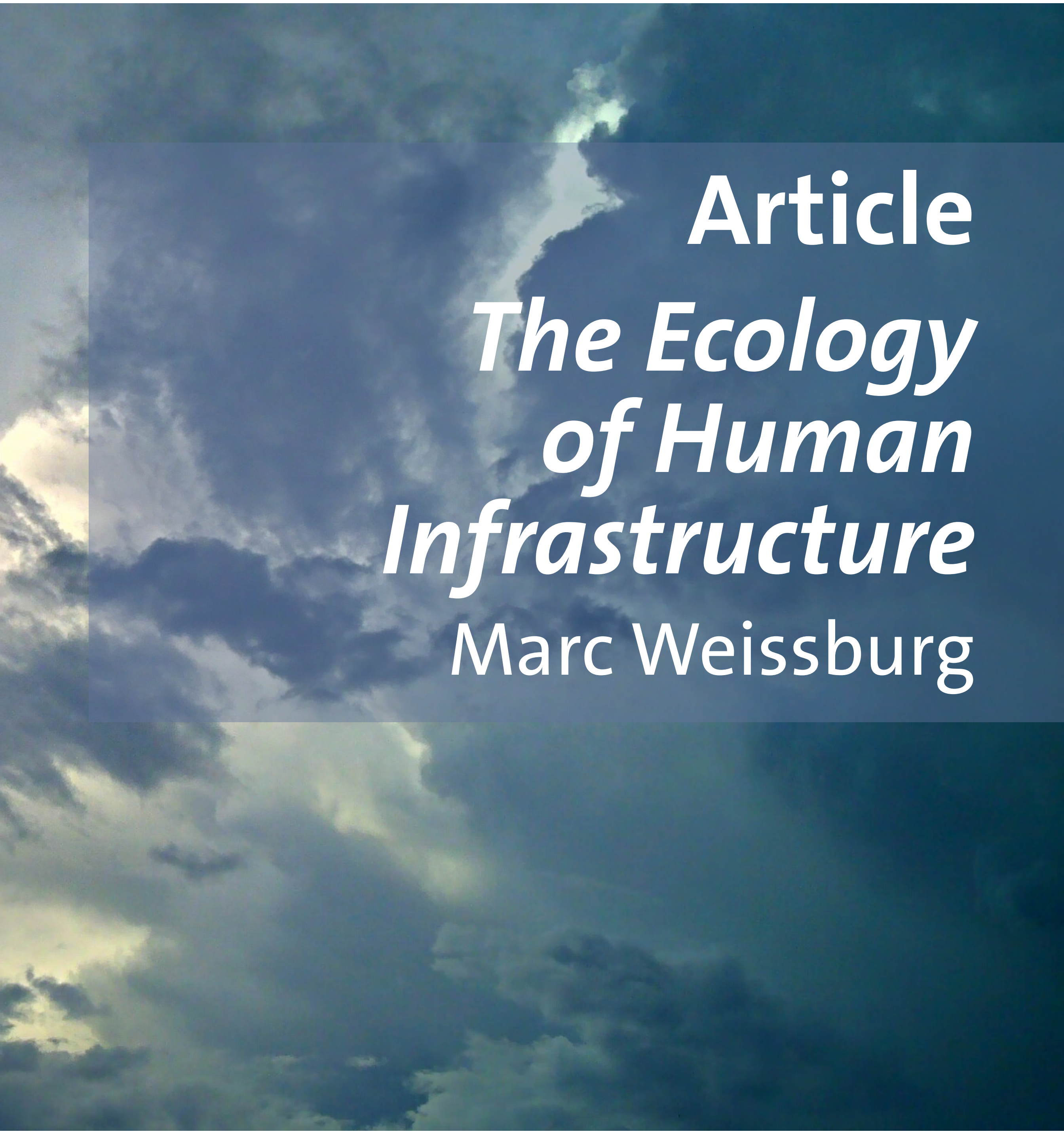
Photo: My Blue Van, 2011 | Flickr cc



Article

The Ecology of Human Infrastructure

Marc Weissburg

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Article
The Ecology of Human Infrastructure

Author:
Marc Weissburg

The Ecology of Human Infrastructure

Marc Weissburg is Professor of Biology and co-founder and Co-Director of the Center for Biologically Inspired Design at Georgia Tech. He has taught biologically inspired design for undergraduate students, practicing professionals, and at NSF workshops for 10 years, and works with a variety of industries and clients to develop bio-inspired design solutions for specific problems. His interdisciplinary efforts in BID include infrastructure and industrial ecology, the pedagogy of bio-inspired design and informal science education using bio-inspired design.

As the human population continues to expand, we put more stress on natural systems by increasing the rate at which we draw on natural capital, and the rate at which we create toxic substances or materials that do not easily reintegrate into natural cycles. The sustainability of our production cycles is questionable, and the search for how to construct more cyclic systems has become a critical activity. We all are aware of the limited supply of fossil fuel, but how many of us realize that the supply of extractable phosphorous, essential for modern agriculture, is estimated to be exhausted in approximately 100 years? Similar problems plague our infrastructure systems designed to deliver and manage our transportation, water, energy and other needs; these operate in a non-sustainable way, and their performance becomes increasingly important as we transition to a world where the majority of people live in dense urban aggregations.

Understanding the natural world has been thought to enable construction of more cyclic economies and systems. The field of i*ndustrial ecology* (IE), as the name suggests, looks to natural systems to provide important insights into creating sustainable human ones. *Ecology* is used here to indicate that all industrial activity (much like the activity of organisms) resides within a more complex and mostly closed system of the biosphere, the entirety of the physical and biological environments and their interactions. However, our inquiries about the value of natural systems for understanding our own systems mostly rest at the level of metaphor. IE has used natural systems to argue for the importance of cyclic processes by invoking the mantra "waste equals food." This is merely a high level *description* of the properties of a cyclic and inherently sustainable system rather than a *prescription* for how to achieve one.

Despite invoking a systems perspective, a great deal of work in industrial ecology is technology related and systems are conceived very narrowly. Typically, IE focuses on specific products or processes, and although the analysis might be deep and comprehensive, it ignores how a product or process interacts with others. A common and important approach is *life cycle analysis* (LCA), which attempts to calculate the total cost (energy, carbon, or other currencies) of a product from its origin to the time it is retired. *Cradle to Cradle* design is an expression of the idea that the characteristics of the product during its use do not account for all of the impacts of this product

Tawny owl | Photo: Captain Chickenpants, 2006 | Flickr cc over its lifetime. There is admittedly a systems perspective here in that the overall life cycle of the product is being considered, but the perspective is not really systems-oriented; the assumption is that the effects of human industrial activity can be ameliorated if we can get the design right. The problem is framed narrowly and with respect to technological solutions, and the fix resides at the level of the individual process relating to some aspect of the product's manufacture, operation or disposal.

Ecology as a science raises a different perspective: the sustainability and resilience of natural systems are properties that arise from interactions among the components within the context of the overall system. Understanding these individual interactions is essential but is not sufficient; these interactions create phenomenon that are not predictable until they are examined in the context of all the other interactions taking place. This property is often called emergence, and a variety of ecological phenomena from the behavior of fish schools and bird flocks to the stability of ecosystems are interpreted as emergent. A common lament among ecologists is that studying how species interact directly does not reveal, and may even obscure, what happens when these species are observed in an ecosystem. It's not unusual, for instance, to see that a particular prey species actually does better in the presence of two different predators than it does in the presence of either predator alone. That's not supposed to happen. The explanation for these counter-intuitive effects is that there is another interaction whose significance is not apparent unless the system is studied as an aggregate. In this case the behavior of the two predators is such that they interfere with each other when hunting, thus releasing the prey at least partially from the baleful effects of each predator attempting to find dinner.

This same issue plagues our understanding of complex human systems, but IE has been slow to respond to this challenge. Consider for example the benefits of electric cars (EVs); they clearly use less fossil fuel energy than the alternatives and so are considered a more sustainable method of transport. However, their overall carbon footprint depends greatly on the energy source used to generate the electricity; substituting an electric car powered by a coal fired plant hardly reduces the carbon footprint of the EV compared to the gas powered alternative. Such savings are only realized when the electric power is derived from renewables such as solar, wind or hydroelectric power generation. Thus, a full assessment of an EV depends on the overall system in which it operates. Conversely, electric vehicle use affects other components of the system. Extensive use of EVs can create radical environmental damage by creating over-exploitation of local watersheds, directly in hydroelectric power generation as well as for cooling of thermal power stations (fossil fuel, nuclear or solar), and for cleaning solar arrays in arid regions (Bras, Leigh, & Yang, 2012). Thus, the consequences of conversion to EVs have system implications - optimizing at the level of the EV is not the answer and may limit the benefits. Similarly, many industrial processes are already highly optimized on a unit level with limited potential for large future gains. Most modern steel mills or car manufacturing plants can reclaim nearly all of the "waste" water used during production

Hiding | Photo: Urban Mongoose, 2014 | Flickr cc

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Article
The Ecology of Human Infrastructure

Author:
Marc Weissburg

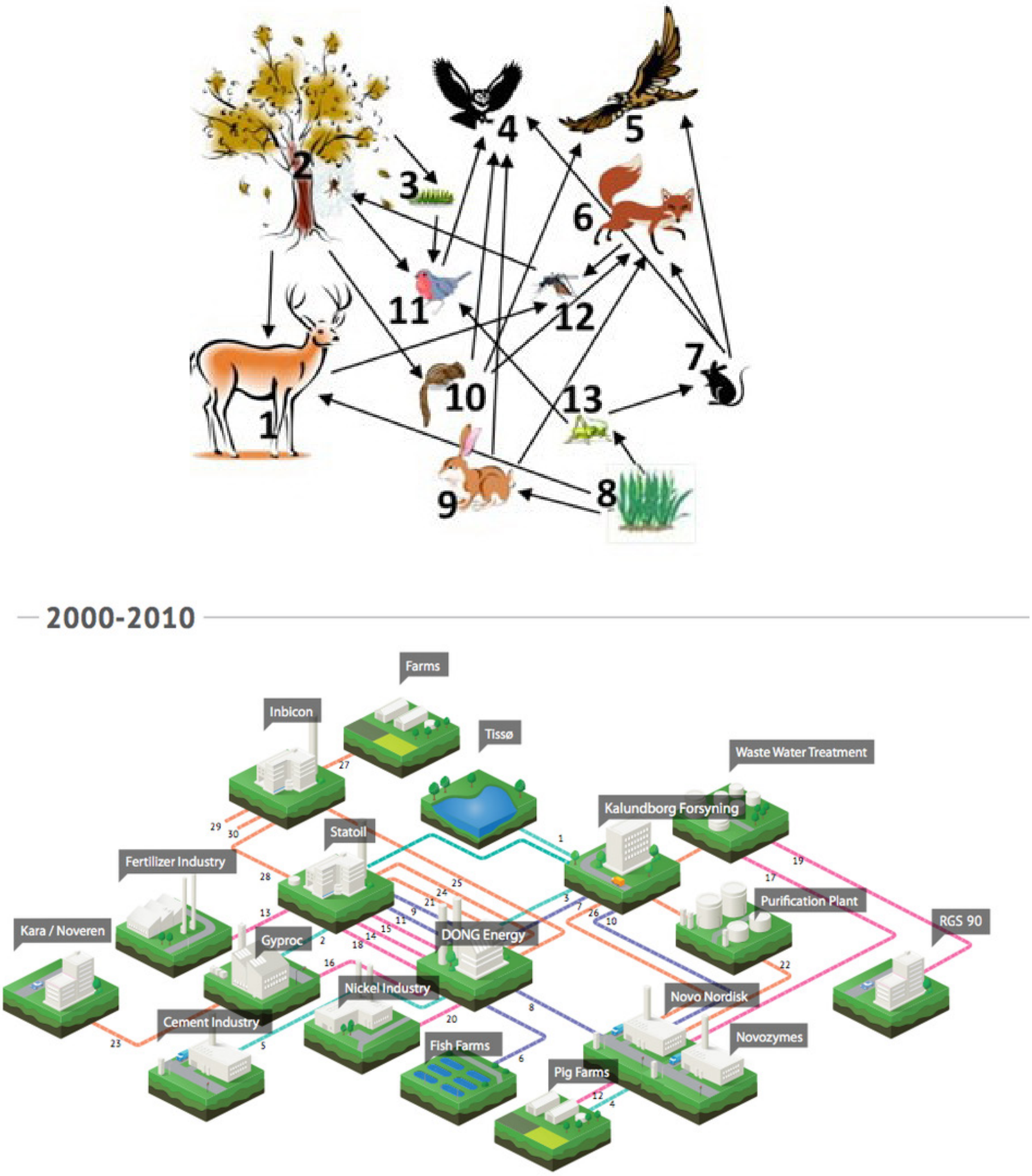


Figure 1: A food web (top) is functionally similar to collections of human industrial or infrastructure systems that exchange material or energy (bottom, Kalundborg Symbiosis). Both may be envisioned as a set of elements linked by material or energy transfer.

for recycling. Thus, any further gains in resource use must come from examining things at a systems level.

The size, scope and complexity of human built systems that power our cities, supply our water, and produce our food require new analytical frameworks that some have called *infrastructure ecology* (Pandit et al., 2015). Fortunately, it is possible to migrate deep ecological principles and techniques into the technological world since human systems are ecologies in the most fundamental sense (Figure 1). Collections of interacting co-located industries or cities require inputs of raw material and energy, which are transformed as they are exchanged by various actors (industries, species) in the system until they leave the system as usable material or waste. The properties of the system are determined by the throughput of material and energy, as well as the organization of those transformations - the network (food web) structure. These deep parallels are the basis for new efforts that use fundamental ecological principles to inform the organization and operation of human systems.

Ecologists have long understood that the properties of ecological systems are strongly influenced by the structure of the food web, which defines the network of interactions between predators and prey that exchange material and energy. The sustainability and resilience of ecosystems emerges from this web of interactions. In fact, the growth of ecology as a field of inquiry is closely tied to the pioneering efforts of Forbes, Lindeman, Elton and others to understand the system level properties of species networks that exchange material and energy between themselves and with the environment. One could argue that ecology as a science was first defined by Forbes' attempts to understand how the physical and biological properties of a lake are governed by the complex web of interactions produced by the component species.

Eugene Odum was perhaps the first modern ecologist to speculate on the ways in which understanding ecosystems could help organize human activity into a more benign form. He posited that mature ecosystems operate in conditions of relative scarcity of available materials but that less mature systems operate in conditions of surplus. There are large differences between a mature temperate forest and a young one developing in the same area, say after a disturbance. Mature forests have a web like organization of interactions through diverse components, with long-lived organisms geared for resource use efficiency and low production. Most energy and nutrients are invested in the living components, are rapidly cycled between them and spend little time in the non-living components; the system is therefore relatively closed. Such systems are relatively resilient except to very large forces. Early stage systems, such as a meadow, are quite the opposite. Instead of a food web there is a food chain with organisms geared for rapid production and low resource use efficiency. A great deal of the available nutrients and energy is found in the non-living components, and this energy can leave the system easily because it is not bound to the living organisms (Odum, 1969).

Odum noted that most human systems, such as agriculture, are geared for production, and typically resemble younger ecosystems. We mine nutrients locked up deep in the earth, apply them profligately (often using massive amounts of water), and these nutrients then wash out of the system where they cause substantial harm

Hiding | Photo: London looks, 2009 | Flickr cc

vol 3 | 2016

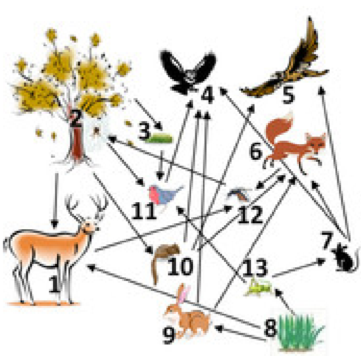
Article
The Ecology of Human Infrastructure

Author:
Marc Weissburg

in other areas, such as the nutrient-fed oxygen depleted zones occurring in the Gulf of Mexico. Our industrial production systems are similarly open loop and wasteful. Shifting the emphasis so that human systems embody the features of mature systems would result in the human systems better able to use resources efficiently. Despite such speculations, the relationship of ecology to industrial ecology remains tentative, and deep principles from the former have not penetrated into the latter with sufficient frequency to be useful.

Food webs such as those studied by Forbes and Odum represent natural experiments that allow insight into what properties produce ecosystems that efficiently cycle materials, which from a human perspective would correspond to energy or material use efficiency and waste minimization. Given N species (where each species can be both predator and prey) a food web can be expressed as a N by N table of ones and zeros, where each cell indicates the presence or absence of a predator-prey link. If the i^{th} predator consumes the j^{th} prey, the value for that cell is 1, otherwise that cell would be assigned a value of zero (Figure 2). This simple formulation permits the calculation of a very large number of properties, including the potential for cyclic exchanges, which are pathways that consist of a series of links that originate and end at the same species. At the risk of belaboring the obvious, cyclic pathways (cycles) retain energy or material in the system rather than exporting it, and thus reduce draws from the environment as well as exports to it.

Ecologists have generated a large and robust food web data set that suggests key features which increase energy and material cycling efficiency. These features summarize network structure as defined by the number, type and strength of connections (or links) between species. The number of connections between predators and prey fall within relatively narrow boundaries,



F =

predators

prey	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	0	0	0	0	0	0	0	0	0	0	1	0
2	1	0	1	0	0	0	0	0	0	1	1	0	0
3	0	0	0	0	0	0	0	0	0	0	1	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	1	0
7	0	0	0	1	1	1	0	0	0	0	0	0	0
8	1	0	0	0	0	0	0	0	1	0	0	0	1
9	0	0	0	1	0	1	0	0	0	0	0	0	0
10	0	0	0	1	1	1	0	0	0	0	0	0	0
11	0	0	0	1	0	0	0	0	0	0	0	0	0
12	0	1	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	1	0	0	0	1	0	0

Figure 2: Predator/prey matrix representing the food web from Figure 1

and the diversity of interactions seems key; there are extremely few specialized predators that consume only one prey, and very few prey that are consumed only by one predator. These conditions create a diversity of pathways by which energy or materials can be cycled before they leave the system. These pathways often are long and contain sub-cycles. Most ecosystems contain several interlocking cycles, and the interaction of a given cycle with other pathways greatly enhances the capacity for internal exchanges that prevent exports.

Has industrial ecology fulfilled its promise of creating cyclic human systems that reproduce desirable features of natural ecologies? Not entirely. Layton (2015) analyzed the structure of nearly 40 industrial networks (eco-industrial parks and other examples of industrial symbiosis) using ecological methods by positing that each component industry can be assigned roles of predators and prey as defined ecologically. An industry that uses material (waste or processed) or energy from another acts as a predator in this interaction, whereas the other industry is prey. Layton found these networks have structures that permit only limited cycling at a level far less than their natural analogs. Compared to food webs, industrial ecologies have a larger number of specialized "predators" and "prey", and a lower average number of prey "consumed" per predator and predators exploiting a particular prey. Although designed to create a cyclic economy, the organization of material or energy flows is concentrated only in focal industries, and pathways are simple and non-interacting, often with only a single cycle that involves a small subset of the actors in the system. Compared to food webs, industrial ecologies have far fewer cyclic pathways (after adjusting for size) and this limits their performance; they resemble young ecosystems as Odum suggested.

Importantly, treating industrial ecologies or infrastructure as food webs is both *descriptive* and *prescriptive*. That is, we can understand why a system might not function as intended, but also predict the effect of changes. Thus, the observations on food web structure constitute design rules that can guide the development of more benign human systems.

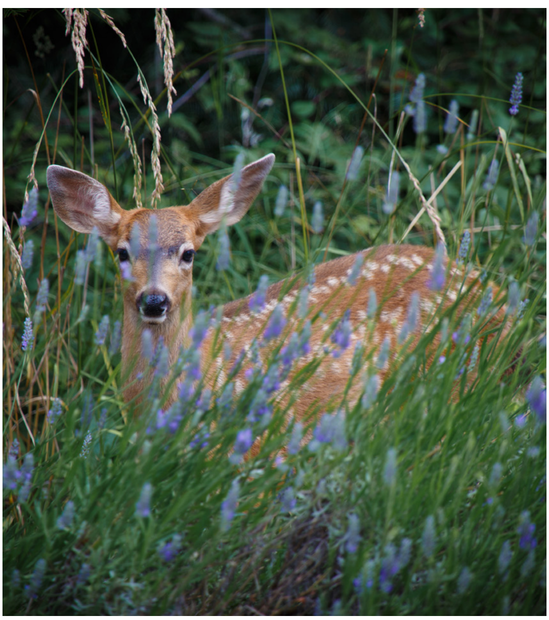
Layton and colleagues (2015) tested this hypothesis using a complex carpet recycling network

Fox

Photo: Janne Heinonen, 2011 | Flickr cc

Peek a boo | Photo: kennethkonica, 2015 | Flickr cc

with nearly 40 actors (species) consisting of carpet manufacturing and recycling centers, landfills and carpet buyers for which all the manufacturing, and other data could be obtained. Objective Function Maximization (OFM) is a common engineering tool used to predict resource efficiency and waste output, requiring a complex series of equations incorporating all the network costs and emissions, including energy and waste materials associated with transport, raw and finished materials, manufacturing, usage and disposal. It's not uncommon to have 20 equations that must be solved simultaneously - a tedious and involved calculation that depends on a rather large body of information. Layton and colleagues generated random carpet recycling network configurations, and computed both ecological metrics (such as the number of specialized predators and prey, and average number of prey consumed per predator) and the performance of these networks using OFM analysis. The closer the ecological parameters of a given recycling network were to the average values displayed by food webs, the better the network performed when evaluated using OFM. In fact, Layton was able to obtain the best performing network by converging only four simple ecological parameters to the values displayed by food webs. Ecology recapitulates industry!



Fawn hiding in the lavender

Photo: PTMurphus, 2016 | Flickr cc

Similarly, Bodini and colleagues (2002) were able to pinpoint, and suggest corrections for, deficiencies in a water distribution system using a comparable approach. They examined the network structure, again computing parameters such as number of specialized predators and prey, and the number of prey consumed by each predator. This analysis highlighted the absence of critical links that would increase cycling by connecting sub-cycles already extant in the system. They then linked these components, and showed using modeling that the new network more effectively cycled water. These efforts show it is possible to design a well-functioning infrastructure network or intervene to improve the performance of existing infrastructure easily and accurately with knowledge only of the linkage structure.

Using ecological network analysis (ENA) suggests a number of "design" principles guiding the organization of human industrial activity:

1. A restrictive focus on a single product or process that ignores the larger system of exchanges required may limit interventions that can increase efficiency and reduce waste.

2. Efficient networks are not composed of few large cycles; they are composed of many small and interlocking cycles that allow for multiple pathways of energy or material exchange.

3. Creating interlocking cycles can be accomplished by reducing the number of specialized consumers and producers.

4. Another strategy is to increase the number of producers utilized per consumer and the number of consumers utilizing a particular producer. Median values of these parameters in real food webs are 4-6.

5. Size of the network is less relevant than the pattern of connectivity.

6. A well-functioning network is virtually impossible without at least one actor that can be characterized as a recycler or reuser (or decomposer, as an ecologist would say). The majority of energy and material in any ecological system flows through decomposers. The humble worm, not the noble lion, is king.

Spurred on by observations and analysis of ecology, as well as an increasing awareness of the importance of system properties, collaborations between engineers, biologists and other scien-

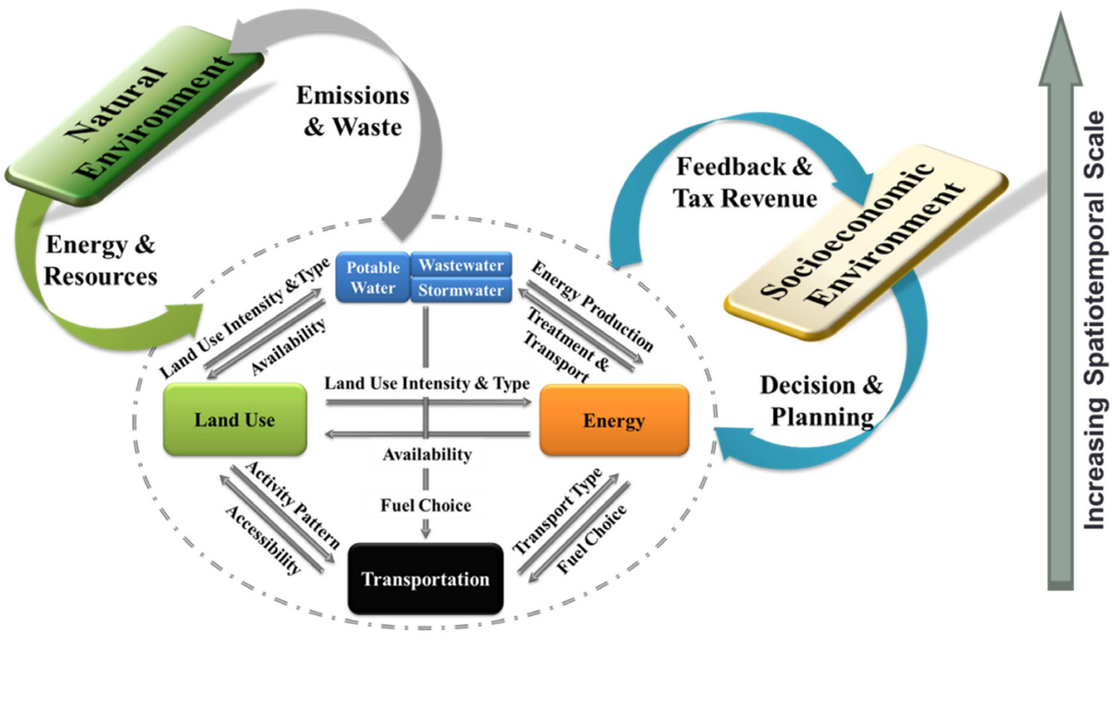


Figure 3: Interconnectedness within the Urban Infrastructure System (UIS) and the interrelation of UIS with Natural Environmental Systems and Socio-Economic Systems.

tists are encouraging the new paradigm of *infrastructure* ecology. This effort emphasizes the need to recognize interactions between components, and understand the emergent properties that occur when these components interact. Insights gained using ecological methods and approaches are in principle appropriate for any "system" that transacts material or energy; the scale matters little. Indeed, ENA has been applied to engines, eco-industrial parks (EIPs), cities (Chen & Chen, 2012), and urban/natural/cultural systems (Pandit et al., 2015; Figure 3). The limiting factor is the degree to which the network structure can be obtained, and analysis of city scale systems currently has used a much reduced number of actors, making the results merely descriptive. Richer network models certainly are possible. Over many scales, insights from ecologically inspired systems analysis will become increasingly important as we seek to transition to a sustainable economy, our systems become more complex, and resource scarcity and amelioration of environmental damage become more important. ×

Key readings

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Image Credits:

Figure 1 (food web): From Layton et al., 2015

Figure 1 (Kalundborg Symbiosis): retrieved 2016/07/17 from https://www.ellenmacarthurfoundation.org/case-studies/effective-industrial-symbiosis

Figure 2: From Layton et al., 2015

Figure 3: From Pandit et al., 2015

Hiding | Photo: LastBestPlace, 2008 | Flickr cc

Cicada

Photo: Henry McLin, 2013 | Flickr cc

Science of Seeing

Listening to the Desert

Adelheid Fischer

Listening to the Desert

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

Cicadas are the sound of water in the Sonoran Desert. In the hot, dry fore-summer of June, the insects begin to emerge from their underground burrows and climb up plant stems and patio furniture where the adults shed their nymphal exoskeletons and set about the urgent task of mating. A few soloists issue their buzz-saw calls during this droughty period, but the full chorus usually doesn't sound until the monsoon season begins. That's when the summer sun heats the continental air, causing a shift in the winds so that they stream up into the desert interior from the Sea of Cortez and Pacific waters off Baja. These airflows pick up moisture from the ocean, elevating humidity levels in places like Phoenix where I live.

One of the telltale signs of the onset of the summer monsoon is the formation of afternoon thunderheads on the horizon. The desert's iconic skies of unblemished turquoise roil with bulbous clouds, the kind that singer/songwriter Joni Mitchell once described as the "clouds of Michelangelo/muscular with gods and sungold."

The other monsoon giveaway, of course, is the Halleluja Chorus sung by a massing of Apache cicadas. In the desert preserve behind my house, the insects, with their stubby-cigar-shaped bodies and clear, stainedglass wings, perch on the stems of creosote bushes and palo verde trees. Their calls begin with a low, hesitant rasp, like a chainsaw sputtering to life, before revving up an octave to hover on an impossibly high note that I swear could shatter a wineglass. To create this sound, cicadas contort their bodies, causing a pair of membranes that are located on either side of their bodies, known as tymbals, to vibrate. Only recently, however, have scientists made a counterintuitive discovery about the mechanisms responsible for the cicada's earsplitting song. The insects are able to turn up the volume not by aligning the vibrations of each tymbal but by desynchronizing them. The result: maximum sound with a minimum of energy, a feat that engineers are anxious to replicate. In some years cicadas are so abundant that the intensity of their chorusing, which can top 90 decibels, exceeds the sound levels of rush hour in Manhattan. During those times I walk on high alert. More than once I have wandered too close to an anxious rattlesnake because the cicadas' frenzied free-for-all has drowned out the chika-chika-chika of its warning.

Long before people could call up a weather report at the tap of a screen, they undoubtedly marked such auditory signals as important milestones in their seasonal calendars. The ancient Hohokam, who farmed the region around my home in Phoenix, surely rejoiced at the chorusing of the cicadas. Their emergence heralded the coming of the summer rains that would re-

Cicada | Photo: Gail Hampshire, 2013 | Flickr cc plenish the canals that watered their fields. Like me, the Hohokam probably also sharpened their hearing during this time in order to tease apart the sounds of the insects from the rattling of snakes.

Our physical experience of the desert has changed, however. Of all the senses that modern humans have dispensed with in the desert, I would argue that hearing tops the list. We have decoupled the gleaning of useful information from the sounds that we hear. Several years ago I met someone at a party who was surprised to learn that the monsoon buzz was caused by insects. She simply assumed that the triple-digit temperatures of summer had somehow overheated the powerlines, causing a kind of seasonal electric sizzling.

Not so for our ancestors. Honing one's listening skills, however, stemmed from more than just the obvious need to detect danger—distinguishing the shake of a rattler's tail, say, from the amplified broadcast of a cicada's mating maracas. The acoustic ecologist Gordon Hempton, for example, was intrigued by the fact that humans "have a very discreet bandwidth of supersensitive hearing" that's designed to intercept sounds that range between 2.5 and 5 kilohertz. What in the natural world of our ancestors, he wondered, emitted sounds within these frequencies? Hempton rifled his database of audio recordings from natural environments around the world and hit on an answer. Birdsong. "Why would it have any benefit to our ancestors to be able to hear faint birdsong? Why would our ears possibly have evolved so that we could walk in the direction of faint birdsong?" Hempton asked. His answer: "Birdsong is the primary indicator of habitats prosperous to humans."

Being "attuned" to the world not only helped to ensure our ancestors' physical survival but also enriched their cultural connections to place. Recent evidence from the emerging field of archaeoacoustics (the study of sound in archeological spaces) suggests that ancient people sought out locations where the surfaces of the rock amplified clapping, singing or the spoken word. Other spaces were valued for the quality of their resonant echoes, which some experts suggest were interpreted by ancient people as emanating from spirits or ancestors. Archaeoacousticians have uncovered a statistical correlation between these sonic sweet spots and the siting of ceremonial pictographs and petroglyphs.

It wasn't until I had a conversation with my colleague Garth Paine, an acoustic ecologist and musician at Arizona State University, that I began to pay much closer attention to the role that sound plays in the experience of my own desert home. It wasn't just about tuning in more closely to the chatter among the birds in my neighborhood. At Garth's urging, I began to listen to the "materiality" of those sounds—and, moreover, to the acoustic signatures of the places themselves. In December 2015, for example, Garth lent me a microphone that I carried on my annual solo hike to the bottom of the Grand Canyon. The sonic diversity that I recorded along the trails surprised and delighted me. Along Bright Angel, one of the main trails that leads into the canyon, I experienced stretches where the sound of my crunching footsteps became sharp, almost crystalline. I would turn the corner of a switchback, however, and the acoustic edginess suddenly became blunted. It was akin to walking in tap-dancing shoes across a ballroom floor and then abruptly switching into sneakers to enter a small closet. Along these reaches, the air around me felt close and dense. In the dampened silence, the trickle of water from a spring under a rocky overhang or the tumbling of a pebble that became dislodged from the canyon wall could be heard in startling detail.

Most captivating, though, were the sections of trail along the creekbeds. The streams would twist this way and that through narrow canyons or across broader stretches of braided channels. Sometimes the water sounded over my left shoulder; at other times, it whispered downstream to my right. Most memorable of all, though, were the intervals in which the sounds of flowing water bounced off the rocky walls all around me, creating a kind of ecstatic sloshing, as if I were swimming in reverberations.

For millennia, humans have walked the Bright Angel Trail, one of the few traversable paths between the the canyon bottom and the rim world of the Colorado Plateau. Surely like me they experienced their trek as a series of sonic compartments, maybe using these acoustic intervals as trail markers or as prompts for the telling of myths and stories, much like the songlines of aboriginal people in Australia.

One balmy evening last spring my ASU colleague Prasad Boradkar and I packed a picnic supper and headed into the Sonoran Desert with Garth to talk about the field of acoustic ecology and to practice some listening ourselves. Below is a link to some excerpts from our conversation. I hope they will help you to listen with new ears to the sounds in your own habitat. ×

Soundcloud link

Cicada, Gray Hawk Ranch

Photo: William Herron, 2013 | Flickr cc

Off the Wall #2 (Crested gecko)

Photo: Kellar Autumn

Portfolio

Kellar Autumn

In addition to his photography work, Kellar Autumn is also a professor of biology at Lewis & Clark in Portland, Oregon.

Kellar Autumn's research focus lies at the interface of biology (biomechanics), engineering (contact mechanics and materials science), and physics (intermolecular and interfacial forces.

When he was studying at the University of California at Santa Cruz, Kellar was a staff photographer for the student newspaper City on a Hill, and covered the anti-apartheid riots. Kellar received his Bachelor's degree in Mathematics and Biology in 1988, and his PhD in Integrative Biology at UC Berkeley in 1995. He continued at Berkeley as an Office of Naval Research Postdoctoral Fellow until 1998, and joined the faculty of Biology at Lewis & Clark in Portland, Oregon in the same year. In his lab he and his students study the mechanisms and evolution of animal locomotion and develop biologically inspired materials and machines. National Geographic sponsored research, and photography, have also taken him to Tibet and the Taklimakan and Gobi Deserts of central Asia.

Could you tell us about how you got started in photography?

I've been taking photographs since I was in high school. I was a photographer for City on a Hill, the UC Santa Cruz newspaper when I was an undergrad. But, I didn't get truly serious about photography until it became a research tool.

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

Because I often have to shoot uncooperative animals that move quickly and can't take a lot of heat, I rely on strobes a lot. I discovered that very strong backlighting can create luminescence and bring out deeper colors. Its essential to work in RAW, and use the full color spectrum, so I like Adobe Lightroom.

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

I've been taking fewer images, and spending more time getting it right the first time. Of course, it's important to experiment, but I rely less on taking hundreds of images and more on planning each shot.

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

I think the way I see the world influences my photography--not the other way around! They say the devil is in the details, but there is beauty in the details too. As a scientist who studies animal function from the macro to the nanoscale, I love creating images that present the beauty at each scale of the hierarchy of life.

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

Mysteries and unanswered questions are inspiring to me. I feed on trying to find the next one and solve it. Maybe I'll take some pictures along the way :-)

Off the Wall #1 (Crested gecko) | Photo: Kellar Autumn

What is the last book you enjoyed?

Peter Hamilton's science fiction novel, *Pandora's Star.*

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

http://www.livescience.com

Because science is cool and exciting, and I never want to stop learning.

http://www.howstuffworks.com

Because technology is cool and exciting, and what I said above.

https://artofvisuals.com/

Because I want to be a better photographer.

http://dilbert.com

Because I can relate to Dilbert's world.

What's your favorite motto or quotation?

"No Nature cannot be improved upon... but to find a dead pelican, photograph a few inches of its wing, so that white quills dart from black barbs, like rays of light cutting a night sky –this is not copying Nature but using her with imaginative intent to a definite end." - Edward Weston 1931

"If your belief system is not founded in an objective reality, you should not be making decisions that affect other people." - Neil deGrasse Tyson, 9/14/2014 ×

Off the Wall #4 (Crested gecko) | Photo: Kellar Autumn

Bibron's gecko and friend | Photo: Kellar Autumn

Tokay gecko | Photo: Kellar Autumn

“In your face” (Crested gecko) | Photo: Kellar Autumn

Tail end of a tokay gecko | Photo: Kellar Autumn

Es camp de mar

Photo: bortescristian, 2013 | Flickr cc

Interview

Daniel Christian Wahl

Daniel Christian Wahl is an international sustainability consultant and educator specializing in biologically inspired whole systems design and transformative innovation. Daniel originally trained as a biologist (University of Edinburgh, 1996 & University of California, 1995), holds an MSc in Holistic Science (Schumacher College, 2001) and gained his PhD in Design for Human and Planetary Health from the University of Dundee in 2006. He has worked with local and national governments on climate change impact, foresight and futures. Daniel has published a wide range of articles and academic papers on ecological design and biomimicry since 2003. His first book, *Designing Regenerative Cultures* (http://www.triarchypress.net/designing-regenerative-cultures.html), was published by Triarchy Press (UK) in May, 2016.

Daniel Wahl

Photo courtesy of D.Wahl

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

More and more people are beginning to understand that humanity has lost a vital connection with the natural world – a connection that until recently informed and sustained our species. The scientific and industrial revolution brought us fantastic, almost miraculous, technological progress, but also a mindset where progress meant substituting the old with the new, and humanity and culture came to be thought of as being separate from nature. More than once we have thrown out the baby with the bathwater, and declared vital wisdom as "primitive" in the rush for technological "progress". We should have paid more attention to the guiding wisdom of place-based cultures co-evolved in intimate reciprocity with the bio-cultural uniqueness of their bioregions.

Many biomimics are indirectly perpetuating the entirely mind-made divide between humanity and nature by the way we use language to describe what we do. The boom in design and technology inspired by nature is – for the most part – still undertaken within a mindset that is based on *learning from nature*. It is time to recognize that we *are* nature and have to re-indigenize to fit our human cultures into the life-sustaining ecosystems functions of the places and regions we inhabit.

Cala Marcal

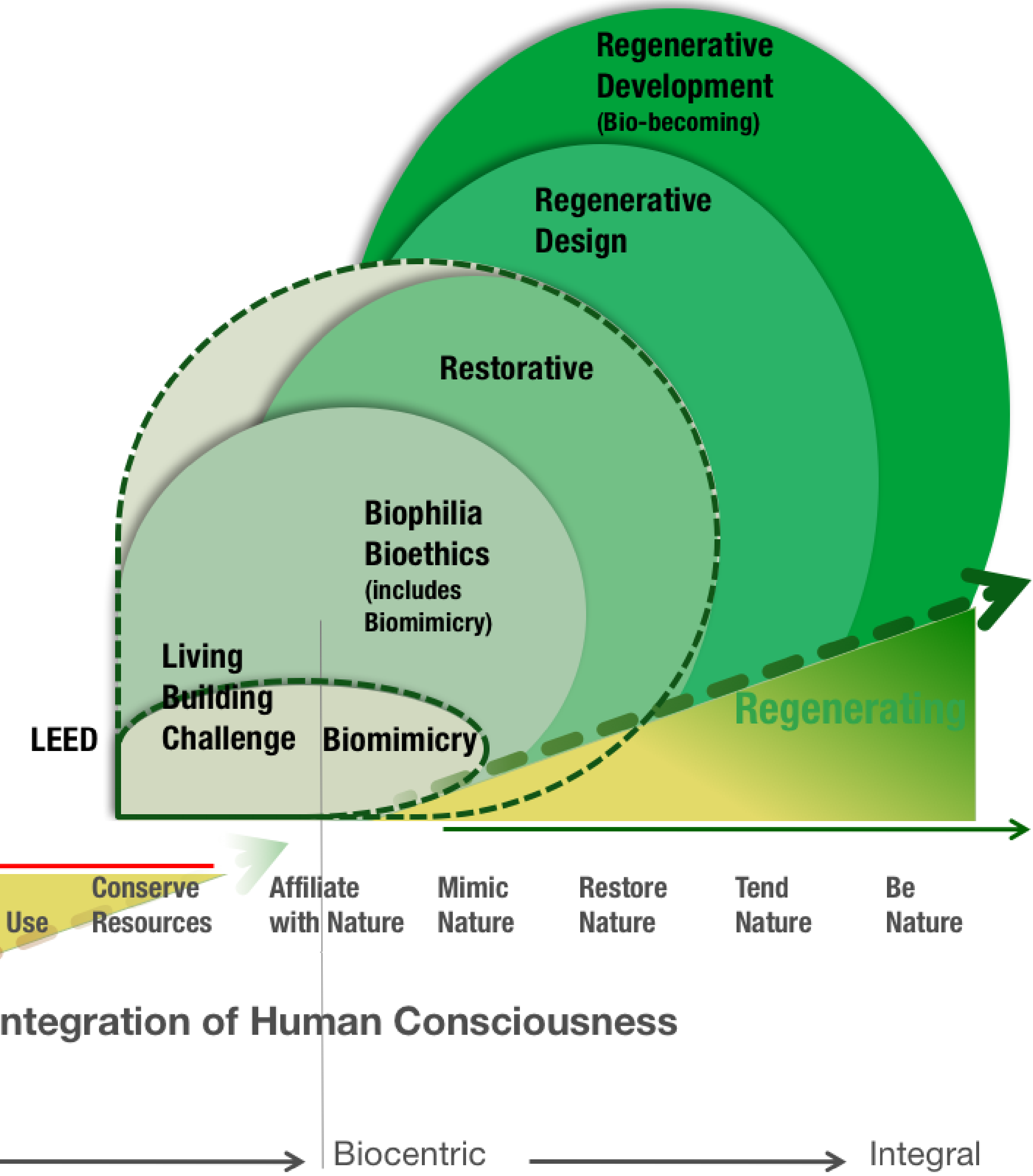
Photo: bortescristian, 2013 | Flickr cc

We have to learn to *design as nature*. The first step in this process is to accept that as biological beings we are participants in and expressions of natural processes. Culture does not have to necessarily be divorced from or in competition with the rest of nature. All action or inactions are interventions in the socio-ecological systems we participate in. This participatory worldview is both relatively new in science (second order science) and very ancient, as most indigenous cultures share a participatory awareness of nature as the ground of our being. I believe that learning from traditional indigenous wisdom – or what has also been called Traditional Ecological Knowledge (TEK) – is also an important aspect of biomimicry practice.

What do you see as the biggest challenges?

What puzzles me about our field is that with so many excellent people sharing such positive intentions, we still seem to lose too much energy exploring our differences and not enough time celebrating these differences as the source of the necessary requisite variety we need for rapid adaptive responses to a changing environment. Let's care less about labels and brands: biomimicry, bionics, regenerative or ecological design – what matters are the shared intentions.

There are also some negative side-effects of sound-bite culture and the kind of oversimplification of the biomimetic process and practice that goes hand in hand with TED-talk story telling which was so important for spreading the passion for biomimicry widely. These side-effects are setting recent converts to biomimicry up for disappointment when they realize that the translation process – from



Regenerative Design and Consciousness,
Reproduced with permission of the Regenesis Group

natural form, functions and process to creating technological and industrial innovation – is in fact hard work and often takes years of trial and error.

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

I believe that we urgently need to become good at the practice of integrated regenerative whole systems design at the regional scale. Such a regenerative design approach weaves the production of food, materials and products into synergistic relationships with the generation of renewable energy and the regeneration of top-soils, forest and healthy ecosystems functions, while effectively (up-)cycling biological and technical resource streams. This is what we are talking about when we speak about systemic biomimicry. McDonough and Braungart's *The Upcycle* is really a book about systemic biomimicry and regenerative industrial design.

The global biomimicry and bio-inspired design networks could play an important role in facilitating collaboration and knowledge exchange to help apply Nature's operating principles to re-regionalizing production and consumption. In order to play this role effectively we need to put

Daniel Wahl speaking and teaching at the European Institute of Design, Madrid, 2015

Photo courtesy of D.Wahl

aside the issues of semantic differences between biomimicry, bionics, biomimetics, bio-inspired design, regenerative design, and so on, which – at least in Europe – seems to have slowed down effective collaboration among already existing and broadly aligned networks of practitioners.

I worked with Forum for the Future (https://www.forumforthefuture.org) and the Belgian company Ecover (http://ecover.com) on exploring the feasibility of creating detergents and cleaning products for the tourism industry on Majorca almost entirely from organic waste streams generated on the island from agriculture, forestry and municipal organic waste. While the project was only a year-long pilot and has been put on hold since 2014, we did learn a lot from this hands-on exploration of the design of circular regionally focused bio-economies and decentralized manufacturing in action, in particular which questions we needed to ask.

One conceptual strong point was linking the 35 years' experience of a company like Ecover, selling to a global market, to the local chemical industry and local production capacity in SMEs to not only innovate new products but a new business model for global-local collaboration and innovation. This kind of innovation could pioneer a path for place-sensitive local design solutions that enable global companies to shift to distributed manufacturing (Project website: http://glocal.ecover.com/).

What is your best definition of what we do?

Biomimics – at their best – aim to design *as* nature. To me, that means creating conditions conducive to life, aiming to create salutogenic or health-generating design, while pursuing whole systems optimization rather than the maximization of individual and isolated parameters.

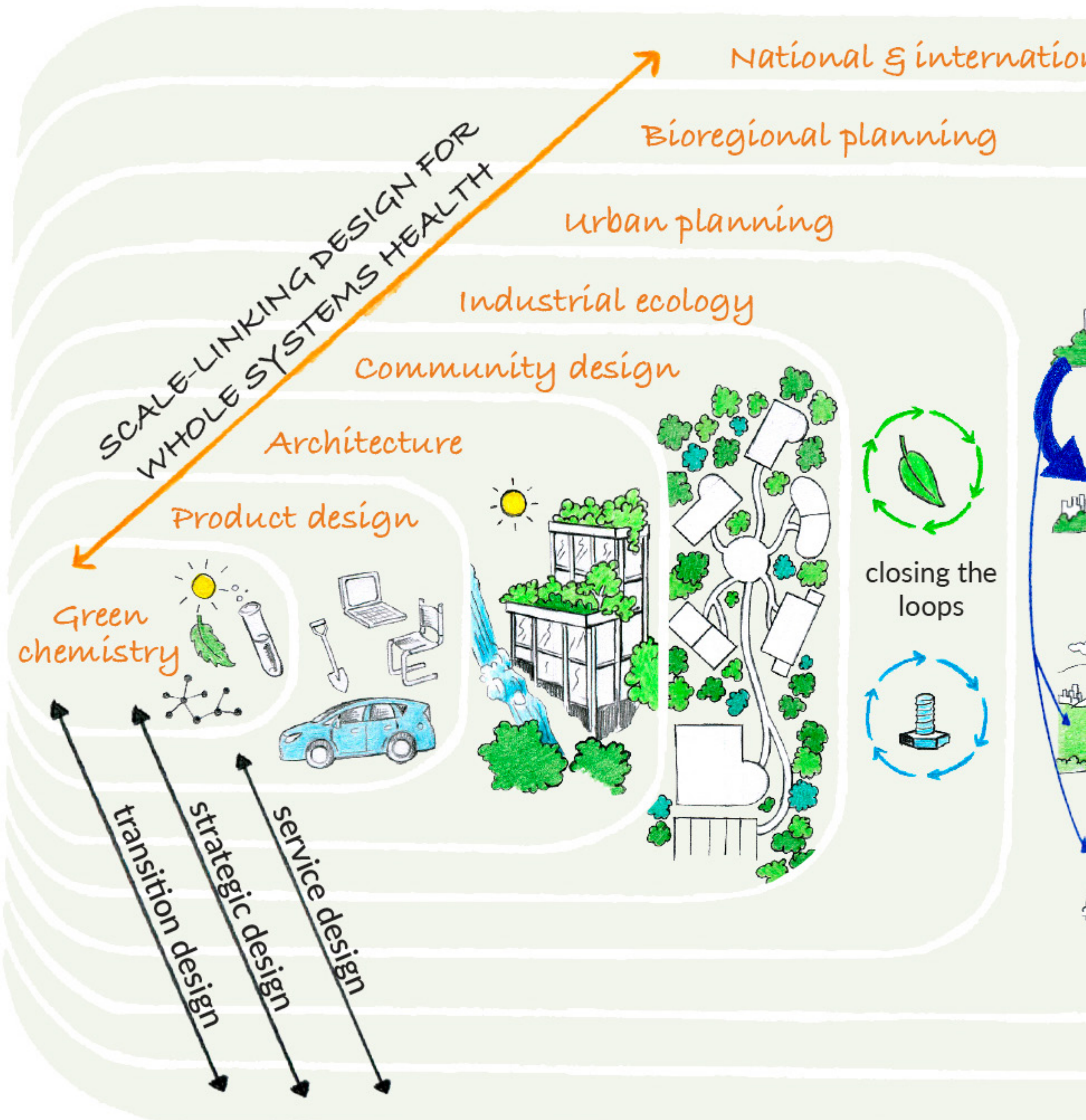
It is time to go beyond sustainability and aim for a positive and regenerative impact. Our goal should be to contribute to the transition towards diverse regenerative cultures elegantly adapted to the bio-cultural uniqueness of the places they inhabit.

I believe that a vital skill for people who want to work with truly systemic biomimicry is to be able to facilitate multi-stakeholder and multi-disciplinary dialogue, and to do so by helping to "translate" between the disciplines and invite people to map out a multi-perspective based understanding of the complex and dynamic socio-ecological systems in which we participate at various scales. Once we learn to access the collective intelligence that comes from acknowledging the contributions of different perspectives and ways of seeing, we can more appropriately and wisely *design as nature*.

By what criteria should we judge the work?

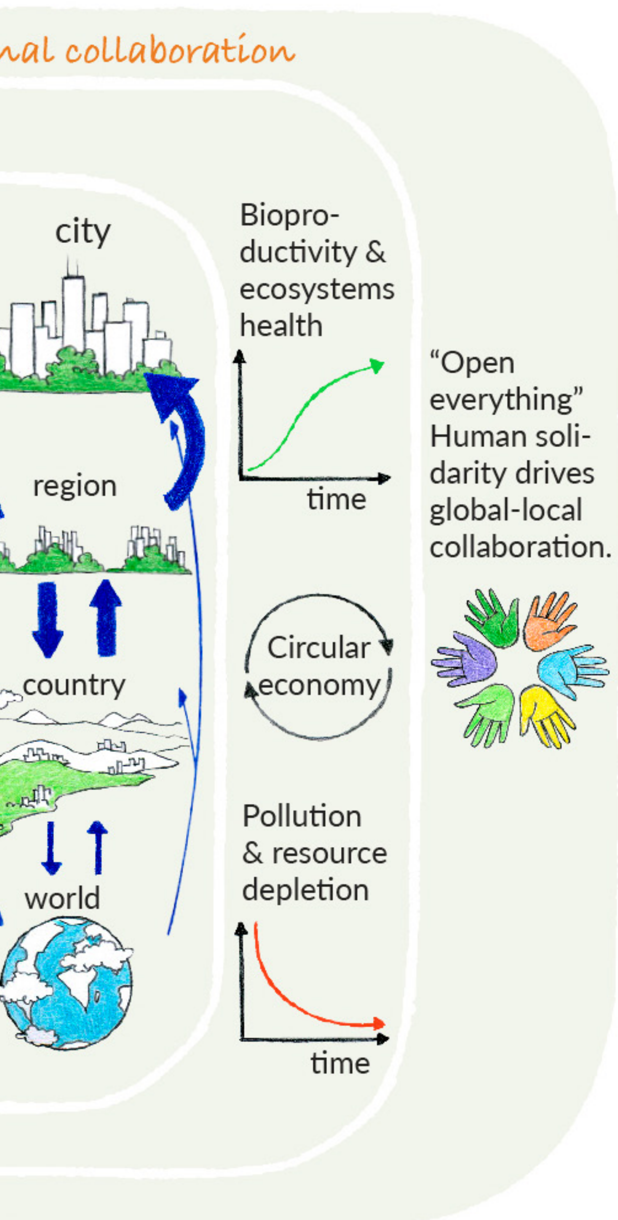
In my seminars at universities and design schools, I often quote William McDonough's important question *"can anything be considered truly beautiful if it creates ill health, suffering, or ugliness elsewhere?"* We should also ask:

- How is the proposed design contributing to the regeneration of bio-cultural diversity and healthy ecosystems functioning at local, regional and global scale?
- In what way is the design creating conditions conducive to life?



The Scales of Regenerative Design for Systemic Health, from Designing Regenerative Cultures

Graphic courtesy of Daniel Wahl, 2016



- Can we communicate the story of this design in ways that dissolve the nature/culture divide and invite people into a biophilia-based relationship with nature?

- What aspects of the total life cycle of the design have potentially degenerative impacts on socio-ecological systems, and how is regenerative activity designed into the entire supply chain necessary to create this design?

I believe that we have it wrong when we hope to create cultural guidance systems that help humanity into a sustainable or regenerative future based on set of recommended silver bullet “solutions”. How often in known history have yesterday’s solutions turned into today’s problems? How can we possibly presume that our solutions will not also reveal unforeseen side-effects or simply cease to be adequate responses to changing situations within a continuously transforming whole?

I believe that a more appropriate culturally regenerative compass to hand from generation to generation will be a set of questions we aim to improve and expand upon. We can better learn from our temporary answers and solutions by seeing them as transient means to ask better questions. Herein lies the path of transformative innovation and adaptation to life’s continuous exploration of novelty.

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

I studied biology in the early 1990s because I wanted to understand how life works and what life does. As a fledgling marine mammal biologist I became very dissatisfied with the one-sided approach of a statistics-dominated science that seemed to only value the quantifiable and measurable, while practically ignoring systemic relationships and interconnections that were intuitively perceivable and could be mapped, yet – driven by qualitative relationships and systemic interconnections – were hard to narrow down to a p-value of statistical significance.

This eventually led me to turn my back on conventional research science, and – after a short period as a dive-master, scuba diving instructor, and environmental activist – led me to enroll in the Masters in Holistic Science at Schumacher College. During my time there, I read Janine Benyus' book in 2002 and came to see ecological and bio-inspired design as the practice end of the holistic sciences.

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

At Schumacher College in England, I had an opportunity to include a three-week intensive on ecological design with John Todd, Nancy Jack-Todd and David Orr into my degree. They helped me understand that design was a much bigger and much more important activity than I had previously assumed as a biologist and systems scientist. I wrote my Master's thesis on the relationship between holistic science and ecological design.

My PhD supervisor Prof. Seaton Baxter helped me to get a funded PhD scholarship at the University of Dundee's Centre for the Study of Natural Design where I received my PhD in 'Design for human and planetary health' in 2006 and published my first academic paper on biomimicry.

In 2012, after moving back to Spain, I co-founded Biomimicry Iberia together with Theresa Millard, Andrea Monge, Manuel Quiros and others, and in 2015 we hosted the first Biomimicry Practitioners Camp of the European Biomimicry Alliance on Majorca, where I now live.

Design is an ongoing culturally creative conversation by which we are bringing forth a world together. Paying attention to life's 3.8 billion years of distributed collective intelligence coded into a marvellous diversity of species *and* the relationships between them within an undivided continuously transforming whole can teach us a lot about how to design and act more wisely.

What are you working on right now?

I am promoting my book *Designing Regenerative Culture* as an invitation to engage in deeper and broader conversations that I believe we urgently need to have in our communities, boardrooms, and government offices.

In an ongoing collaboration with the Rhode Island based design firm Tellart and the Dubai Futures Foundation, I am helping to create an edition of the annual 'Museum of the Future' exhibition that will be focused on the kind of regenerative practices and technologies that we will have at our disposal in 20 to 30 years' time.

I work part time for Gaia Education and have just completed a review and expansion of the four dimensions (social, ecological, economic and worldview) of its UNESCO endorsed on-line curriculum in 'Design for Sustainability'. The feedback from students logging in from all over the world is deeply rewarding and motivating. The next steps are to develop a 25-hour online course that will help communities take ownership of and play an active role in implementing the Sustainable Development Goals at a local scale, followed by the development of a more regionally focused blended-learning program that will focus on bioregional, transformative innovation and social entrepreneurship.

I also work with the new S.M.A.R.T. UIB project at the University of the Balearic Islands. We are in the process of creating an international program in innovation, sustainability and design, and are partnering with diverse businesses and public authority to use the 18,000 people community and infrastructure of the university as a test-field for innovation within the wider bioregional test-field of the island of Majorca. We will run a seminar on systemic biomimicry and transformative innovation in June 2017.

What is your favourite biomimetic work of all time?

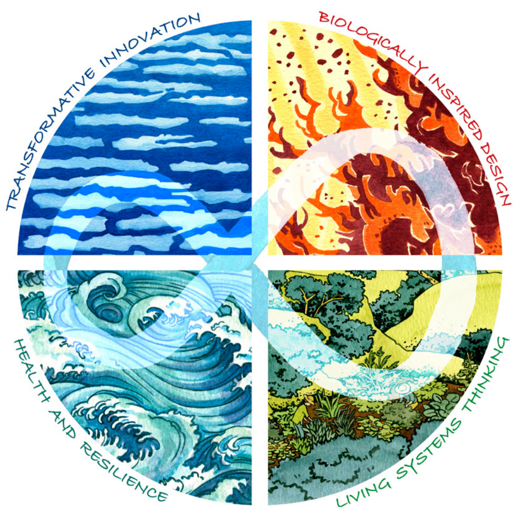
I very much love and respect the work of Jason McLennan and the folks at the International Living Futures Institute. I also look forward to seeing further development of Michael Pawlyn's vision of re-greening the desert through the Sahara Forest Project. The whole ecosystem of innovations around morpho-mimicry of the sharkskin denticles make for a fascinating and inspiring case of biomimicry in action, as does the work of John Warner and Amy Cannon in Green Chemistry.

What book did you enjoy recently?

In the process of doing the research for my book I read many inspiring books. To name just a few of them: Giles Hutchins' *The Nature of Business*, Ethan Roland and Gregory Landua's *Regenerative Enterprise*, Jay Harman's *The Shark's Paintbrush*, Tom Atlee's *Reflections on Evolutionary Activism*, Robert Steele's *Open Source Everything*, Bill Sharpe's *Three Horizons – A Patterning of Hope* and, most recently, *Transformative Innovation* by Graham Leicester.

Who do you admire? Why...

I deeply admire my 99-year-old grandmother. She has taught me to never lose my curiosity for life and to always see the beauty in front of



Cover Illustration of *Designing Regenerative Cultures*, by Daniel Christian Wahl, 2016

Illustrator: Flavia Gragiulo

me in the little things many people tend to walk past every day, whether it is the colour or shape of a flower, the architecture in a blade of grass, or the warmth and compassion in a caring human interaction. She is a seemingly eternal practical optimist and her experience makes her a great mentor in the art of the long view.

What's your favourite motto or quotation?

I have a number of favourite quotations:

> *Life creates conditions conducive to life*. (Janine Benyus)
>
> *The universe is not a collection of objects but a communion of subjects*. (Thomas Berry)
>
> *My life is a gift, from the whole of life, to the whole of life*. (Tom Atlee)
>
> *I live on Earth at present, and I don't know what I am. I know that I am not a category. I am not a thing – a noun. I seem to be a verb, an evolutionary process – an integral function of Universe*. (Buckminster Fuller)

What is your idea of perfect happiness?

Hiking in the Tramuntana mountain range on Majorca with my partner Alice, or chanting mantras on my stand-up paddleboard while gliding over the mirror-flat Bay of Palma as the sun rises. There are also good meals with friends, or the buzz on day two of a really creative workshop with a group of committed co-learners.

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

I love stepping into all three of these roles and feel privileged to be part of a new generation of professional generalist who are specialized in many things but not to the depth where we are susceptible to extreme cases of silo-sitis. At some point I might reinvent myself as a documentary film-maker to reach a wider audience and respond to the sad fact that too few people have the time to read books anymore.

I also love carpentry and working with wood. Once I start working on my own home, I want to return to doing my own woodwork again. I also look forward to planting an analogue forest (https://en.wikipedia.org/wiki/Analog_forestry) along the northern edge of the house and hopefully I will live long enough to watch the trees grow to maturity. ×

Palma de Majorca | Photo: bortescristian, 2013 | Flickr cc

Little gecko ‘recent foot’

Photo: p for petrina, 2012 | Flickr cc

Opinion

Biomimicry: what's in it for us?

Alyssa Stark

Author:
Alyssa Y. Stark

A biologist's perspective on how biomimicry can inform studies of the natural world

Biomimicry is a highly interdisciplinary endeavor. Biomimicry practitioners come from all walks of life including, but certainly not limited to: science and engineering, the arts, business, humanities, and many others. In fact, one of the most remarkable properties of biomimicry is its ability to unite people around the central theme of taking inspiration from nature to solve human challenges.

Earlier this year Dr. Emilie Snell-Rood, a biologist at the University of Minnesota, Saint Paul, wrote a telling commentary for the renowned science journal *Nature* (Snell-Rood 2016). Here she outlined some interesting facts. First, she found that the field of biomimicry is composed primarily of chemists, engineers and material scientists. In fact, in 300 recent studies over the course of three months, less than 8% of these studies had a biologist on the team. Second, over the course of a year, more than 80% of the scientific papers published on biomimicry only investigated one generalized "biological element" (like a cell, enzyme or species). This last point is often called the "white rat syndrome", named after the prevalence of using the lab rat as the primary model for research in many fields, such as medical research. While the importance of having a well-understood model that can be tested in different ways over and over is clear, the problem with studying just one "biological element" is that we are missing the extraordinary biodiversity available to us - which incidentally is something many biologists spend their lives studying. Thus, despite the unifying nature of biomimicry, in general practice within science and engineering, there is one important group often left out - the biologists. With a field termed biomimicry, the absence of this group seems surprising, to say the least.

So, what are the consequences of the missing biologists and their knowledge of biological diversity at the biomimicry design table? In many ways there may be very little consequence. Some of our most impressive biomimetic accomplishments and designs are from brilliant teams of chemists, engineers and material scientists. However, these teams owe their ideas and ultimate success to nature, and by extension to the biologists who gathered and reported their findings of the natural world. Thus, the question remains - can we do better? Let's take the white rat example again. In May 2016, a new study published in the Proceedings of the National Academy of Sciences, estimated that there could be as many as 1 trillion species on the planet (Locey & Lennon 2016). To put this into perspective, there may be more species on earth than stars in our galaxy. By this approximation, to say that biomi-

@thebeach | Photo: votoWorxx, 2015 | Flickr cc

Tokay gecko | Photo: ReptilesPlus, 2012 | Flickr cc metic studies have even scratched the surface of the world's biodiversity is a dramatic understatement.

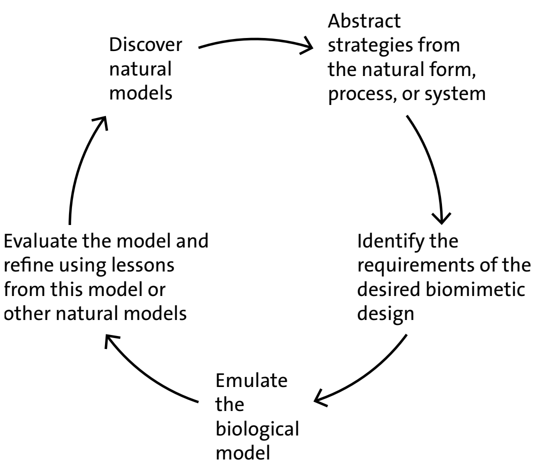
In reality, sorting through a trillion life forms is impossible, but consider the benefits of inserting the direct source of knowledge about life on the planet into a design team. Furthermore, consider the insights about system-level biological processes that can be gleaned by having a biologist at the table. Certainly the lack of biologists in science-based biomimicry research is clear, and the limitations of this are outlined by Dr. Snell-Rood's commentary, but what is the hold up? In this article I would like to build on Dr. Snell-Rood's thoughts, and focus on what I believe is a major tripping point in getting biologists to join the biomimicry team. For those who have pioneered biomimicry thinking in a company, team or institution, I believe the same tripping point we all encounter holds true for biologists. The "what's in it for us?" question. My goal is to highlight how biomimicry can aid the study of the natural world by using a case study from my own work, emphasizing that biomimicry doesn't have to be a one-way street for biologists, where knowledge is shared and used for biomimetic solutions unilaterally. I do have to point out here that I make one critical assumption: the research team already wants to, and is prepared to collaborate with a biologist. Getting to this point can often be a separate and significant challenge itself.

Biomimicry in Practice

While the process of biomimicry can be just as challenging as it is rewarding, it tends to follow one of two paths. The first is observation of a natural form, process, or system that is used as inspiration to solve a human problem, known as the "Biology to Design" path (Baumeister 2014). The example I'll focus on in this article is the sticky gecko toe. Early thinkers such as Aristotle noticed the remarkable capabilities of the gecko to cling and run across virtually any surface, even up-side-down (Autumn 2006). Observations like this, and many detailed studies, lead to the design of hundreds of gecko-inspired synthetic adhesive tapes that can be used over and over again like the gecko foot. The second path is the reverse. Here a person or team outlines a human problem, and then searches through biological knowledge to find potential strategies that nature has developed over evolutionary time. This is the "Challenge to Biology" path (Baumeister 2014). An easy way to think about this approach is to ask the question: "how does Nature ...?" This question search, and a database of potential answers, is available at AskNature.org. While both paths can be highly fruitful, often biologists connect with the first, and engineers and industry professionals use the second (though not always). The path of least resistance may be to use the biologist's natural line of inquiry to seed biomimetic collaborations in the "Biology to Design" pathway. I will focus on this approach and later suggest ways of engaging biologists in "Challenge to Biology" projects.

Scientists, including biologists, use the Scientific Method to answer questions about the world around them. Specifically, the Scientific Method is a way to investigate, measure and gather evidence, which can be used to test predictions which were based on observation. In principle it is fairly simple. First, a scientist makes an observation, which naturally leads to questions. For instance, you observe that a bee lands on a yellow flower. Then you notice that it moved from this flower to another that is also yellow. At this point you may start to ask questions like: Does this type of bee only land on yellow flowers? Is it just this species of plant or all yellow flowers? Clearly the questions can go on and on. Next, scientists formulate hypotheses and/or testable predictions based on current knowledge and the observations they made to answer their most interesting question. For instance, you hypothesize that the bee species you observed only lands on plant species A, which you know based on other scientists' work is specific to that area. To answer this, you collect observational data on bee visits to plants near the hive and find that bees of this species land on plants of species A, B, and E, but not C or D. These results lead you to reject the hypothesis that this type of bee only lands on plant species A. For scientists rejection isn't a bad thing, it's good. It means we can move on to the next question, which often stems from the results, circling back through the scientific method again and again until we understand the system more thoroughly than we did before. This can seem monotonous and tedious to outsiders, but to scientists it is the most rigorous way to answer a question, and believe it or not, we find it exhilarating!

Perhaps the reason why biologists and other scientists often connect with the "Biology to Design" path, is because there are many parallels with the Scientific Method (Figure 1). For example, similar to the Scientific Method, the "Biology to Design" biomimicry path begins with an observation or discovery of a natural model. Then the team works to abstract the strategies of that biological form, process or system, and identify the context and function appropriate for the proposed design (i.e., the requirements). This is not unlike gathering information and observations to formulate a testable hypothesis in the



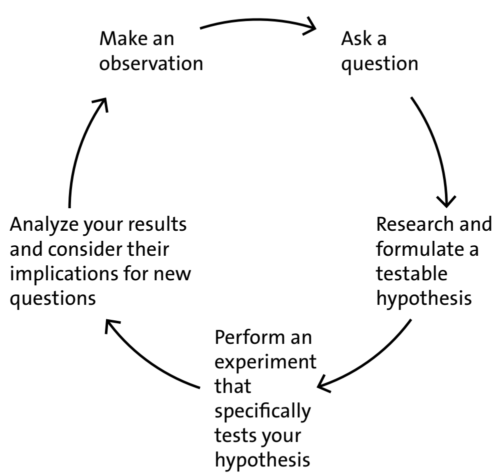


Figure 1. "Biology to Design" method (A; adapted from Baumeister 2014), and the Scientific Method (B).

Scientific Method. In both processes the next steps get a bit messy. During this stage experiments or design ideas are brainstormed, tested, improved, and reevaluated until either the hypothesis is accepted or rejected in the Scientific Method process, or the biomimetic model meets the requirements the team outlined in the "Biology to Design" pathway. Clearly there are major differences between these two processes as well, particularly when considering their desired outcomes. Specifically, the Scientific Method is driven by the goal to develop a reliable explanation for the initial observation, whereas the "Biology to Design" process works to create new opportunities inspired by, and perhaps eventually very tangential to, the initial observation.

One of the hardest steps in the "Biology to Design" path is appropriately extracting relevant features of the biological model (Kennedy & Marting 2016). Likewise, one of the hardest steps in the Scientific Method is designing an experiment that only tests your hypothesis or prediction. For biologists, experimental design becomes particularly difficult because the natural world is complex and interrelated. For instance, in the bee example, how could you be sure the hive you studied did not have some bias towards plant species A? Perhaps a predator in this area lurks at all other plants except species A, or the hive you choose suffers from a genetic anomaly which makes yellow flowers on species A more conspicuous than all others. To avoid bias, scientists use experiments with control groups, or collect data on multiple groups with just one difference between them, keeping all other factors the same, to single out the answer to their question. Another way to test a hypothesis, particularly one that has too many potential biases, is to compare the complex biological system to a model that has controlled parameters. It is here where I see the opportunity to engage biologists, ultimately opening the door that brings them to the biomimicry design table.

Gecko Adhesion as a Case Study

Getting a biologist to the biomimicry design table, and really any table can be challenging - especially with field biologists who probably actively avoid being indoors and sitting at tables as much as possible! I believe the solution to getting a biologist to the table, and ultimately answering the "what's in it for me?" question, is to supplement the scientific method with biomimetic models. Specifically, by drawing on the similarities between the Scientific Method and the "Biology to Design" path, common challenges with the translation of processes and culture between fields are reduced. Additionally, for biologists, the ability to control and manipulate a model to better understand the complexities of the natural world should perk the interest of most. Certainly many already use this technique. In my work on gecko adhesion, I had the opportunity to take just such an approach. Specifically, I used a biomimetic model to investigate a standing debate in the field which had been stalled for years due to the inability to separate several complex factors in the natural gecko adhesive system. Interestingly, not only did the biomimetic model help me test and answer several important hypotheses, the use of a biomimetic model helped generate more questions and hypotheses to explore. Ultimately this allowed us to further refine our understanding of the gecko adhesive system, which is the end goal of the Scientific Method.

In 2008, my PhD advisors, Dr. Peter H. Niewiarowski (a biologist) and Dr. Ali Dhinojwala (a polymer scientist) at the University of Akron, Ohio, teamed up to study how geckos stick in hot and humid conditions. The reason they asked this question can be separated by their fields. Biologically, the question is interesting because many species of gecko are native to hot, humid, tropical environments and thus, we would expect the adhesive system of tropical-dwelling geckos to have some mechanism to maintain function in this climate. From a material science perspective, testing and eventually understanding how an adhesive works in high temperature and humidity satisfies not only the scientific interest of how two materials interact in such an environment, but also provides potential biomimetic design strategies to improve or optimize current gecko-inspired synthetic adhesives, or perhaps even design new ones. The results of this study showed that gecko adhesion increases as humidity increases, but only at low temperature. At high temperature humidity had no statistically significant effect on adhesion (Figure 2; Niewiarowski et al. 2008).

Over the years our group and other scientists worked to understand this result, but continued to only get partial answers. The best answer we have so far is that the tiny hairs on gecko toes, which are the key to their adhesive success, get softer and more flexible in high humidity. This softness produces a better grip on surfaces due to increased contact area (Prowse et al. 2011).

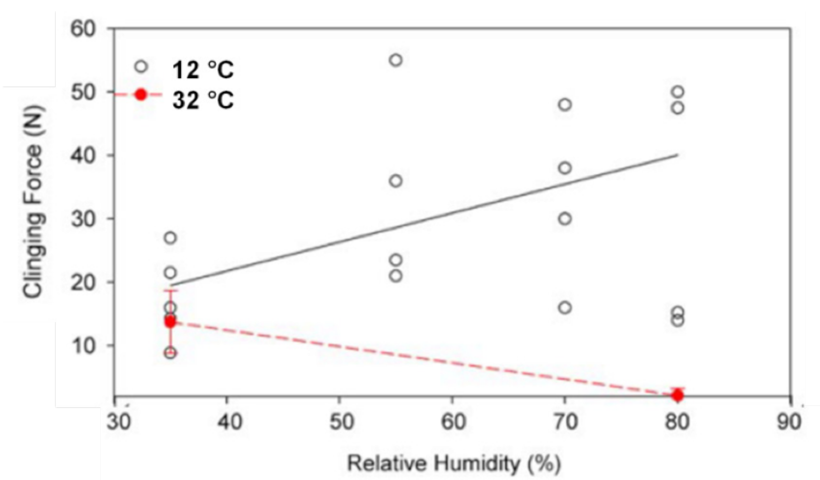


Figure 2. Gecko (*Gekko gecko*) adhesion in high (32°C) and low (12°C) temperature in varying humidity (adapted from Niewiarowski et al. 2008). Changes in humidity affect adhesion at low temperatures but do not have a significant effect at high temperatures.

However, this and other studies did not vary temperature and humidity, and rather, focused on humidity alone. Clearly this is a major limitation to our current understanding. The next logical step would be to independently investigate how temperature affects the tiny hairs (i.e., do the hairs also soften as temperature varies?). While this has not been done yet, studies on humidity and water have since complicated the original question. For instance, in wet conditions, like in high humidity, the tiny hairs not only get softer, but they change chemistry or become wet, both of which have the potential to effect adhesion (Pesika et al. 2009; Hsu et al. 2012; Stark, Sullivan & Niewiarowski 2012). Thus, softness many not be the only reason why adhesion changes, and instead it can be any number of independent and interrelated factors related to humidity and temperature. This is where the biomimetic model comes in.

In 2014 we tackled this complex question by teaming up with Dr. Metin Sitti and his group at Carnegie Mellon University, home of one of the best known gecko-inspired synthetic adhesives. This adhesive mimics the tiny gecko hairs using a plastic material that is shaped like a flattened mushroom. Much like the gecko toe, many tiny polymer mushrooms increase contact area and thus increase the stick (Murphy, Aksak & Sitti 2007). Ultimately, the gecko-inspired synthetic produced by Dr. Sitti and his team performs similar to the gecko in that it is strong, glue-free, reversible, and reusable, unlike many of our commercially available tapes. While Dr. Sitti's team continues to refine, and even sell this product

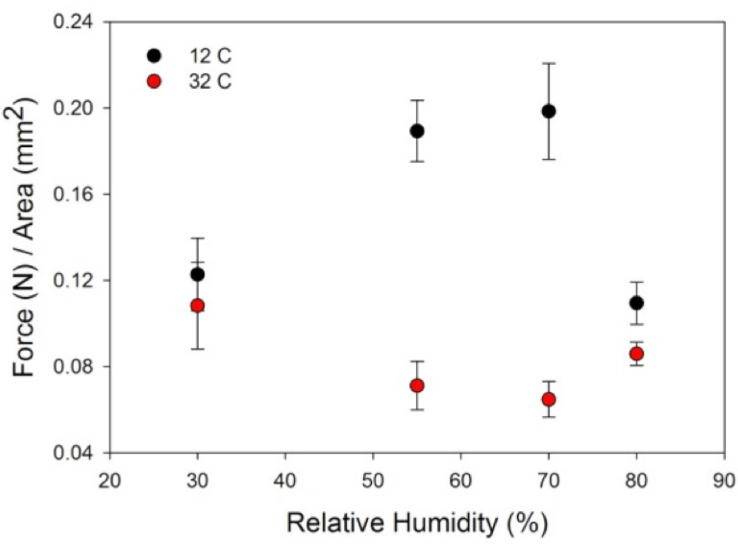


Figure 3. Adhesion of the gecko-inspired synthetic across the same temperature and humidity conditions of the gecko (adapted from Stark et al. 2016). Overall, the results were similar to those observed in geckos except at 12°C and 80% RH.

commercially (nanoGriptech, Inc.), in this study we focused on the biological system. Specifically, Dr. Sitti's tape provides us with a control model. Because his tape does not change shape, softness, chemistry or wet like the gecko (in either temperature or humidity), we can test the most basic question about our complicated system; does adhesion of a hairy structure vary based on temperature and humidity alone? Again, the use of the model cancels out all of the other options we found in the gecko (i.e., softness, chemistry, wetting), leaving us with just the environment (i.e., temperature and humidity) and what this may do to adhesion. After testing the synthetic adhesive in the same conditions my advisors tested the geckos in years earlier, we found that the synthetic showed nearly the same behavior as the gecko. In fact, the natural and synthetic systems only diverged at very high humidity and low temperature (Figure 3; Stark et al. 2016).

So what do our results mean? Well first off, our hypothesis that softening and other factors are the primary source of increased adhesion in the natural system can be rejected, at least in the specific context of this study. Instead, the way hairy adhesive structures interact with their environment (temperature and humidity) appears to be strong enough to drive the changes we see in both the controlled synthetic model and the uncontrolled gecko system. Secondly, the mismatch between the two systems at high humidity and low temperature highlights a context where the gecko material may be changing in ways the synthetic cannot (i.e., remember, the synthetic does not get softer, change shape or chemistry). For instance, is this where the gecko's ability to soften the adhesive hairs becomes important, making the gecko's design more robust than the current synthetic at that extreme? Thus, our next steps are to 1) understand what environmental factors causes the gecko and the synthetic gecko-inspired tape to get stickier at low temperature and high humidity (i.e., at high temperatures does more water deposit on the surface, making both systems slip?), and 2) understand why the two systems differed at the extreme (i.e., is it the softening or chemistry changes in this condition that give the gecko the advantage?). This last point in particular showed us that using a biomimetic model easily generates new questions and hypotheses to more completely explore the system, and ultimately keep the Scientific Method and its generation of knowledge flowing. Exploring these and other questions will lead to a better understanding of how geckos stick, and also provide unique perspective on how to change, and even optimize, biomimetic designs that can function in complex environments.

Although this case study shows how a bio-inspired design can help test questions about a biological system, it is limited in one key way. Specifically, collaboration occurred after the natural and the synthetic systems had been investigated. There is no right way to make use of a bio-inspired design or biological data, but imagine a different scenario. Consider the possibilities of this collaboration if it had begun as a joint endeavor, and included designers and other members of a more classical biomimicry team. I imagine something like the following. First, each collaborator identifies priorities, interests and desires, leading to an outline of common goals. In this example it may be related to developing a synthetic that can stick in high humidity and high temperature for the material science and design teams, and for the biologists, it may be understanding if geckos from the tropics can maintain adhesion on a hot, humid day. The next course of action would then be more integrative than the case study. For example, perhaps multiple species of gecko would be tested to find those that adhere best in the desired environmental conditions, and synthetic tapes that vary parameters like softness and chemistry independently would be produced, all circling back to the main question: how do geckos stick when it is hot and humid? By forming this relationship early, the entire team benefits from active participation in both the Scientific Method and the

Gecko foot

Photo: Hugo Wetterberg, 2007 | Flickr cc

"Biology to Design" path. Regardless of how the details of this interaction occur, the point is that collaboration between these stake-holders can advance all of their interests.

The Hook

So, how do you hook a biologist into joining a biomimicry team? Certainly there are many amazing biologists who are already "hooked", and contribute greatly to the field of biomimicry, however there are many who either do not know about the field or who are not interested. As many biomimicry practitioners find out quickly, everyone, biologist or otherwise, needs a "hook" or as I like to call it, a "currency". When the "what's in it for me?" question rears up, it is because everyone at the table needs to have some form of currency at play to make the time and effort worth their while. For industry and business professionals, this could be a leg up on their competition or a more refined cost-saving process, for example. For a biologist, the gecko case study shows that having access to a biomimetic model, or perhaps even further, being actively involved in the design process, could help answer and generate questions which keep the cyclic Scientific Method moving in new and exciting areas.

Presumably everyone at the biomimicry design table has a couple common limitations. Often money and time are the biggest. For a biologist in academia this is no different. Money often comes from grants, which are becoming more and more difficult to get. Time is split between teaching, department and university service, mentoring, research and of course, grant writing. Like everyone else, coming to the design table needs to have a pay-off. In this article I have highlighted one potential currency that is relatable to a biologist - the ability to test and formulate new questions about the biological system. Using this, the "Biology to Design" process is no longer a one-way street for biologists, but can be a dynamic, interactive collaboration where questions and challenges can be posed and tested,

Tokay Gecko

Photo: ReptilesPlus, 2012 | Flickr cc

designs refined and tested again, and ultimately those same two outcomes, knowledge and a biomimetic solution, can be achieved. This requires give and take, where all parties need to be willing to sacrifice their own time and goals a bit for the good of the team. Once "hooked" it is also possible biologists will continue to collaborate on future projects, perhaps even working on a human problem, directing appropriate lines of inquiry and providing biological knowledge (the "Challenge to Biology" pathway). This hinges on how valuable support from a biologist is viewed at the design table, and how much currency a biologist can keep in the game. Certainly there is much more to this idea of mine, but as most biomimicry practitioners can attest, often the most monumental first step in biomimicry is to simply get everyone sitting down at the table. ×

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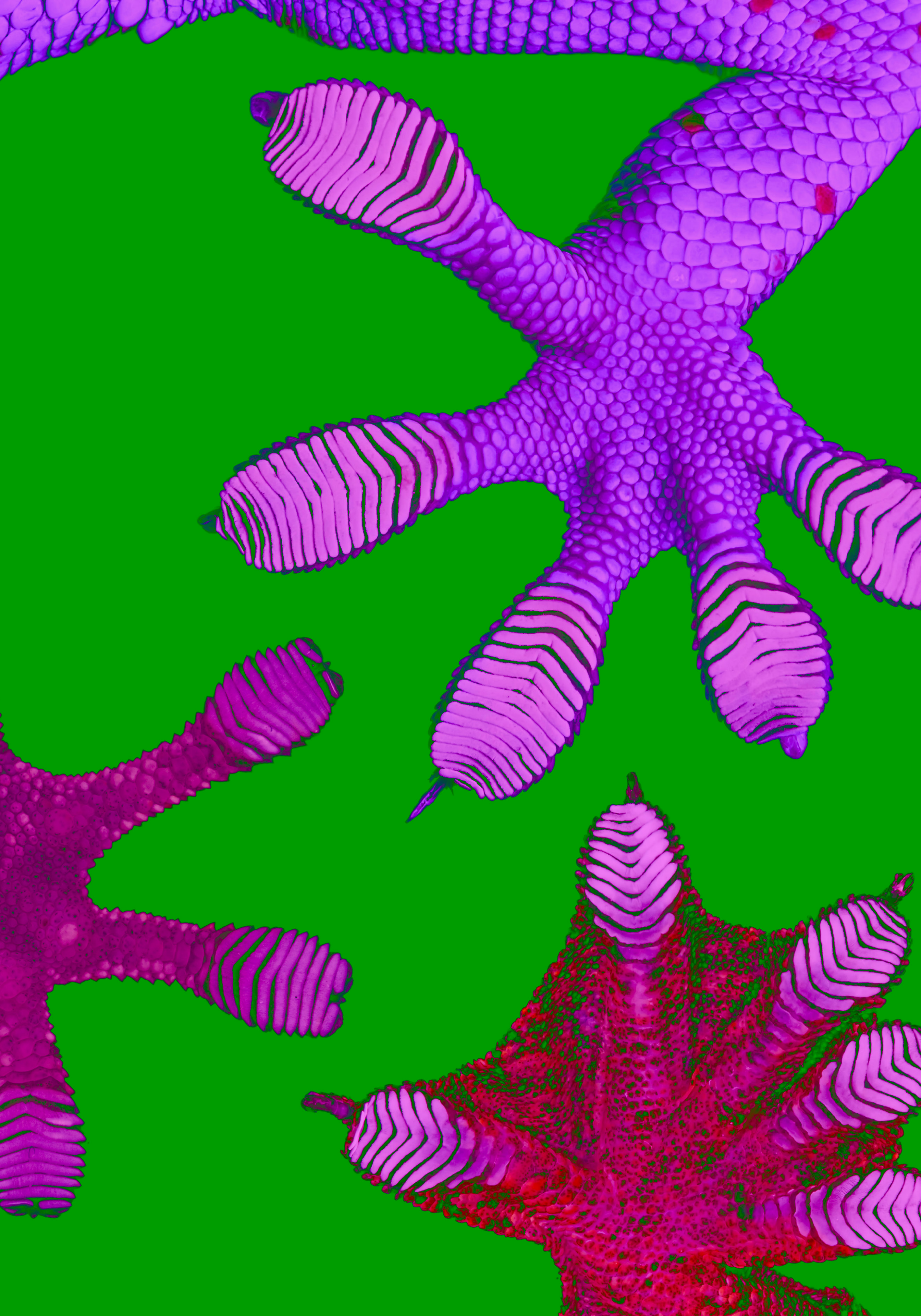

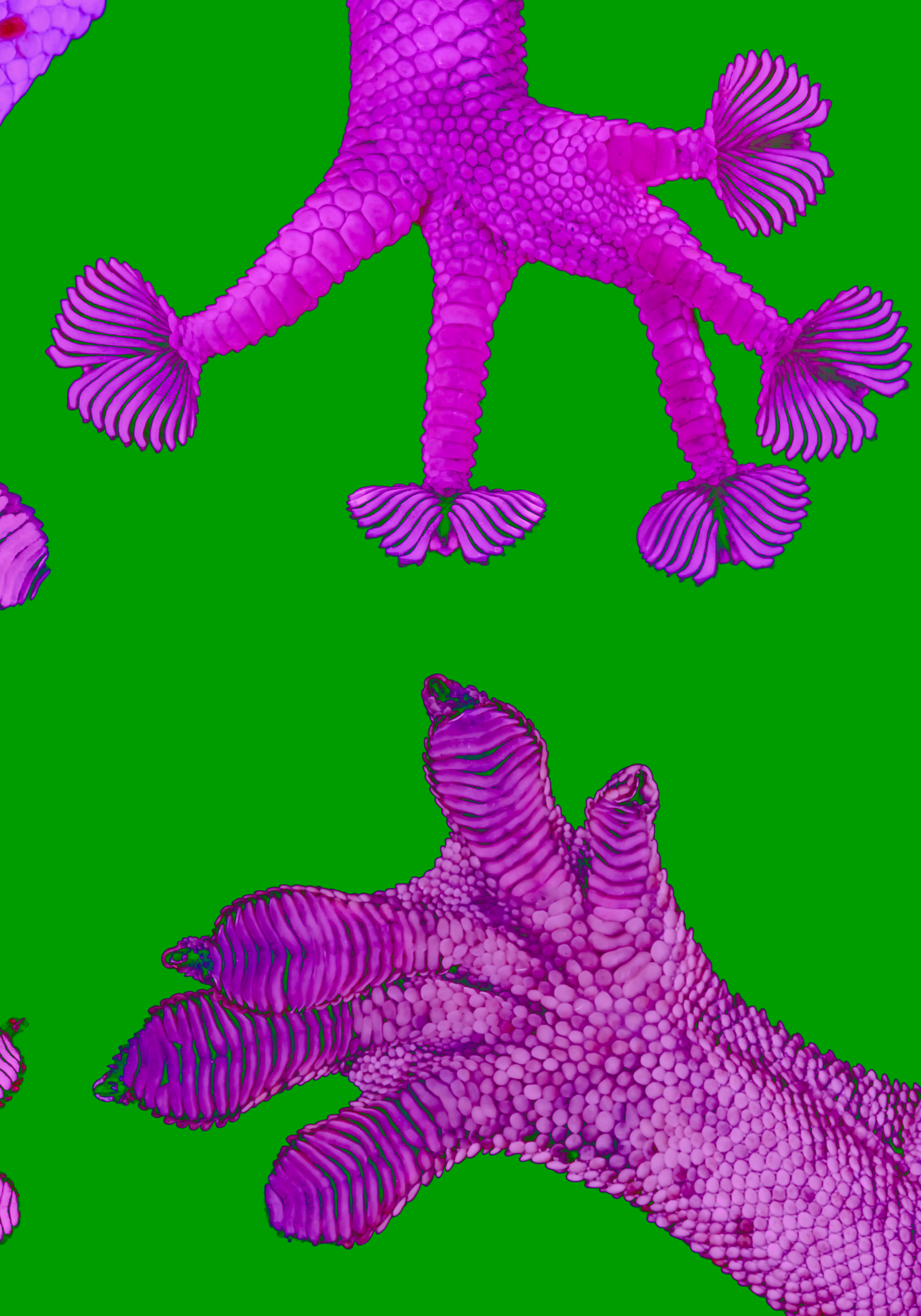

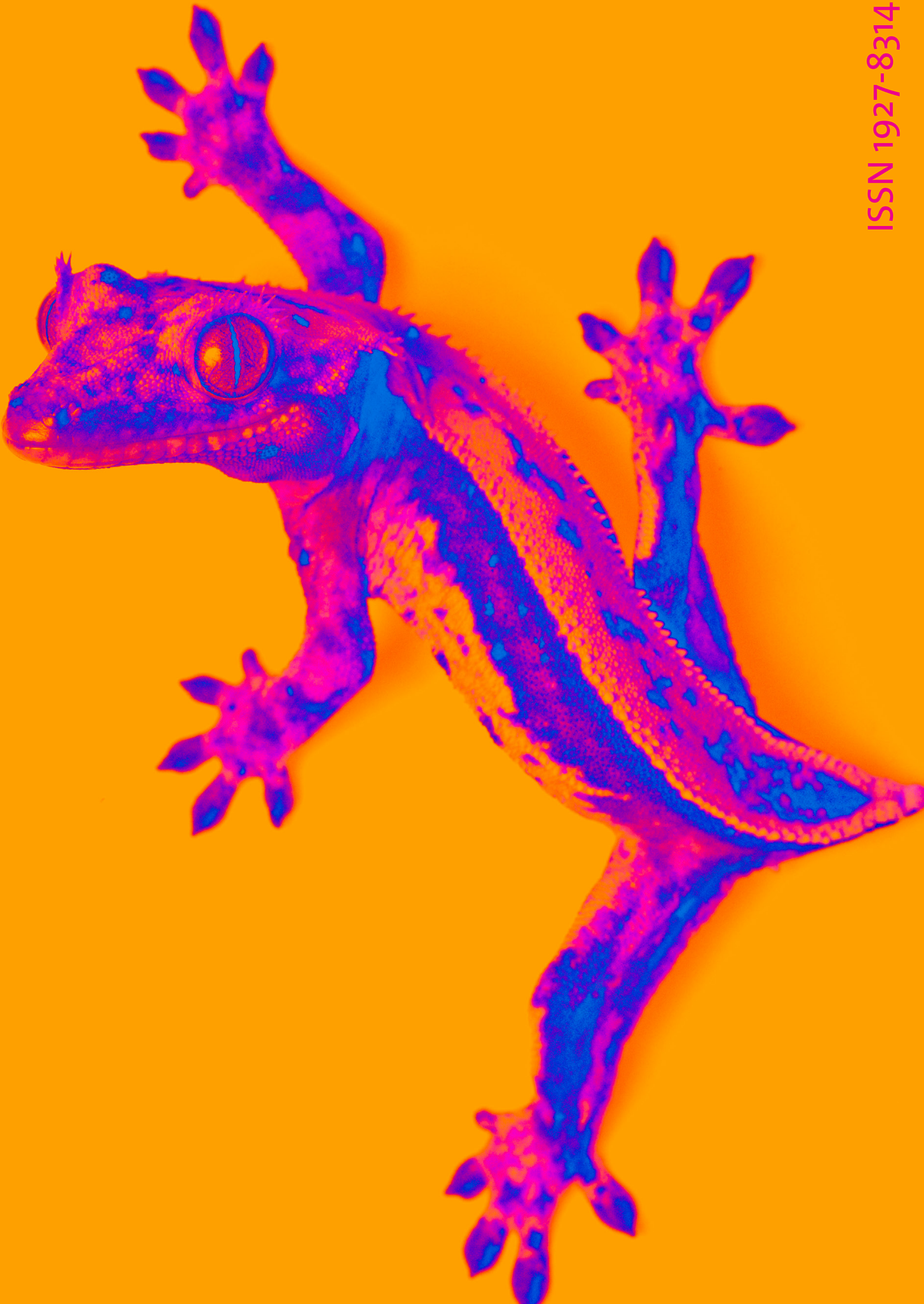

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