
zq39
VOL 3 | 2025

About Zygote Quarterly

Contact
info@zqjournal.org

Cover art
Cover: KateMccGwire | ***Flux*** (detail), 2017 | Mixed media with magpie feathers | 107 x 123 x 16 cm | pp. 2-3: KateMccGwire | ***Blister*** (detail), 2025 | Mixed media with pheasant feathers in walnut frame | 31.4 x 31.4 cm | pp. 122-123: KateMccGwire | ***Maelstrom*** (Neap), 2024 | Mixed media with rooster feathers in walnut frame | 62.4 x 62.4 cm | Photos: JP Bland.

Design
Marjan Eggermont

Web
Colin McDonald
Norbert Hoeller

ISSN
1927-8314

Kate McCGwire
Taint (detail), 2022 | Mixed media with pigeon feathers and lead | 66 x 66 x 9 cm.
Photo: JP Bland

Editorial

Many themes run through this issue, but one that emerges strongly is "equilibrium". It figures prominently in our feature article, *Forward Motion*, chronicling the extraordinary career of UC Berkeley integrative biologist Robert Full. In his research and education work studying the mechanics of legged animal motion he has aimed at both a metaphorical and literal balance.

Our *Portfolio* artist Kate MccGwire is also fascinated with imbuing her work with the equilibrium formed by opposites. The results are sensuous constructions of feathers and bones juxtaposed to unlikely settings.

Chemoreception experts Arindam Phani and Seonghwan (Sam) Kim, in an interview with Shoshanah Jacobs, discuss the challenges facing bio-inspired designers, including the transformation of current engineering systems that "seek static equilibrium" to a dynamic biological model that thrives on feedback loops.

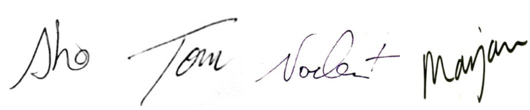
Marti Verdagner Mallorqui, in *Cutting Without Cutting: Lessons from the Sawfly* describes his research journey to understand the functional principles underlying this insect's shearing precision. He explains the critical perspectives that both surgeons and the animal itself brought to the application insights gained from a complex, but passive, mechanism; one reliant on the right balance of morphology, material composition and function.

Heidi Fischer, in *Plant It and They Will Come* reports on the outsized impact that an Arizonan couple has chronicled in their native plant garden, creating a balance of conditions for a rich and diverse array of animal life.

In *Building with Biology*, Emilie Snell-Rood advocates for joining under this umbrella heading the current, disparate bio-inspired problem-solving approaches. She further suggests that networks, centers, seminars and workshops be employed to act as bridges to unite the different fields.

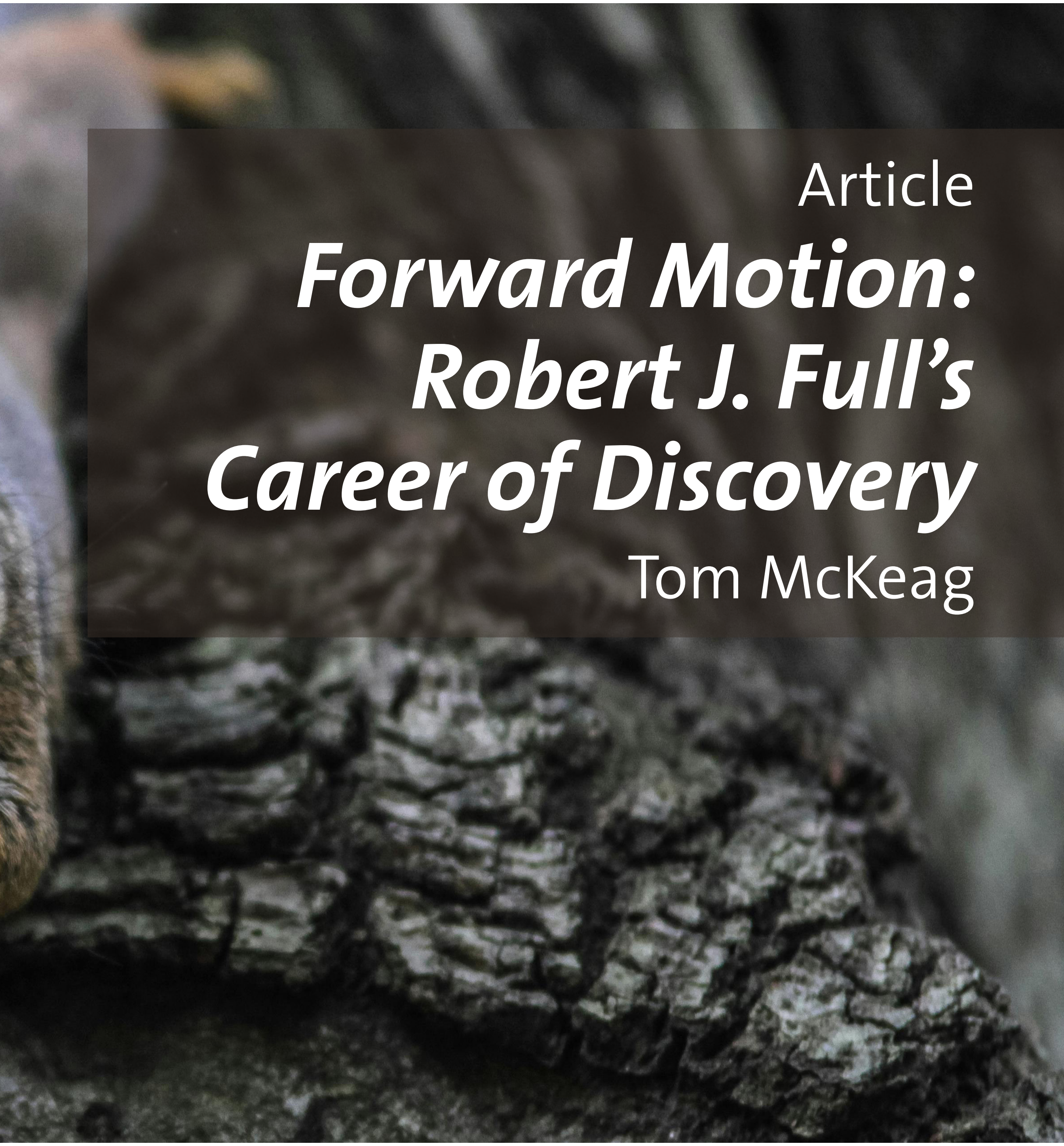
Brook Kennedy and Anna Bieri share Kennedy's insights about successful patent authorship in *Turning Bio-inspired Ideas into Patents*. In this article they share thoughts about misconceptions and the convergence of factors that must happen for success.

Finally, we review Michael Pawlyn's latest edition of *Biomimicry in Architecture*. This book continues to rely heavily on a systems approach as its foundation and, according to our reviewers, strikes an admirable balance between context and examples, scientific explanation and readability. Many thanks go to our readers, Hope Ameh, Thomas Boyster, Denise DeLuca, Cornel Schoombee, Janet Stewart and Emma Winter. Happy reading! ×



Contents

Squirrel on Tree Bark
Photo: Francesco Ungaro | Pexels cc



Article

Forward Motion: Robert J. Full's Career of Discovery

Tom McKeag

Forward Motion: Robert J. Full's Career of Discovery

Tom McKeag

Walking on the Ceiling

In a small suite of subterranean rooms in the monolithic Valley Life Sciences Building at UC Berkeley a knot of students is watching earnestly as a wizard of biomechanics explains just how ornery the Tokay Gecko can be. Dr. Robert J. Full is gently holding the lizard in his heavily-gloved hands; his eyes light up in merriment as he highlights the sequence of research that had led to his lab's discovery of how that gecko could stick to the ceiling overhead. It is the year 2000, and his research team, led by graduate student Kellar Autumn (see *ZQ* issue 17, 2016) had just published their findings in the journal Nature. Geckos employ a dry adhesive, taking advantage of the molecular attraction of van der Waals forces by having evolved a hierarchical and cross-scale arrangement of minute and microscopic hairs or setae on their footpads. The geckos can quickly "peel" and unstick these pads at will, allowing them to scamper about upside-down.

Robert J. Full

Years of interdisciplinary collaboration would follow in the continuing quest to refine the research and find practical applications for this phenomenon, hailed at the time as "the next VELCRO®". The Full biology lab collaborated most notably with engineers at Berkeley, Stanford and the University of Pennsylvania to design the world's first climbing robots, via the RiSE (Robots in the Scansorial Environment) project, from 2003-2008. This led to the development of the climbing robots Stickybot in 2007, and the Dynaclimber in 2012. The capabilities of synthetic fibrillar adhesion were demonstrated dramatically by a volunteer climbing up the glass wall of a building using a hand-held ascender called Gecko Gloves at Stanford in 2014.

These were exciting times indeed for the discoverers of this disruptive technology, and Dr. Autumn remembers them fondly:

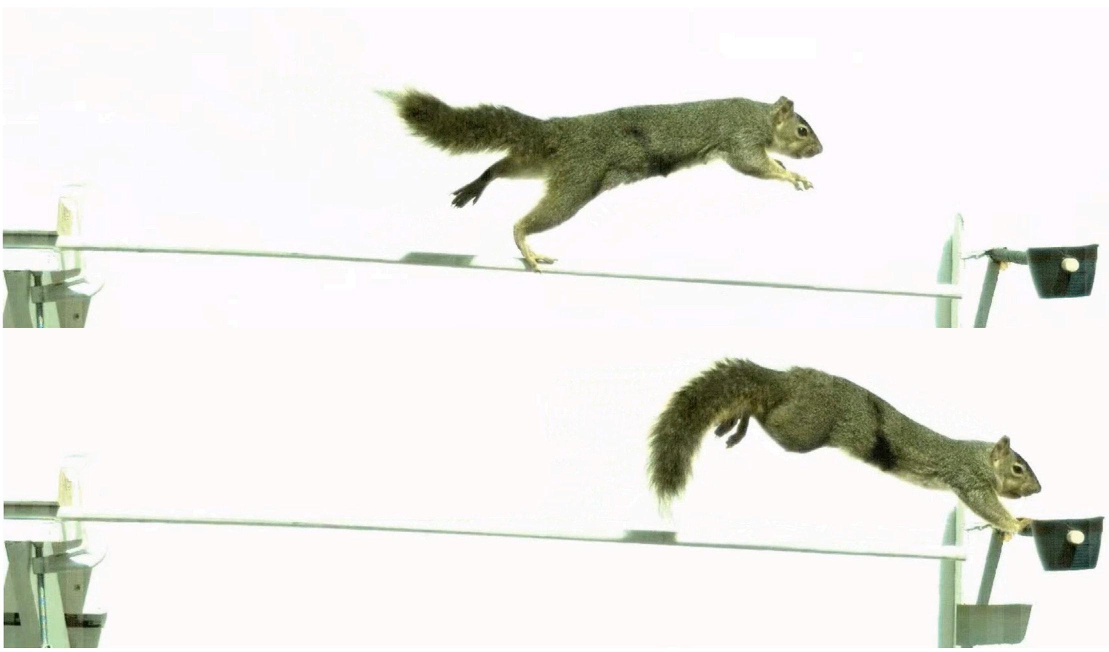
> *Bob Full has been my advisor, mentor, colleague, and friend for more than three decades. Working with him was the greatest privilege of my career, and the greatest*

Off the Wall #2 (Crested gecko)
Photo courtesy of Kellar Autumn, 2016

fun as well. Together we uncovered how geckos adhere and helped create a new subfield at the interface of biology, physics, and materials science. We carried those discoveries into bioinspired robotics, building climbing machines that were science fiction only a few years earlier. Bob sets a standard of excitement, curiosity, clarity, and generosity that I still try to live up to.

Several laboratories have pursued the application of this disruptive technology. A team at the University of Massachusetts Amherst, for example, developed Geckskin in 2012, with the insight that a stiff backing to the compliant pad was needed to recreate the effect. They made synthetic stiff "tendons" to reinforce the backing skin, thereby allowing the pad to drape over a surface while maintaining stiffness and rotational freedom. This product, which does not have the nano or micrometer features of the animal's footpads, is currently being employed commercially as a weather seal.

A synthetic tape, having micro-wedges that more directly mimic the gecko's setae, has also been developed at Stanford and birthed a startup, geCKo Materials. It was founded by Dr. Capella Kerst, who had developed the tape as part of her PhD thesis. The



Squirrel jungle gym.
Courtesy of Robert J. Full

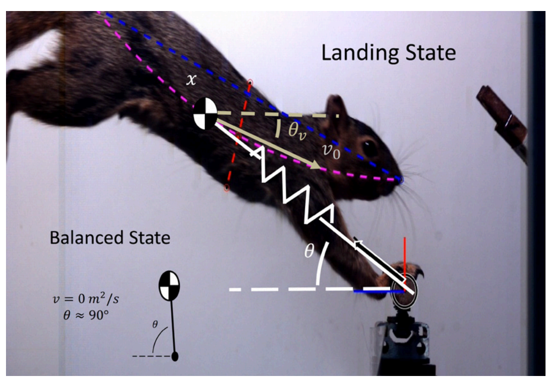
company is in funding rounds to acquire the capital to scale up production. The clearest application advantages of this dry adhesive appear to be in the pick-and-place sections of manufacturing lines; the company claims that their tape can be reused 120,000 times without fatigue, and, unlike suction methods, spreads its force evenly over an object's surface, rather than concentrating it: very handy, say, if you are picking up eggs.

From geckos to cockroaches to squirrels, Full and his teams have been pioneering our way to understanding the foundational forces that allow animals to amaze us with their feats of locomotion and survival. Equally important, Full has pioneered our way of training young researchers in the academic rigor and collaboration needed to pursue the field of bio-inspired design. In 2021, the lab turned its research focus to a common, but extraordinary, mammal, the squirrel.

Sticking the Landing

When you walk onto the UC Berkeley campus from the west one of the first things you notice is the strong smell of eucalyptus. Around you, piled on the ground are the shreds of bark and long, sickle-shaped leaves of the Blue Gum (*Eucalyptus globulus*); when you gaze up along the massive trunks in the grove around you, they seem to go on forever, lost in the towering foliage. Some of them are 180 feet tall, taller than the second growth coast redwoods on campus and, indeed, they are the tallest non-native trees in America. They create their own world; of light, smell, space and life.

One of the creatures that has made a comfortable home here is the fox squirrel (*Sciurus niger*), a common and cute beggar of student lunches, but also a small-but-mighty gymnast. The Full lab, with its long track record in biomechanical discoveries, realized that it had a champion biological mentor right in its own backyard. Full, and then-graduate student Nathan Hunt, now an associate professor at the University of Nebraska, set out to devise some innovative field experiments with these free ranging but people-tolerant squirrels.



Lee, Wang, Kuang, Wang, Yim, Hunt, Fearing, Stuart, and Full.
Free-ranging squirrels perform stable, above-branch landings by balancing using leg force and nonprehensile foot torque.
Courtesy of Robert J. Full

Forward Motion: Robert J. Full's Career of Discovery
Tom McKeag

They wanted to know how the squirrel accomplishes its acrobatic feats; what decisions and adjustments are made when a squirrel makes those seemingly death-defying leaps from branch to branch. To do this, they set up right in the Eucalyptus grove, constructing a simple jungle gym with photo-friendly backdrop: an artificial branch was positioned a short distance away from a stationary landing arm with a bait cup. Squirrels were enticed with peanuts to climb the branch and leap for their reward. Branches of different compliance or flexibility were installed for different rounds of high-speed filming and analysis.

They found that learning (leap correction) occurs in just a few jumps, that the squirrels will adjust their body orientation midair, and that they have a distinct repertoire of maneuvers to compensate for "bad" landings. Never did they see a squirrel fall from the target perch although the animals missed "sticking" the landing often. In those instances of either overshooting or undershooting the mark, the squirrels would employ their strong claws and a swinging maneuver to hoist their trunk (and center of gravity) back up onto the bar. Hunt observed that the squirrels had to make a tradeoff between the branch flexibility and

Fox squirrel (*Sciurus niger*)
Photo: Aaron Jacobs 2005 | Wikimedia Commons

the length of the gap, with the bendiness of the branch being much more determinant to the animal's choice. In another surprise, squirrels even employed parkour moves to bounce off the back wall of the photo booth to reach a distant target.

The team recorded that their subject squirrel, when confronted with an unknown launch platform and distance, would combine learned behavior with its innate abilities and its repertoire of landing techniques. The squirrel would gauge how far out on a branch to go in order to get as close as possible to its target without losing the branch stiffness needed to launch. At the other end of the jump the animal had several swinging behaviors to recover from under and over-shooting the mark. As the researchers introduced more compliant "branches" to launch from, the squirrels would adjust their behavior over the course of five runs. While no squirrels fell, they consistently increased their launch velocity and employed these strenuous recovery behaviors, sometimes hanging by one foot below the target before swinging back up to the bar.

It appears that this observed performance could be another example of Nature "designing to the adequate", rather than to some idealized perfection. With learned behavior for decision-making, reactive stabilization maneuvers and a bag of recovery tricks, the rodents do not have to "stick" the landing every time.

The Berkeley biomimetics research on squirrels was trans-disciplinary, with Professor of Psychology Lucia Jacobs, an expert in animal psychology, participating in the field biology experiments. Later, Hunt and Full would join forces with long-time collaborator Ron Fearing of the UC Berkeley Electrical Engineering and Computer Science Department (EECS) and his students in applying lessons learned from biology to the field of robotics. The researchers aimed to learn if they could apply the launching

Salto-1P
Photo: Justin Yim

Forward Motion: Robert J. Full's Career of Discovery
Tom McKeag

and landing expertise of the squirrels to the Salto-1P robot, a monopedal, hopping mechanical device with claws, hinges and onboard micro-computer and actuators. Could Salto acquire some useful modifications that would mimic the squirrel's recovery techniques?

The answer was "yes". Writes Dr. Fearing:

> *The "Salto" jumping robot provided an interesting test case, as it could stably balance after landing on a branch with negligible gripping torque, using only body forces. These body forces are also available to the squirrel, giving it a wider range of stable landings.*

In a recent 2025 article in *Science Robotics* this interdisciplinary team described their refinement of the robot to include a balance wheel and greater leg length control for improved balance recovery on landings. They used the same leg actuator that initiates the leap to act in the reverse on landing, constricting the force control area and working with the greater radial force control gained by the balance wheel. The radial force control is akin to the way a tightrope walker might wheel his arms around to maintain balance. This strategy increased the range of initial angular momentum that can be balanced by the robot by 230%.

Dr. Fearing explained further the wider implications of this interdisciplinary research and how it had exemplified Full's pioneering research paradigm:

> *Bob has pioneered a research paradigm which is the symbiosis of "Science for Robotics" and "Robotics for Science". "Science for Robotics" uses discoveries to find bioinspired design principles. "Robotics for Science" uses advances in robot technologies, in particular manufacturing techniques, such that robots can be constructed specifically to test biological hypotheses. Bob's abstraction approach (as exemplified in "Templates and Anchors" with Daniel Koditschek) provided the simplified spring-based locomotion model that directly led to whole families of highly dynamic and capable legged robots including RHeX (2001), Sprawlita (2002), DASH (2009), and VelociRoACH (2013).*

Squirrel (*Sciurus niger*) parkour
Courtesy of Robert J. Full

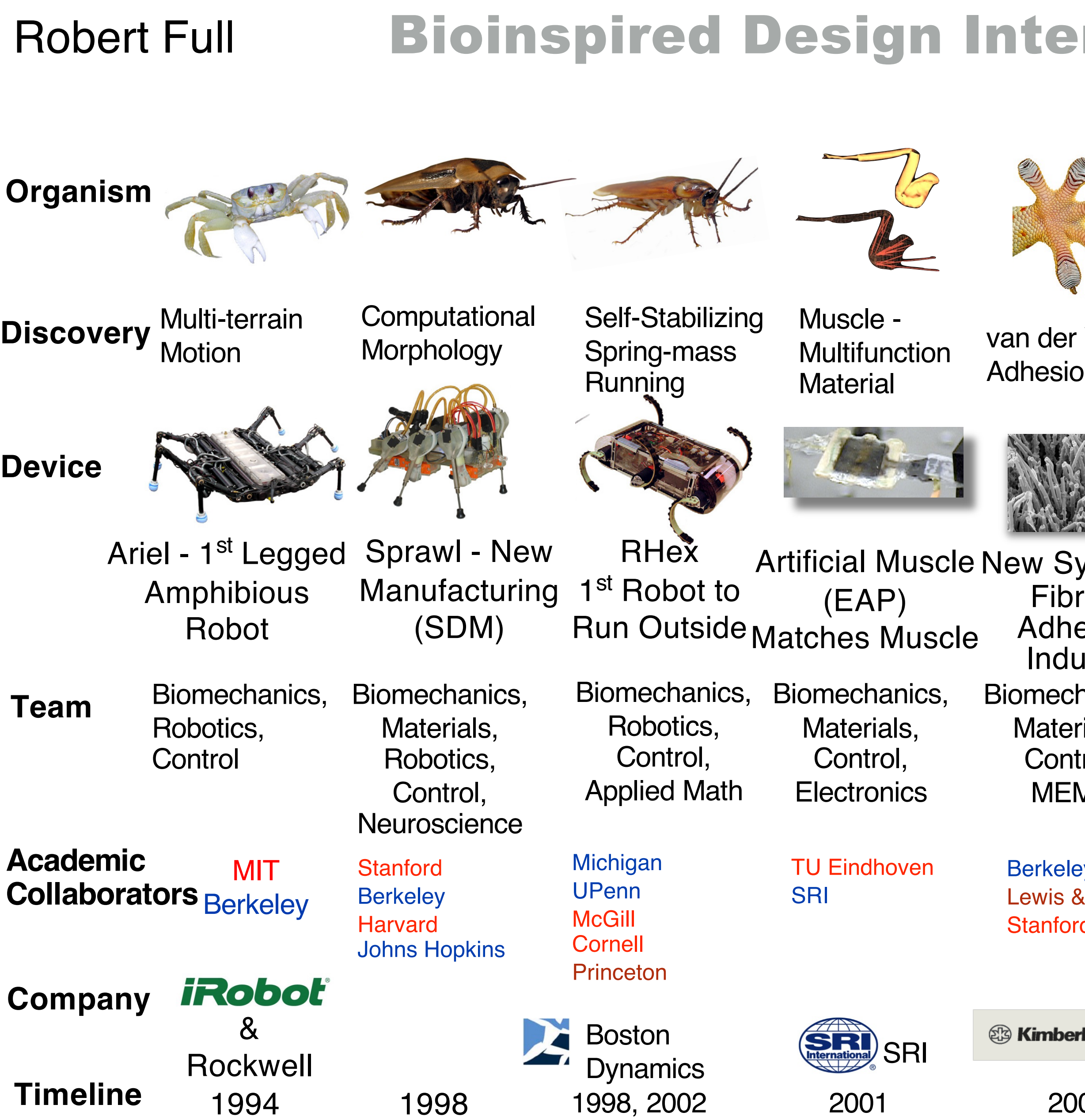
At the University of Pennsylvania Daniel E. Koditschek, a longtime collaborator, and his group are carrying applications of the research further. Dr. Koditschek is the interim director of Penn Engineering's General Robotics, Automation, Sensing and Perception, or GRASP, Lab, and is collaborating with a range of experts from the University of Illinois, Urbana-Champaign, Johns Hopkins, and UC Berkeley. The main thrust of the research is to imbue robots with the kind of "embodied intelligence" that the squirrels have; using limbs as sensors as well as actuators and learning new forms of locomotion based on their interactions with the environment.

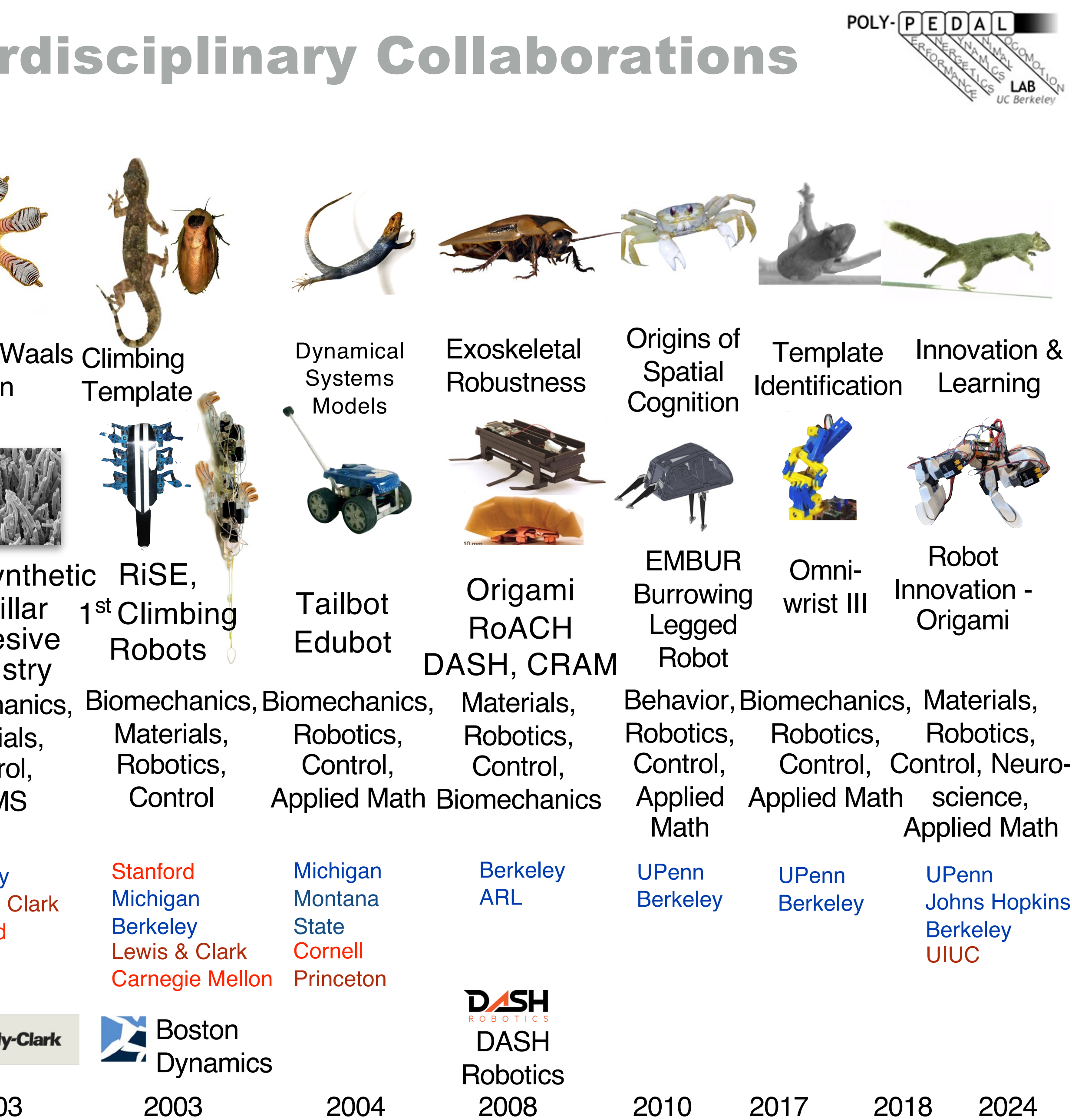
The research is using the squirrel as a biological model and researchers will aspire to replicate the parkour moves observed in the Eucalyptus glade at Berkeley. The parkour moves represent an entire array of complex animal behavior. Whether running down a tree or running on level ground or leaping across space the squirrel exhibits a plethora of tactics: changing the distribution of their body mass, adjusting grips, tuning a leg muscle to the springiness of a branch, gauging the trajectory of a jump. These sensations, responses and decisions happen through different timescales and the team aims to understand how and when this information and energy exchange between the environment and the animal's integrated body-brain intelligence happens. Further, they hope to apply that understanding to the construction of a new generation of robots.

This research has required experts in animal cognition and biomechanics as well as neurophysiology and neuromotor control, asking how the brain and the nervous system interact with the muscles and the skeleton when adapting to the environment. The team also includes mathematicians, engineers and experts in programmable materials to design novel, kirigami-based, shape-shifting structures that can be incorporated into the robotic squirrel's limbs. The results have been the prototype Dynamic Origami Quadruped (DOQ), developed by the Sung lab in the GRASP group. The untethered robot is able to walk, bound and pronk, that all-fours vertical rise that antelopes do when startled. The light weight of the origami tubes has meant that more mass can be devoted to actuators; about 50%.

Pursuing the Principles

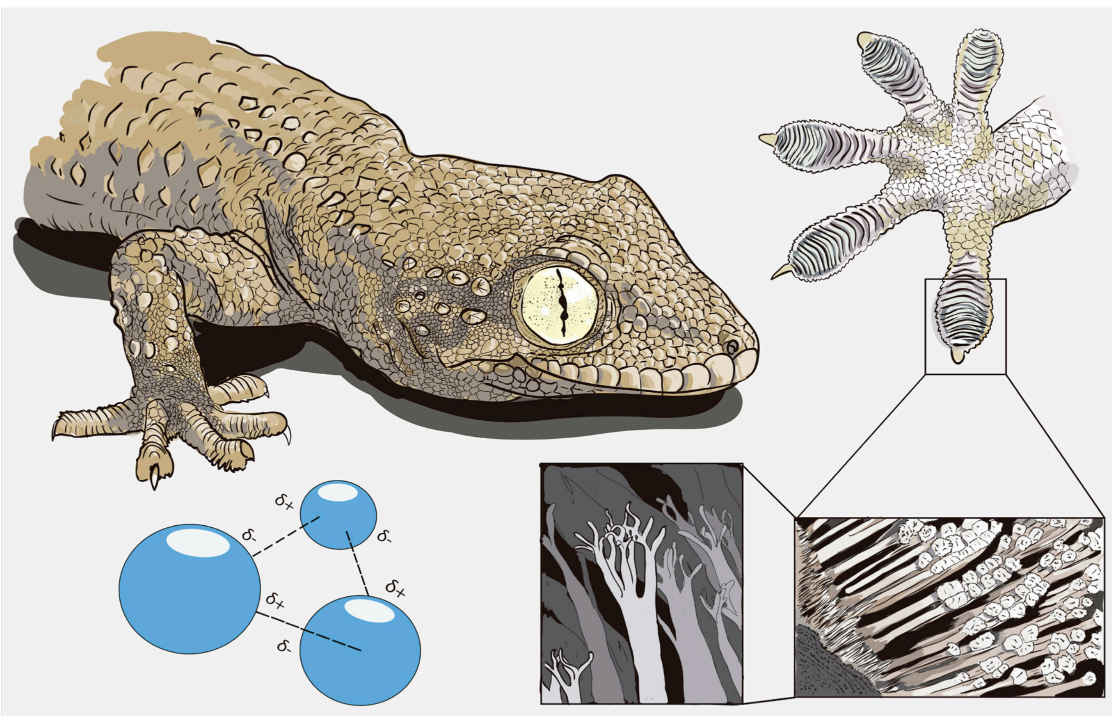
There is a familiar Chinese saying that "the Cantonese will eat anything with legs but the table", and perhaps the same could be said about the research investigations


Robert Full
Bioinspired Design Inte
Organism
Discovery
Multi-terrain Motion
Computational Morphology
Self-Stabilizing Spring-mass Running
Muscle - Multifunction Material
van der
Adhesio
Device
Ariel - 1st Legged Amphibious Robot
Sprawl - New Manufacturing (SDM)
RHex 1st Robot to Run Outside
Artificial Muscle (EAP) Matches Muscle
New Sy
Fibr
Adhe
Indu
Team
Biomechanics, Robotics, Control
Biomechanics, Materials, Robotics, Control, Neuroscience
Biomechanics, Robotics, Control, Applied Math
Biomechanics, Materials, Control, Electronics
Biomech
Materi
Contr
MEM
Academic Collaborators
MIT
Berkeley
Stanford
Berkeley
Harvard
Johns Hopkins
Michigan
UPenn
McGill
Cornell
Princeton
TU Eindhoven
SRI
Berkeley
Lewis &
Stanford
Company
iRobot & Rockwell
Boston Dynamics
SRI International
SRI
Kimberl
Timeline
1994
1998
1998, 2002
2001
200


rdisciplinary Collaborations
POLY-PEDAL LAB
ENERGETICS PERFORMANCE DYNAMICS NEURO-MECHANICS LOCOMOTION
UC Berkeley
Waals
n
Climbing Template
Dynamical Systems Models
Exoskeletal Robustness
Origins of Spatial Cognition
Template Identification
Innovation & Learning
ynthetic
illar
esive
stry
RiSE,
1st Climbing Robots
Tailbot Edubot
Origami RoACH DASH, CRAM
EMBUR Burrowing Legged Robot
Omni-wrist III
Robot Innovation - Origami
anics,
ials,
rol,
MS
Biomechanics, Materials, Robotics, Control
Biomechanics, Robotics, Control, Applied Math
Materials, Robotics, Control, Biomechanics
Behavior, Robotics, Control, Applied Math
Biomechanics, Robotics, Control, Applied Math
Materials, Robotics, Control, Neuro-science, Applied Math
y
Clark
d
Stanford
Michigan
Berkeley
Lewis & Clark
Carnegie Mellon
Michigan
Montana State
Cornell
Princeton
Berkeley
ARL
UPenn
Berkeley
UPenn
Berkeley
UPenn
Johns Hopkins
Berkeley
UIUC
y-Clark
Boston Dynamics
DASH ROBOTICS
DASH Robotics
03
2003
2004
2008
2010
2017
2018
2024

of Robert Full's PolyPEDAL lab at Berkeley. Within the name is an acronym that tells the focus of the lab, manifested by 38 years of effort: the *Performance, Energetics and Dynamics of Animal Locomotion*. In that time, Full and his students and colleagues have studied cockroaches, ants, grasshoppers, beetles, centipedes, spiders, salamanders, toads, stomatopods, crabs, octopus, geckos, lizards, and squirrels.

More important are the biomechanical insights that have been formed. In addition to the disruptive technological discovery of gecko adhesion, Full has explained the natural motion of diverse legged runners using simple models like pogo sticks and pendulums. He has revealed that animals make use of mechanically tuned or "smart" bodies that result in passive dynamic, self-stabilization and distributed mechanical feedback, allowing for simple locomotion control. His investigations have also illuminated the role that feet and tails play in enhancing stability and maneuverability through what is known as inertial assisted control. Inertial assisted control is



Gecko's secret power
Photo: Matteo Gabaglio, 2015 | Wikimedia Commons

an important navigational concept in any autonomous vehicle, making use of internal sensors to gauge motion changes in order to locate the object in space by dead reckoning. In engineering models this can be achieved using accelerometers, gyroscopes and magnetometers.

In the field of comparative physiology Full has demonstrated that the energetic cost of locomotion is dependent on body mass, but not how many legs an animal has, or its morphology or skeletal type. He also was a leader in the effort to show how intermittent locomotion affects endurance in legged runners.

The lab's work has been responsible for the crab inspired Ariel (iRobot) and digging EMBUR, cockroach inspired Boadicea, Sprawl, RHex (Boston Dynamics), DASH, RoACH, gecko inspired RiSE, Stickybot, Dynaclimber, lizard inspired Tailbot, and squirrel inspired Dynamic Origami Quadruped (DOQ).

Long-time collaborator Dr. Mimi Koehl of the Integrative Biology Department at UC Berkeley notes that a basic characteristic of Full's work is the search to discover the underlying principles for how organisms perform biomechanical functions. She recalls how his study of cockroach running revealed basic principles about the underlying physical mechanisms, which inform our understanding of the stability, robustness, control, and energetic costs of running that could be applied to any legged animal.

She also notes his advocacy of cross-disciplinary collaboration:

> *Bob is a master at working between disciplines. His own research is at the interface between biology and engineering, both using engineering techniques to figure out how organisms work and using principles learned from organisms to inspire engineering designs (ranging from running robots to adhesives informed by gecko toes). His lab was filled with students and postdocs from physics and engineering as well as from biology.*
>
> *In my research experience with him, we coupled my expertise in biological fluid dynamics with his expertise in the mechanics and physiology of legged locomotion to figure out things like aerodynamic drag is responsible for a significant proportion of the metabolic cost of running by insects, or (with students from both of our labs) how crabs run in air vs. in water.*

A key working principle of this collaboration is what Full calls "mutualistic teaming". In this process individual team members pursue components of a challenge with the skills and processes of their own disciplines. The resultant discoveries and innovations

Forward Motion: Robert J. Full's Career of Discovery
Tom McKeag

are shared with the entire team, both enriching and advancing the work of the other disciplines, but also rewarding the researchers within their own career paths. What emerges are collective discoveries that would not be possible from any single discipline or from a team that subjugates the disciplines to a single investigative model.

Full, with his engineering colleague Dr. Koditschek, has also influenced greatly how the scientific community approaches complex motion systems. Their 1999 paper in the *Journal of Experimental Biology*, "Templates and anchors: neuromechanical hypotheses of legged motion on land" has been cited 1590 times. The paper advocates for an approach that uses the interplay of simple mechanistic models (templates) with more representative and detailed models (anchors) that can serve as a context in which to test a hypothesis.

Enriching Education

Dr. Full believes that research and education should be thoroughly mixed, as they each enhance the other and produce a sum greater than its parts. Further, he believes strongly in the sharing of results, and sums his philosophy with the phrase *Synthesis, Synergy and Sharing*. He has, therefore, leveraged his graduate student

Berkeley Biodesign
Composite image: EECS, University of California, Berkeley

research successes and CiBER (Center for Bioinspiration in Education and Research at Berkeley) and PolyPEDAL lab models into an expansion of his educational impact. Over his career, this has been manifested through teaching classes to over 4400 undergraduate students, and 700 graduate students and mentoring the research of over 200 undergraduates.

Writes Dr. Koehl:

> *Bob and I taught together for many years in courses ranging from undergraduate lecture classes for hundreds of students to graduate lab classes and graduate seminars with only 20 to 30 students. Bob is a clear, dynamic, and very effective lecturer, and has been an enthusiastic and inspirational mentor for his undergraduate research students, graduate students, and postdocs. He is passionate about teaching, especially discovery-based learning, and we have studied and published about the effectiveness of such approaches.*
>
> *In teaching our students about interdisciplinary research, we stressed that you need to have deep knowledge and experience in your own discipline, but that you also need to learn what the tools are in another field with which you want to interface, the meanings of the jargon they use, and especially the big questions in that field that drive those researchers. A productive interdisciplinary collaboration has questions that are exciting to all the participants.*

Through the *Eyes Toward Tomorrow* program Full and his colleagues have sought to create a wider community of learning, practice, and social exchange. The program combines the excitement of Bioinspired Design (offered through the CiBER and PolyPEDAL labs) with the relatively new Maker Movement (supported at the on-campus Jacobs Institute for Design Innovation). At its foundation is a large undergraduate course in bio-inspired design run by Full and his graduate students, with practical lab experience for smaller teams within the course, and spin-off opportunities for participation in so-called DeCal (student led) courses, and membership in a campus-wide club, the Berkeley Biodesign Community. The emphasis is on the interdisciplinary, student initiative and collaboration, and practical project applications.

The structure and principles of the main course are worth noting for all BID practitioners, particularly its approach to designing. The course is divided into two sections, process and case studies, and students move from individual skill-building work to team projects. First, the course coaches students to learn the process of scientific discovery through the lens of bioinspired design. From this basic science literacy in research, students are guided through the elements of a design process with lectures on constraints, scaling, complexity and selection. Key activities are the decomposing and extraction of principles from journal papers, and the use of an analogy checklist to aid them in the translation from an observed biological phenomenon to a designed application.

The tools developed for these activities are the *Discovery Decomposition and the Analogy Check*. The *Discovery Decomposition* is a flowchart that helps students map the basics of a scientific paper without having to understand all the technical details: what was known, done, measured, and discovered in order for them to understand a biological principle that they can use in design. The *Analogy Check* helps students compare similarities and differences of the subject organism and proposed design in the parameters of structure, size, operating environment, mechanism, specification, performance and constraints.

As participants move into the team phase of the course they are tasked to design several widely different objects: a seed dispersal device; a child's hand prosthetic; a dry adhesive tape; an insect-inspired origami robot, before selecting and designing something of their own choice. All of the guided designs are supported by actual experience from the Full lab, and case studies of a wide range of problem sets and applications are integrated into this phase.

The description of the biodesign lectures for the course is useful to understand the core principles of the UC Berkeley team and the substantive knowledge that they wish to impart. Here, in loose translation, are ten basic practices that the course instructors try to impart:

1. Define the process of BID: translation approaches can be characterized in two ways: biology to design (phenomenon to problem), or design to biology (problem to phenomenon). A hybrid of the two, where there is interplay between the two approaches often leads to exciting and novel solutions. The course focuses on biological discovery, the extraction of a fundamental principle, and the creation of an analogy to use this principle to solve a human problem.
2. Focus on direct experiments with treatments and controls. Balance discovery with theory.
3. Practice interdisciplinary collaboration; what, in the course, is labeled mutualistic teaming.

4. Know well the scientific process and communication. To impart this, the course offers the *Discovery Decomposition* tool to guide students' analysis of a scientific paper.
5. Review and choose a useful analogy: the course surveys a wide range of analogy models that the students can review and offers the simple *Analogy Check* tool to guide this review of models as well as project work.
6. Make peace with the uncertainty of the discovery process and the iterative nature of testing hypotheses derived from Nature as well as the tremendous potential for disruptive technological advancement.
7. Dispel the notion that Nature's creatures are optimally designed by evolution and should be copied or mimicked. The course characterizes Nature as a tinkerer, rather than an engineer, with the idea that outcomes are neither controlled nor predictable. Organisms are severely constrained by their development, evolutionary history, multifunctionality, and sexual selection. These *bioconstraints* should be top of mind in all analogies.
8. Distinguish between the scales and subsequent approaches of natural and human technologies. Scale matters and understanding *bioscaling* is vital since both natural and human technologies vary across 12 orders of magnitude of linear scale.
9. Conquer the challenge of extracting simple biological principles from incredibly complex organisms. Study the use and pitfalls of models; *templates* (mathematical models) and *anchors* (representative model that allows a testing of a hypothesis). Appreciate the importance of physical models, prototypes that illuminate things that theoretical models cannot.
10. Embrace diversity, which leads to discovery. In their *Bioselection*, the course instructors write: *"Students discover that they can select by exceptional performance, learn from convergent evolution, examine trends from evolutionary history, take advantage of model organisms, be guided by general relationships, and/or use extreme or unique solutions"*. The

Robert J. Full in the classroom

Forward Motion: Robert J. Full's Career of Discovery
Tom McKeag

> program mantra is *Diversity Enables Discovery*.

In the fall of 2025, Full brought these guided discovery techniques to the Sutardja Center for Entrepreneurship and Technology at Berkeley by creating a new course, the Bioinspired Innovation Challenge, a 16-week project-driven course that uses the investigation of nature's secrets to transform students' entrepreneurial vision and problem-solving methods.

Broadening the Field

Dr. Full has led in the fields of comparative biomechanics and bio-inspired design by his research discoveries, but also by his service to the disciplines themselves. He was one of the founders of the first Departments of Integrative Biology in the U.S., and, in 1990 led the forward-looking transition of the American Society of Zoologists to the Society of Integrative and Comparative Biology, the nation's leading professional society in organismal-centered biology. Professor Full was founder and elected Chair of the Comparative Biomechanics Division of the Society of Integrative and Comparative Biology, the first recognized international home for this field.

Full has also shaped the approach of several fields of allied endeavor by organizing symposia in Comparative Physiology & Robotics (1995), Biomechanics and Neural Control of Movement (1996), Motion Science (DARPA, Focus 2000), Intermittent Locomotion (2000; featured in Science), Stability & Maneuverability (2001; featured in Science), The Influence of Comparative Physiology on Engineering (2002), Biomechanics of Adhesion (2002; featured in Science), the Neuromechanics of Locomotion (2008; Mathematical Bioscience Institute), and Biohybrid Materials and Technologies for Today and Tomorrow (National Academies of Sciences Workshop, 2023).

Dr. Fearing writes:

> *Prof. Robert Full has changed the way roboticists think about legged locomotion, ...particularly at the small-scale, where highly dynamic interactions make sensory-based responses challenging. He*

Fox Squirrel (*Sciurus niger*)
Photo: Franco Folini, 2013 | Wikimedia Commons

has also taught us to think about bio-inspired designs in a way which captures the underlying principles of the system, and not necessarily the form. He has mentored a generation of scientists and engineers who are continuing to advance bioinspired robots, getting us closer to matching animal capabilities.

He was on the founding committee of the influential journal *Bioinspiration & Biomimetics* (2006) and served as editor-in-chief from 2013-2021. He still serves on the science advisory board of *Science Robotics*.

He has served on the board of numerous governmental agencies and foundations including NASA's Presidential Commission for a Mission to Mars, National Academies Board of Life Sciences, and National Science Foundation, and National Security and Defense Advisory Boards. In addition to these boards, Full contributed to the Presidential Advisory Board of the Research Corporation for Science Advancement and has presented his research at their annual meetings.

Full has also served on scientific advisory boards that included the National Centre of Excellence – Robotics (NCCR) supported by the Swiss National Science Foundation (2011-22), the Wyss Institute at Harvard University (2010-22), and Samsung's Advanced Institute of Technology in Seoul Korea (2004-07).

Of his contributions to the Wyss Institute at Harvard, its director, Dr. Donald Ingber, had this to write:

When I founded the Wyss Institute for Biologically Inspired Engineering at Harvard University in 2009 and we were seeking world-class innovative scientists for our Scientific Advisory Board (SAB), I thought of Bob immediately because one of our major focus areas was bioinspired robotics. Bob has been one of the most enthusiastic, passionate, and active members of our SAB for the past 16 years. His vision, creativity, and kindness are inspirational for our young people and our faculty as well. He is always thinking about how we can make our community stronger and more effective as well as more diverse. Although we have less of a focus on robotics currently, we still view Bob as a critical member of our SAB because his vision is so broad and he cares so deeply about supporting young people and their future in science.

Through research, education and outreach, Robert Full has always been in forward motion, and he has brought us, bio-inspired design, and the community of science with him. ×

Forward Motion: Robert J. Full's Career of Discovery
Tom McKeag

Notes

1. K Autumn, YA Liang, ST Hsieh, W Zesch, WP Chan, TW Kenny, R Fearing, RJ Full. Adhesive force of a single gecko foot-hair. *Nature 405* (6787), 681-685

2. K Autumn, M Sitti, YA Liang, AM Peattie, WR Hansen, S Sponberg, TW Kenny, R. Fearing. Evidence for van der Waals adhesion in gecko setae. *Proceedings of the National Academy of Sciences 99*(19), 12252-12256

3. Kim, Sangbae, et al. "Whole body adhesion: hierarchical, directional and distributed control of adhesive forces for a climbing robot." *Proceedings 2007 IEEE International Conference on Robotics and Automation*. IEEE, 2007.

4. Lynch GA, Clark JE, Lin PC, Koditschek DE. A bioinspired dynamical vertical climbing robot. *The International Journal of Robotics Research*. 2012 Jul;31(8):974-96.

5. Bartlett MD, Croll AB, King DR, Paret BM, Irschick DJ, Crosby AJ. Looking Beyond Fibrillar Features to Scale Gecko-Like Adhesion. *Advanced Materials*. 2012; 24(8):1078-1083: DOI: 10.1002/adma.201104191

6. Elliot W. Hawkes, Eric V. Eason, David L. Christensen, Mark R. Cutkosky. Human climbing with efficiently scaled gecko-inspired dry adhesives. *J R Soc Interface* 1 January 2015; 12(102): 20140675. https://doi.org/10.1098/rsif.2014.0675

7. King, D.R., Bartlett, M.D., Gilman, C.A., Irschick, D.J. and Crosby, A.J. (2014), Creating Gecko-Like Adhesives for "Real World" Surfaces. *Adv. Mater., 26*: 4345-4351. https://doi.org/10.1002/adma.201306259

8. https://www.geckomaterials.com/specifications

9. Kerst, C. F. (2020). *Gecko Inspired Adhesives: Permanent Practical Manufacturing, New Materials, and Applications*. Stanford University.

10. https://medium.com/penn-engineering/new-grasp-project-aims-to-leverage-embodied-intelligence-via-a-robotic-squirrel-87c0e4e7adf9

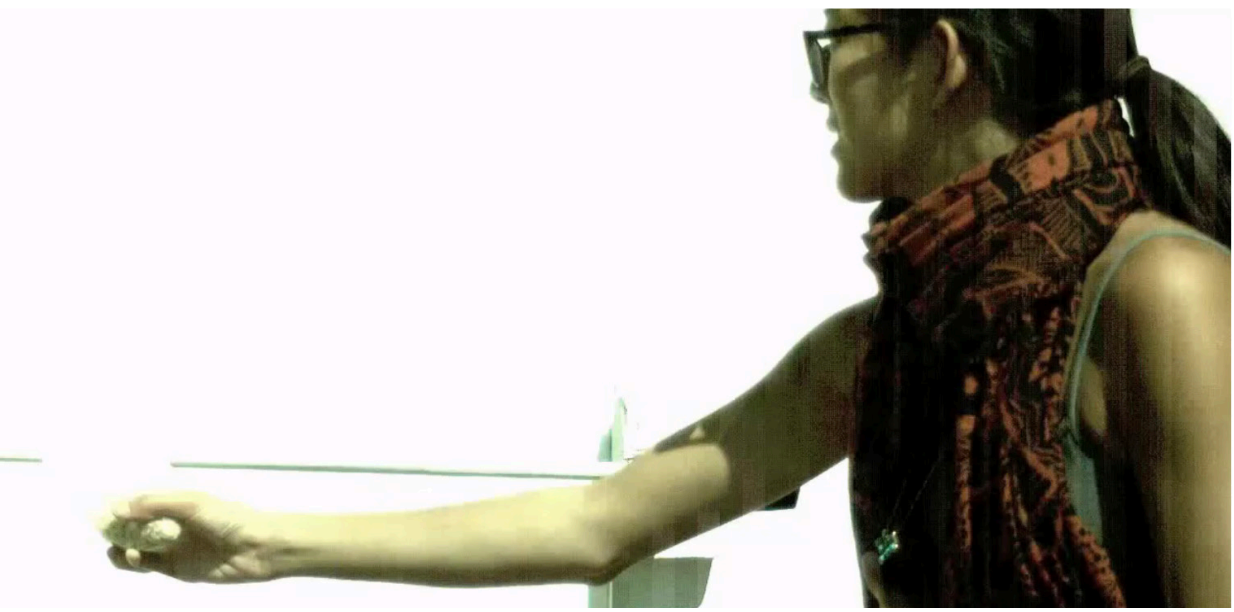
11. Yim, J. K., Wang, E. K., Lee, S. D., Hunt, N. H., Full, R. J., & Fearing, R. S. (2025). Monopedal robot branch-to-branch leaping and landing inspired by squirrel balance control. *Science Robotics, 10*(100), eadq1949.

12. https://sung.seas.upenn.edu/tag/origami/

13. Hunt NH, Jinn J, Jacobs LF, Full RJ. Acrobatic squirrels learn to leap and land on tree branches without falling. *Science*. 2021 Aug 6;373(6555):697-700.

14. Full, R. J., & Koditschek, D. E. (1999). Templates and anchors: neuromechanical hypotheses of legged locomotion on land. *Journal of experimental biology, 202*(23), 3325-3332.

15. Full, R. J., Bhatti, H. A., Jennings, P., Ruopp, R., Jafar, T., Matsui, J., Flores, L.A., & Estrada, M. (2021). Eyes toward tomorrow program enhancing collaboration, connections, and community using bioinspired design. *Integrative and comparative biology, 61*(5), 1966-1980.



Squirrel jungle gym.
Courtesy of Robert J. Full

Kate MccGwire
Deluge (Drench) detail, 2024 | Mixed media with rooster feathers | 36.5 x 61.5 cm.
Photo: JP Bland, 2022

Portfolio

Kate MccGwire

Portfolio
Kate MccGwire

Kate MccGwire (b. 1964) is a British, London-based artist who spent her childhood growing up on the Norfolk Broads. MccGwire's early memories of this distinct landscape, dominated by its wetlands, serpentine waterways and the wildlife that lives along the region's waters, form the foundations of her practice, which is inspired by the cycles, patterns and dualities of nature.

Taking feathers as her primary medium, Kate MccGwire goes through labour-intensive processes of collecting, sorting and cleaning her materials to create muscular, writhing forms reminiscent of Classical sculpture and creatures from mythology. These structures explore dualities of aesthetics, being simultaneously seductive and repulsive; form, being simultaneously organic and abstract; and movement, appearing fluid yet being static. Through her practice, MccGwire celebrates feathers, which are commonly shed or discarded, as the medium through which she articulates enigmatic anatomies that explore physical and introspective space.

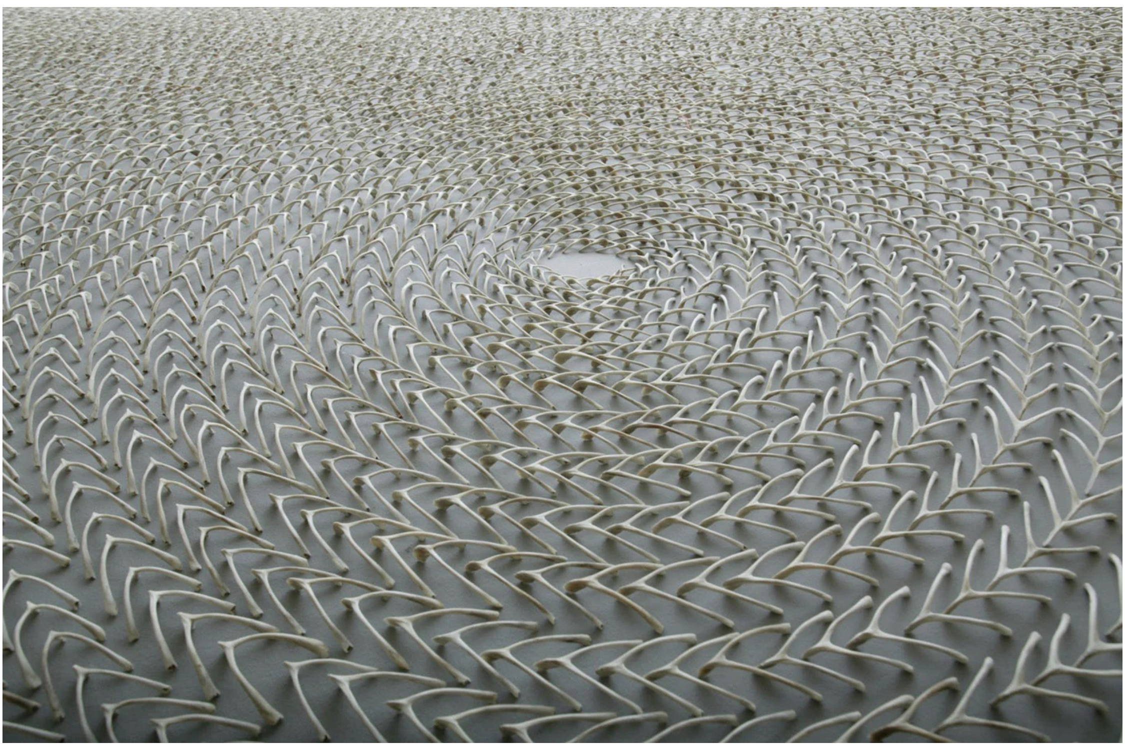
Speaking on her use of feather as a metaphor for what she terms 'the duplicity of nature', Kate MccGwire has said, "My work is inspired by the water forming incredible patterns that are there one second and gone the next. Everything is fleeting on the water, it is beautiful but there is danger and treachery underneath the surface. I'm intrigued by that dichotomy." Situated within a lineage of female artists who have worked with fiber art, soft sculpture and organic material, Kate MccGwire explores form, space and volume through her work. The artist's hybrid, 'boundary creatures' (as termed by Dr. Catriona McAra) often fill their framing devices and appear to writhe within them. On this, MccGwire has said, "I am interested in the interplay

Kate MccGwire
Photo: JP Bland

of opposites which runs like a leitmotif through everything I do. It is as if the work needs that tension to create its own internal equilibrium; it is an expression for me of the duality I see all around me and the materials I choose need to be able to physically embody this."

With titles such as 'Brood', ‘Retch’, ‘Gag’, ‘Heave’, ‘Smother’ and ‘Fuse’, Kate McсGwire’s sculptural installations often refer to the feminine grotesque. Resembling bodily functions, the works often spill out of domestic architecture: stoves, fireplaces and hearths, as though spellbound.

On the process of creation, Kate MccGwire has described her distinct feathering process as compelling and hypnotic: "I lose myself in it for hours, working instinctually – you can't plan how to lay the feathers out, nor can you really teach someone. Each feather contributes to the overall patterning of a piece, and it is this implicit sense of movement in the shifting colours and gentle curve of each filament



Kate MccGwire
Brood, 2004 | Installation with 23,000 chicken wishbones | 540 x 700 x 3 cm.
Saachi Collection

Kate MccGwire | *Brood* (detail), 2004 | Installation with 23,000 chicken wishbones | 540 x 700 x 3 cm. | Saachi Collection

Portfolio
Kate MccGwire

that brings the work to life. This final stage draws on the rituals of craft, on the connection between hand and eye and the natural serendipity that happens when you become fully immersed in giving life to an idea." ×

For more of Kate's work: https://katemccgwire.com/

Kate MccGwire graduated from the Royal College of Art with an MA in Sculpture in 2004 and a BFA from the University College for the Creative Arts, Farnham in 2001.

Selected solo exhibitions include Glitch, Galerie Filles Du Calvaire, Paris (2025); Quiver, Djanogly Gallery, Lakeside Arts, University of Nottingham; Undertow, Galerie Filles du Calvaire Paris (2022); Menagerie, Harewood House, Leeds, UK (2020); Dichotomy, The Harley Gallery, Welbeck, UK (2018); Secrete, Galerie

Kate MccGwire
Sluice, 2009 | Mixed media installation with pigeon feathers | 50 x 450 x 250 cm (variable).
Photo: Francis Ware

Huit, Kwun Tong, Hong Kong (2016); Scissure, La Galerie Particulière, Paris, France (2018); Covert, Musée de la Chasse et de la Nature, Paris, France (2014); and Lure, Cheongju International Craft Biennale, South Korea (2013); Host, Pertwee, Anderson & Gold, London, UK (2011) and Issue, M2 Gallery, London, UK (2005).

Selected group exhibitions include The Ark, The Church, Sag Harbor, USA (2025); Iris Van Herpen: Sculpting the Senses, ArtScience Museum, Singapore (2025); Art Paris 2025, Paris, France (2025); Sunny Side Up, Close Ltd, Somerset, UK (2025); Untitled Art 2024, Miami Beach, USA (2024); Distilled from Scattered Blue, Galerist, Istanbul, Turkey (2024); Summer Show 2024, Royal Society of Sculptors, London, UK (2024); Iris Van Herpen: Sculpting the Senses, QAGOMA, Brisbane, Australia (2024); Seeing Red, Phillips, London, UK (2024); Foreign Flowers, India Mahdavi, Paris, France (2024); Iris Van Herpen. Sculpting the Senses, Musée des Arts Decoratifs, Paris, France (2023); Unbreakable: Women in Glass, Fondazione Berengo, Murano, Italy (2020); Bêtes de Scéne, Espace Monte-Cristo, Paris, France (2020); Feathers: Warmth, Seduction, Flight, Gewerbe Museum, Winterthur, Switzerland (2019); Gaïa, What Are You Becoming?, Guerlain House, Paris, France (2019); Summer Exhibition 2019, Royal Academy of Arts, London, UK); Painting Still Alive, Centre of Contemporary Art, Toruń, Poland (2018); Without a Label I Feel Freer, Anton Ulrich Museum, Braunschweig, Germany (2018); Doing Identity: The Reydan Weiss Collection, Kunstmuseum Bochum, Germany (2017); Erwarten Sie Wunder! The Museum as Cabinet of Curiosity, Museum Ulm, Germany (2017); Entangled: Threads & Making, Turner Contemporary, Margate, UK (2017); Glasstress Boca Raton, Boca Raton Museum of Art, Florida, USA (2017); Memories of the Future, Thomas Olbricht Collection, Maison Rouge, Paris, France (2012); Dead or Alive, Museum of Art & Design, New York, USA (2010); This and That, Shenghua Art Centre, Nanjing, China (2006) and Galleon and Other Stories, Saatchi Gallery, London, UK (2004).

Work in order of appearance

p. 38: ***Retch***, 2007 | Mixed media installation with pigeon feathers | 200 x 120 x 70 cm | Photo: Francis Ware

p. 39: ***Sluice*** (detail), 2009 | Photo: Francis Ware

p. 40: ***Surge*** (Columba), 2012 | Mixed media with pigeon quills | 16 x 22 x 4 cm. | Photo: Tessa Angus

p. 41: ***Tally***, 2013 | Crow quill trimmings on archival board | 125 x 43 x 4 cm. | Photo: JP Bland

p. 42: ***Swathe***, 2014 | Pigeon tail feathers on archival board | 69 x 69 x 17 cm. | Photo: JP Bland

p. 43: ***Sinuate***, 2015 | Crow feathers and quills on board | 60 x 60 x 10 cm. | Photo: JP Bland

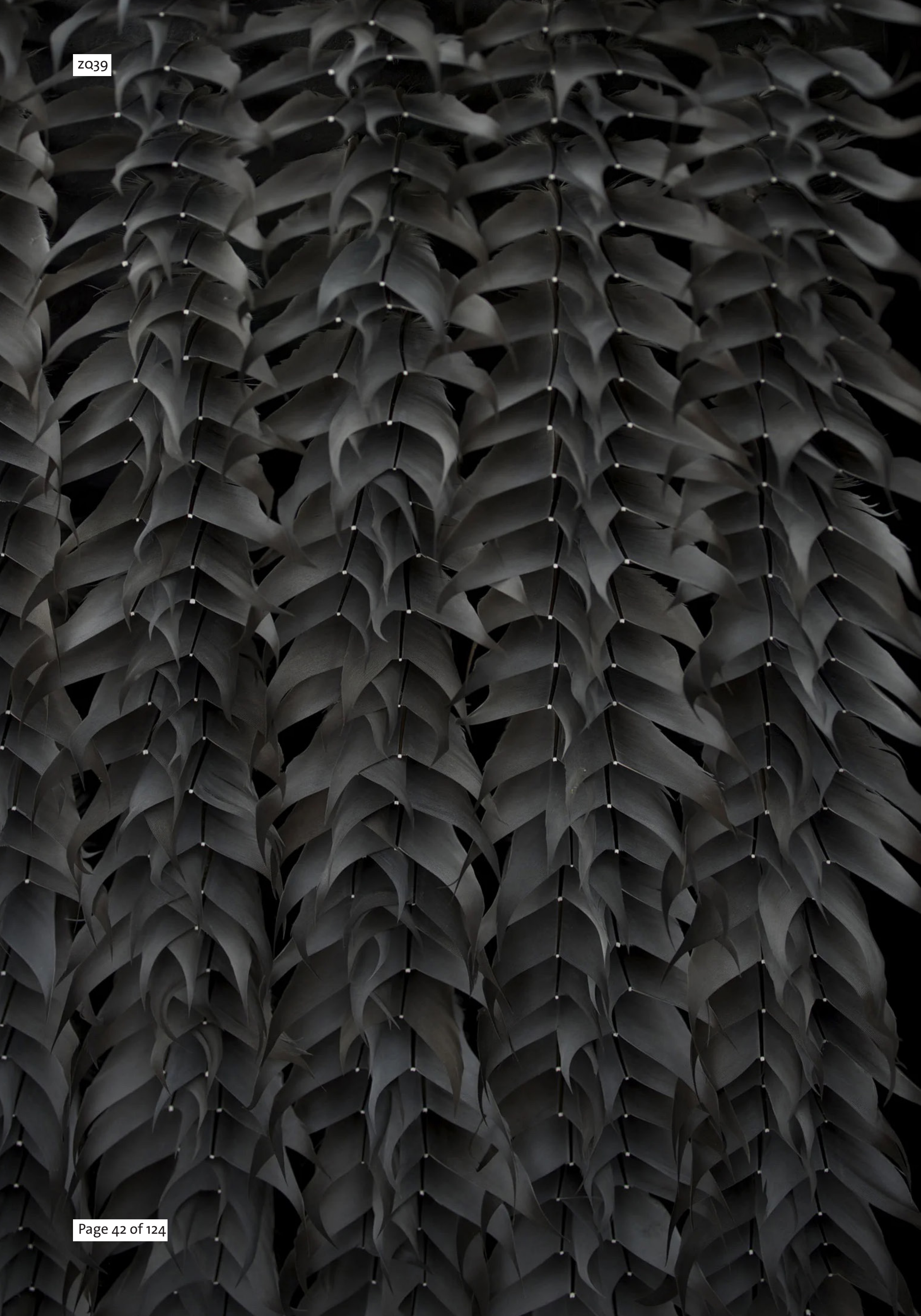
p. 44: ***Drift/Meander***, 2022 | Mixed media with goose feathers and steel frame | 121 x 90 x 10 cm. | Photo: JP Bland

p. 45: ***Effuse***, 2022 | Mixed media with magpie feathers in steel frame | 90 x 70 x 9 cm. | Photo: JP Bland

p. 46: ***Drift/Meander*** (detail), 2022 | Photo: JP Bland

p. 47: ***Tiding*** (detail), 2022 | Photo: JP Bland

ZQ39


ZQ39

A group of barrel cactus longhorn bees (*Svastra duplocinta*) bite onto the stems of a brittlebush (*Encelia farinosa*) along the front driveway, 2023
All photos courtesy of Rick Overson and Laura Steger

Science of Seeing

Plant It and They Will Come

Adelheid Fischer

Plant It and They Will Come

Adelheid Fischer

The more our world functions like the natural world, the more likely we are to endure on this home that is ours, but not ours alone. - Janine Benyus

For years, Rick Overson and Laura Steger lived the kind of nomadic life that is typical of many postgrads in biology. The couple crisscrossed the country pursuing a series of itinerant research opportunities, from identifying new species of ants at the California Academy of Sciences in San Francisco to understanding the dynamics between flowering plants and their insect pollinators at the Chicago Botanic Garden. Although the work was interesting and rewarding, they yearned to return to the Southwest, where they met in 2011 while Rick was working on a Ph.D. at Arizona State University. From the start, the Sonoran Desert became a mutual home for their hearts.

In 2017 the stars aligned when Overson and Steger both landed jobs at ASU. Finally able to put down desert roots, they decided to buy a house, narrowing their search to a neighborhood of modest ramblers in Tempe, Arizona. Their wish list was as brief as their budget was scant. They were on the lookout for a simple house with good bones within biking distance of their jobs. Most everything else was negotiable except this: they wanted the biggest, most derelict yard they could find.

That spring, after a months-long search, the two biologists closed on their dream house—or, more precisely, their dream yard. "It was perfect," Steger recalls still beaming at the memory of it. Out front a few anonymous shrubs huddled along the foundation, forming a perimeter guard along a patchy lawn, parts of which were straw-colored and crunchy as if someone accidentally doused the grass with napalm. In the backyard an oleander bush rose like an isolated atoll out of a sea of wall-to-wall turf. Strung from end to end was an abandoned volleyball net billowing in the breeze. It was the blank slate they had been looking for.

No sooner did Overson and Steger sign the papers for their new house and unload the last of their meager possessions than they headed to the nearest Home Depot for pickaxes, wheelbarrows, hacksaws, rakes and shovels. It was time to finally turn years of fantasy planning into their own one-tenth-acre patch of Sonoran Desert.

And they dug in—literally—with a go-for-broke enthusiasm that made them "go crazy on the yard at the expense of other life needs," Overson observes. In their spare time after work and on weekends, the couple ripped out sod, grubbed the gnarled roots of shrubs and excavated an elaborate crosshatch of trenches in the desert's rock-hard soils for drip-irrigation pipes,

Backyard, 2017 (top) and 2022 (bottom)

Plant It and They Will Come

Adelheid Fischer

Front yard, 2017 (top) and 2022 (bottom) sometimes working long after dark under the glare of floodlights. Once the garden's infrastructure was laid, they raided nurseries, filling entire U-Haul trailers with native species from a dream list they'd already compiled over the years. One by one, each seedling was tucked into the ground. Then came the long wait. For the first several seasons, Overson recalls, the yard was little more than a dirt lot with clusters of bare sticks. It looked less like a garden, he says, laughing, than a state fairground in the middle of winter or, as Steger adds, like a "very bad haircut."

Fast forward eight years. The inside of their house remains spare, though elegant, with a few residual pieces of what Overson laughingly refers to as "pity furniture": items that friends donated early on after they grew tired of eating one too many dinners on REI camp chairs. But step out the back door and you'll find an exterior that is as exuberant as the interior is restrained.

To date, the number of native plants tops 120 species. Documenting the transition from pulped sod to paradise is a diary that the couple meticulously maintained throughout their landscape makeover. Photos of the garden in the spring, for example, feature the concrete pavers that Steger fashioned by hand twisting this way and that through plots of desert bluebells and gold poppies. Contoured garden beds run amok with the sunny blooms of brittlebush and orange mallow. The trumpets of hot-pink penstemon flowers rise on tall stems from the particolored carpet to sway in the breeze. Gray cement-block walls disappear into the deep shade of jojoba, wolfberry, hopbush and creosote. Here and there, the waxy blooms of prickly pear, hedgehog, pincushion and barrel cactus explode in magenta and lime-yellow accents.

After a long day at work, this patch of desert splendor becomes Steger's go-to retreat. "The yard relieves a lot of stress and anxiety for me," she observes, so much so, that "even just thinking about it makes me feel better." And because it's so near at hand, she adds, "I get a chance to interact with nature that I'd otherwise have to go to a wild place to experience."

But the couple didn't design their landscape as a private getaway for their eyes alone. From the start, Overson and Steger looked for ways to multiply the opportunities for as many organisms as possible to feed, breed, nest and rest in the yard. "I am someone who from a very young age was tenaciously and violently obsessed with animals and plants the way other kids might be obsessed with sports or cars," Overson recalls. "All my early childhood memories

California-bluebell (*Phacelia campanularia*), 2024

Arizona Poppy (*Kallstroemia grandiflora*)

Apricot Globe-Mallow (*Sphaeralcea ambigua*), 2023

A fruit fly (*Trupanea nigricornis*) lands on a brittlebush (*Encelia farinosa*), 2024

Scarlet Hedgehog Cactus (*Echinocereus coccineus*), 2024

Barrel Cactus (*Ferocactus*), 2023

Plant It and They Will Come
Adelheid Fischer

are of bugs and fistfuls of worms and ants escaping from jars in the house. So, while planning the yard, we kept saying, let's try and make this as good an approximation of what nature would do."

They succeeded in creating such a convincing facsimile of wild desert that a whopping 73 vertebrate species have either paused on their migrations or taken up residence in their yard. Add to that 174 species of invertebrates, from bugs and centipedes to butterflies, moths and spiders, that the couple has conclusively identified to date. They expect that number to easily exceed 2,000 species once they have labeled all the additional species in a backlog of thousands of photos, pinned specimens and personal observations.

With so many takers, no corner of the yard is unoccupied. By day, native ground-nesting bees, for example, have perforated patches of bare soil with dime-sized tunnels for their nurseries. For eight years now, a pair of curve-billed thrashers (recognizable by the telltale broken beak of one of the birds) has raised generations of chicks in the branches of a neighboring tree. Tucked into the thicket of jojoba bushes along the back wall a gray fox found a hidden refuge for her three kits. By night, the place turns into an

Curve-billed thrasher, 2021
Next page (top to bottom): Ground nesting bee nest, 2025 | A Grey Fox (*Urocyon cinereoargenteus*) running along a backyard fence assesses the danger the photographer poses, 2018 | Ornate Tree Lizard (*Urosaurus ornatus*), 2021 | Potter Wasp (*Eumenes bollii*), 2023

animal dormitory. On headlamp tours in the summer, Overson and Steger have spotted ornate tree lizards sleeping high up in the hackberry canopy where temperatures are slightly cooler. Dozing on dead plant stems, which Overson and Steger are careful to leave in place as roosts and resting places, are damselflies and constellations of potter wasps and barrel cactus longhorn bees. “When you start to see animals using the habitat in the natural course of things, those are spiritual experiences for a biologist and a bleeding-heart naturalist,” Overson says, laughing.

Especially exciting are the return visits by seasonal regulars. The couple suspects that individuals of some of these migrant species, such as white-crowned sparrows and green-tailed towhees, are repeat customers since they “show up at the same time every year and act like they own the place and know what’s going on,” Overson says. They are joined by other routine pit-stoppers such as phainopeplas, glossy black desert birds with feathery mohawks that reliably make an appearance in late spring to gorge on the nutrient-packed fruits of the wolfberry shrub. Occasionally, a rare species such as the ruddy ground dove (a bird that is more commonly spotted in Mexico) touches down bringing with it a paparazzi of eBirders with binoculars to the front yard.

Green-tailed Towhee (*Pipilo chlorurus*), 2020

Ruddy Ground Dove (*Columbina talpacoti*), 2020

Orange-Crowned Warbler (*Leiothlypis celata*) and Spiny Hackberry (*Celtis iguanaea*), 2021

Plant It and They Will Come

Adelheid Fischer

Inca Dove (*Columbina inca*), 2020

From the aerial perspective of Google Earth, you understand how winged critters like rare doves and digger bees have found their way to Overson and Steger's desert garden. It forms a green rectangle in a stark matrix of gravel yards, lawns, concrete driveways and asphalt streets. It's nature's equivalent of a neon light flashing the language of life.

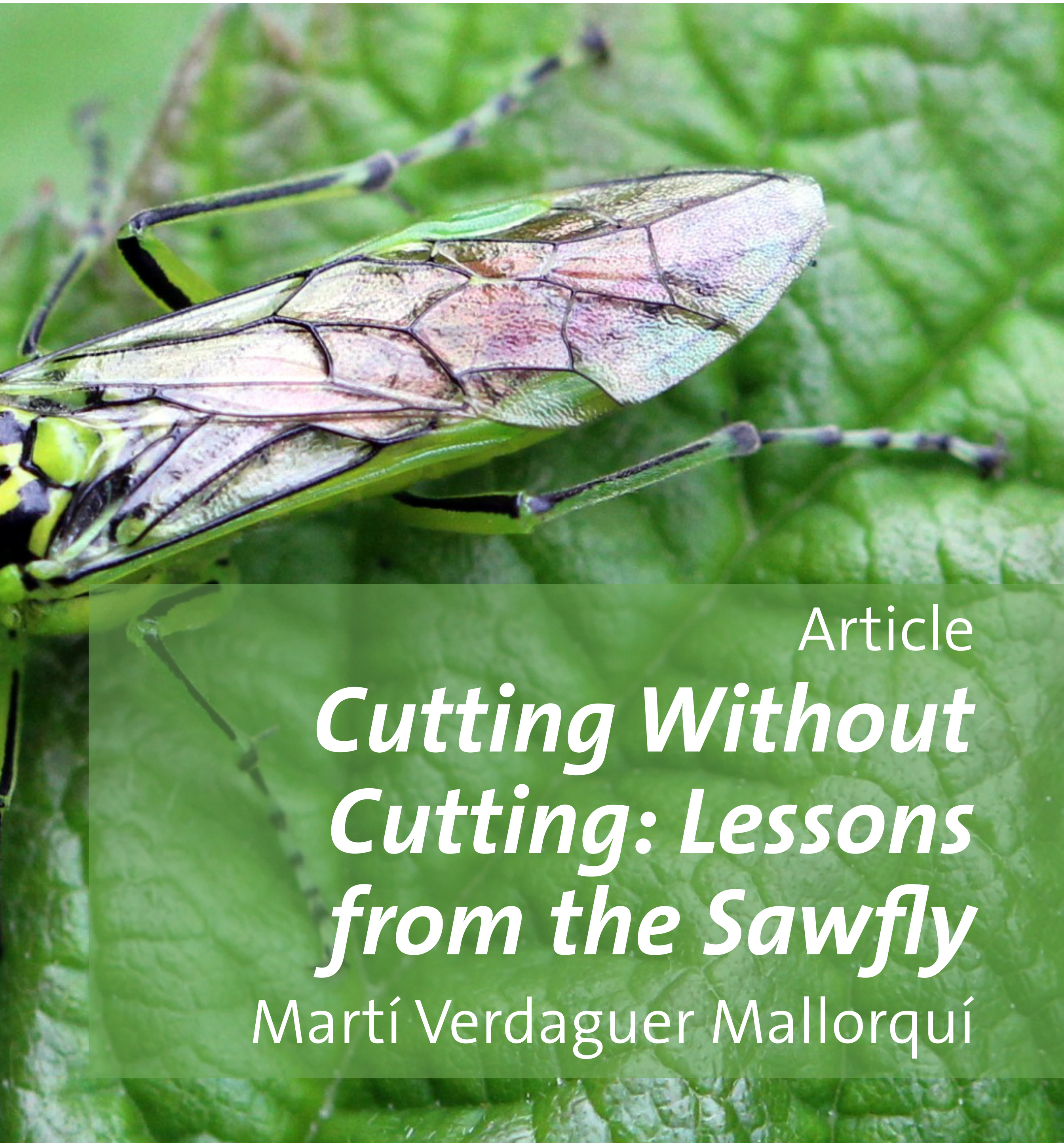
The successful realization of their long-anticipated dream, however, is just the beginning. Overson and Steger hope that the beauty and biodiversity of their yard will inspire others to plant their own patch of desert such that one yard will connect with the next to form an indistinguishable swath of restored native systems. "We will need small efforts like these from lots of people," charges conservation biologist Doug Tallamy, founder of Homegrown National Park, if we want to solve the crisis of species declines and extinctions. Our national parks and other public lands are too small and too isolated "to sustain the species that run the ecosystems that we all depend on," he explains. But the U.S. abounds in ecologically impoverished landscapes near at hand that could be restored to collectively support the needs of an enormous number of native species: railroad and powerline rights of way; golf courses; cemeteries—and the vast numbers of individual backyards in our cities and suburbs.

"Our yard is an example of the tons of simple things that people can do to backfill in biodiversity and create refugia like In-N-Out Burger stops along the highway for migrating insects and birds" Overson observes. "You might think, I have this teeny-tiny backyard. I can't do very much. But you don't need a massive area to provide resources, a stopover, a refuge."

It's a vision "that's empowering," he says. ×

A sleeping bee (*Svastra obliqua*) on fall tansyaster (*Dieteria asteroides*), 2023

Rhogogaster
Photo: AfroBrazilian, 2017 | Wikimedia Commons



Article

Cutting Without Cutting: Lessons from the Sawfly

Martí Verdaguer Mallorquí

Cutting Without Cutting: Lessons from the Sawfly

Martí Verdaguer Mallorquí

The idea to study sawflies didn't come from me. It began with Prof. Julian Vincent, who had long worked on wood wasps that bore into timber. Based on these wood boring wasps, a team lead by Prof. Ferdinando Rodriguez y Baena[1] was able to develop a neurosurgical probe and later a needle, both self-propelled and capable of steering[2]. Later, other researchers continued working on similar devices and other applications of the mechanisms acquired from wood boring wasps.

Prof. Julan Vincent suggested that we investigate sawflies, close relatives of wood wasps. Prof. Marc Desmulliez at Heriot-Watt, after partnering with Dr. Vladimir Blagoderov from the National Museum of Scotland, secured the funding and provided resources as well as guidance. Instead of drilling, sawflies cut with a pair of slender, toothed blades called ovipositors. Different sawfly species target different plants, and their ovipositors vary dramatically in shape. If these structures had evolved to cut particular plant tissues, perhaps they could inspire tools to cut human tissues. This was especially promising for surgery.

I came to the project as a materials and mechanical engineer with no background in insects. The first year was almost entirely spent reading, trying to stitch together fragments of biology into something useful for the project. There were many papers on sawflies naming species and cataloguing structures, but fewer explaining how those structures worked. I would sometimes spend days combing through articles for a single sentence that hinted at a mechanism. Covid restrictions increased the frustration since my access to the lab was limited.

Rather than keep guessing, I went to the people who might one day use such a tool: surgeons. I conducted a long, open-ended interview with a cardiovascular surgeon, then distilled the insights into a questionnaire that eventually reached fourteen surgeons across eight different specialties. Their average experience was more than a decade, and their answers surprised me. Without prompting, the majority raised concerns about tissue damage. Many described the same situation: accidentally cut a vessel and suddenly the surgical field fills with blood, visibility collapses, and control over what is cut is hindered. Several contrasted scissors that are precise, tactile, even "beautiful" to use with electrocauterizing scalpels which seal as they cut but feel inelegant and can damage the surrounding tissue. The message was clear: they valued a tool that could avoid cutting the wrong thing more than one that simply cut faster or sharper. That perspective reshaped the way I looked at the sawflies.

[1] https://www.imperial.ac.uk/mechatronics-in-medicine/research/eden2020/

[2] https://web.archive.org/web/20221125180939/https://www.youtube.com/embed/_wvAyiiuozs

Adult male newly emerged from its cocoon | Photo: Lemen, 2014 | Wikimedia Commons

Cutting Without Cutting: Lessons from the Sawfly
Martí Verdaguer Mallorquí

Knowing what to look for was one thing; getting actual sawflies was another. Museum collections rarely welcome destructive tests. My attempts to catch sawflies in the hills with a net and rear them in the lab ended in failure. Finally, I wrote a letter to the editor of The Royal Entomological Society journal. To my surprise, Andrew Liston, an expert on sawflies, replied. Not only did he have specimens, he was willing to let me dissect them, even destroy them if necessary. It was a turning point: now I had material to work with.

The first sawfly dissections were delicate but awkward. The ovipositor is tiny, and handling it without damaging it was a skill I had to learn. Using scanning electron microscopy and optical profilometry, I began to see the structure in detail: ridges, hooks, and repeating teeth. To understand how those shapes might work, I built a scaled-up cutting rig that mimicked the sliding motion of the blades. At first, I cut anything

Ovipositor of *Sterictiphora geminata*
Adapted from [1]. Open access article (CC-BY 4.0)

I could find, from fruit to bits of lab material. Eventually I settled on agar and ballistic gelatine, workable stand-ins for flesh.

I initially thought the sawfly system was a poor design. My scaled-up rigs struggled to cut, most of the time the samples would just be pushed out of the cutting range - it seemed inefficient. It was only when I stepped back and considered the biology that the pieces began to fit. A sawfly must deposit its eggs inside a living plant, which the larvae will later feed on. Kill the plant, and you kill the offspring. The ovipositor's "inefficiency" was actually a safeguard: it cut enough to insert eggs while sparing critical tissues like vascular bundles. In practice, this meant the ovipositor operated as a selective cutter. It was not built to be the sharpest tool possible, but to cut only what could be sacrificed. This realization turned what had looked like a failure into a principle worth pursuing, and one directly aligned with the concern of the surgeons about avoiding the wrong cut if there is a lack of visibility due to blood flooding the area, or previous surgery had caused the tissues to be harder to differentiate.

Once I had the basic insight, I wanted a way to predict the behaviour of the system before testing it. I developed an analytical model to describe the cutting process: under what conditions the material was cut or slipped away unharmed. It let me vary angles, forces, friction values, and other variables systematically. All variables had an impact, but tooth angle and friction drastically affected the outcome. These were not abstract numbers: they mapped directly to the ovipositor's shape and surface features. Suddenly the model gave me reasons for details I had seen but not understood in the sawfly's ovipositor.

Using confocal laser scanning microscopy and micro-CT, I looked at the ovipositors with new eyes. I could see bands rich in elastic protein between the teeth, allowing them to flex slightly, while the teeth were denser and stiffer. Composition and structure appeared tuned in a way that matched the model's predictions and the functionality of the ovipositor. What emerged was a complex selective cutting mechanism with a primary mechanism and two modifiers, each one related to a different mechanical property:

1. **Selective cutting mechanism**: The primary mechanism operates based on the ultimate stress. If the material to be cut is stronger than a certain threshold dependent on the tooth geometry, it is ejected instead of being cut.
2. **Serrulae**: These tiny saw-like structures on the teeth grip the material to be cut and hold it in place, preventing ejection, and

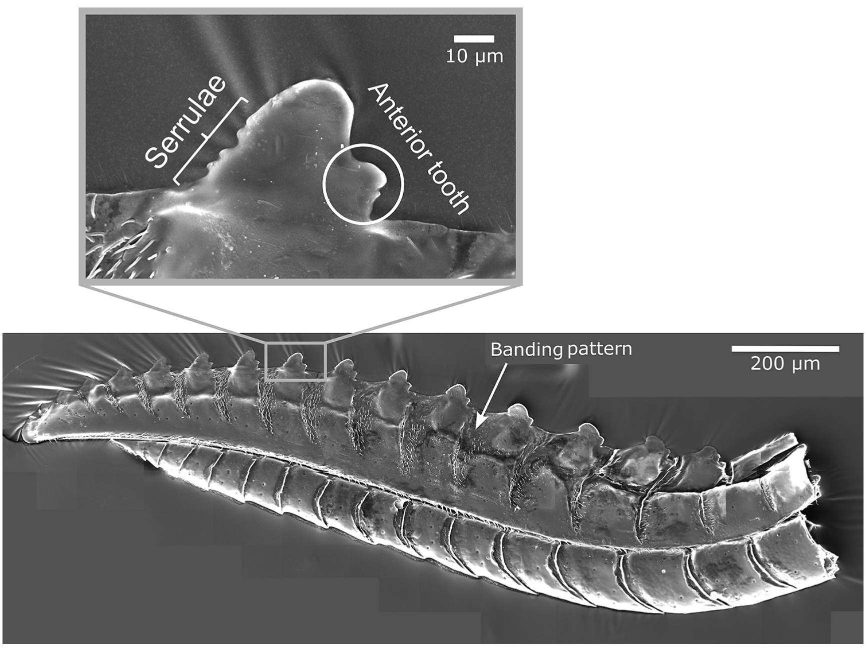
Cutting Without Cutting: Lessons from the Sawfly
Martí Verdaguer Mallorquí

thus modifying the primary mechanism. This modifier is related to the hardness of the material to be cut.

3. **Banding pattern**: These more flexible bands change the teeth angles depending on stiffness of the material to be cut in relation to the stiffness of the bands, further modifying the primary mechanism and therefore what can be cut.

Together these mechanisms created a passive but complex filter, aligning morphology, material composition, and function. It was a level of integration I might have missed without the model pushing me back towards the biology.

Looking back, the path was anything but straightforward. A year spent in the literature, failed attempts at rearing insects, "proofs of concept" that seemed useless, and an apparent inefficiency that later revealed itself as the key - all of these detours were part of the journey. An important step was engaging surgeons early, so their concerns about accidental damage were in my mind when the ovipositor's selectivity finally became clear. The work became a two-way street between engineering and biology; both were informing each other.



Scanning electron microscope images of an ovipositor of *R.Scalaris*. Bottom: panoramic view of the full ovipositor. Top: magnified image of one tooth, displaying serrulae on the apical side and anterior tooth on the basal side.
Adapted from [2]. Open access article (CC-BY 4.0).

The story is far from finished. Although there is still a lot of work to do, the value is already visible. The sawfly ovipositor shows that sometimes the best cutter is one that refuses to cut - this may one day guide safer surgical instruments. Next steps include experimentally testing the modifiers shown by the model, then prototype tools for specific surgical situations. ×

Dr. Martí Verdaguer Mallorquí holds a BEng in Materials Engineering (UB) and an MSc in Mechanics of Materials and Structures (UdG). He has worked in applied R&D at LEITAT, contributing to projects including an airplane seat with Fraunhofer, an armadillo-inspired anti-stabbing device for police use, and bio-based composites. At IFAE, he worked on the Cherenkov Telescope Array, retinal prostheses, and led mechanical projects for CERN's ATLAS detector and the Future Circular Collider. He completed a PhD at Heriot-Watt University, studying sawfly ovipositors as models for bioinspired surgical tools. He recently concluded a postdoctoral position on acoustic microfluidics for microplastic sorting and is currently focused on developing new projects in biomimetic design.

Additional reading

1. Verdaguer Mallorquí, M., Vincent, J., Liston, A., Blagoderov, V., & Desmulliez, M. P. Y. (2025). Knowledge from hymenopteran ovipositors: A review of past and current biomimetic research. *Bioinspiration & Biomimetics, 20*. https://doi.org/10.1088/1748-3190/adc3e2

2. Verdaguer Mallorquí, M., Vincent, J., Liston, A., Blagoderov, V., & Desmulliez, M. P. (2025). A novel bio-inspired passive selective cutting mechanism for cutting surgical tools and other material-selective applications. *bioRxiv*. https://doi.org/10.1101/2025.06.10.658779

3. Verdaguer Mallorqui, M., Vincent, J. F., Liston, A., Blagoderov, V., & Desmulliez, M. P. (2025). Analytical model of the selective cutting mechanism used by ovipositors of sawflies. *bioRxiv*, 2025-06. https://doi.org/10.1101/2025.06.15.659745

4. Verdaguer Mallorquí, M., Vincent, J. F., Liston, A., Blagoderov, V., Mylo, M. D., Tauber, F., Valli J., & Desmulliez, M. P. (2025). Structural and Compositional Analysis of Sawfly Ovipositors. *SSR*. http://dx.doi.org/10.2139/ssrn.5374515

Lauxaniid fly in a garden in Bamberg, probably *Minettia fasciata*
Photo: Reinhold Möller, 2020 | Wikimedia Commons

Interview

Arindam Phani and Seonghwan (Sam) Kim

Shoshanah Jacobs

Arindam Phani and Seonghwan (Sam) Kim
Shoshanah Jacobs

Sensing the Invisible: Bio-Inspired Design at the Molecular Scale

When I sat down with Dr. Arindam Phani and Dr. Seonghwan (Sam) Kim, the conversation erupted with passion and curiosity. Both scientists are engineers, and what struck me most was how naturally they spoke about life itself as a design manual. As humans, we rely heavily on our sense of sight to learn about the world. We often overlook the things that we cannot see within our limited spectrum. Yet, in the animal Kingdom, most of life relies upon smell and taste or chemoreception, to learn about their surroundings. Learning about the processes by which species can sense the world without sight allows us to learn even more about our own surroundings. With their enthusiasm, Dr. Phani and Dr.Kim add poetry to protein folds and reverence for insect adaptations that have ensured enduring lineages. Their work doesn't just mimic natural systems; it listens to them.

Sho: What are your impressions of the current state of biomimicry or bio-inspired design?

Arindam: If you think back, flight was our first bio-inspired achievement. Early attempts to imitate birds failed because we didn't yet understand the physics. Once we grasped lift and drag, flight became possible. It's similar today—biomimicry has evolved from copying biological forms to understanding the underlying physics and chemistry. We're learning that nature's complexity is deceptive; biology is efficient, robust, and adaptable. We're still far from true imitation, but we're steadily evolving toward it.

Sam: Our own work is in sensing—detecting gases and volatile compounds. Insects and dogs are far better sensors than we are. Nature already provides the perfect models for chemical detection; our job is to translate that intelligence into engineering.

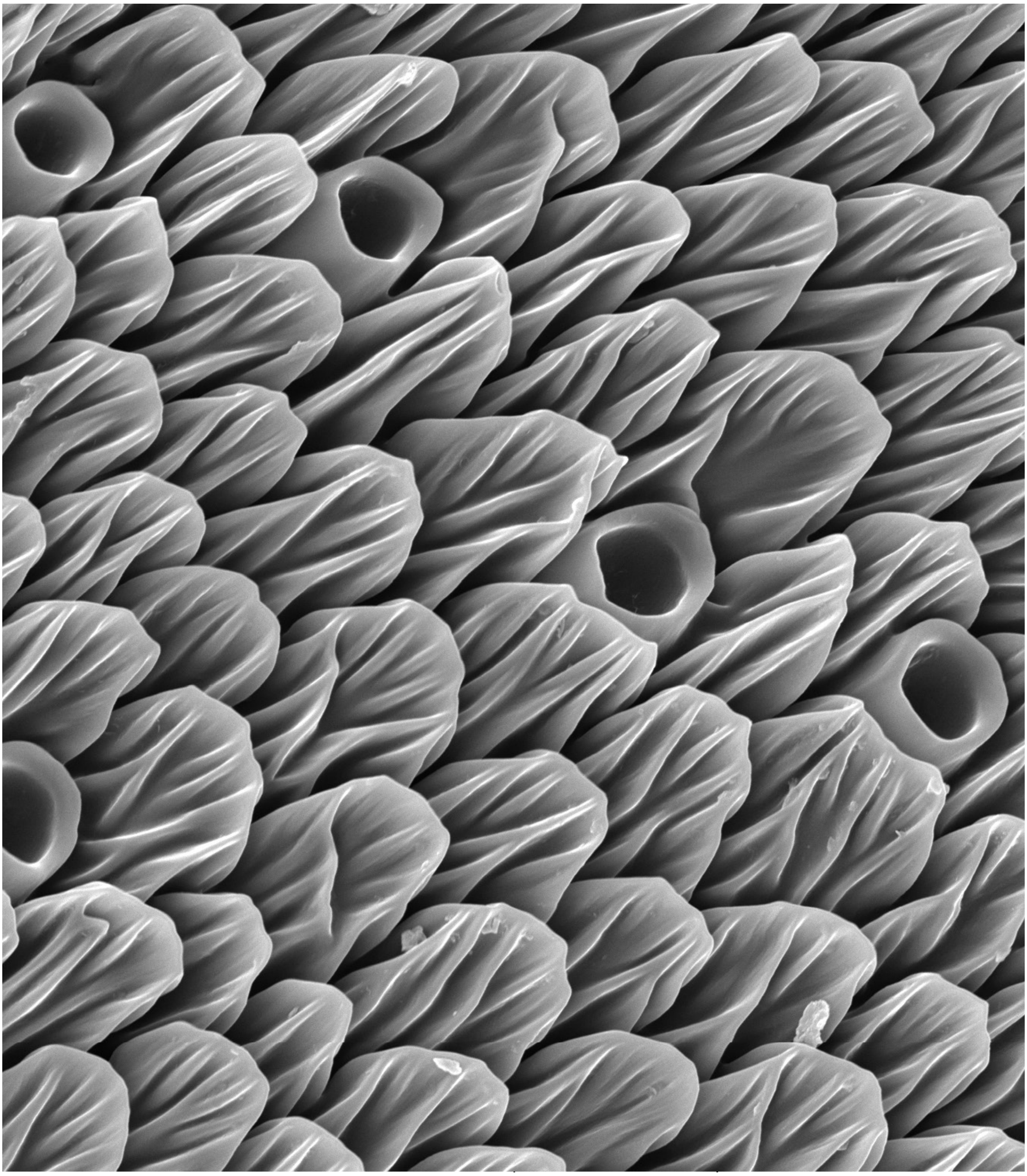
Sho: What do you see as the biggest challenges in the field?

Arindam: Translation. There's an ocean of information in physics, chemistry, and biology—but little communication across disciplines. Physicists rarely talk to chemists, chemists avoid biochemists, and nobody wants to talk to the mathematicians—though everything ultimately runs on math! Unless we connect these fields, we can't replicate nature effectively.

Biology thrives on feedback loops, but our engineered systems seek static equilibrium. We want steady-state outcomes, while life

Fruit fly
Photo: Macrogiants, 2021 | Wikimedia Commons

Arindam Phani and Seonghwan (Sam) Kim
Shoshanah Jacobs



Detail of peacock butterfly's (*Aglais io*) feeler: primarily an olfactory organ and in addition, performs navigation, orientation and balance functions (7500x) | Photo: Pavel Kejzlar 2011 | Wikimedia Commons is dynamic, constantly self-adjusting. That's our biggest gap.

Sam: I agree. Translating fundamental understanding into practical use is difficult because research today is highly segmented. Even mathematical modelling—the foundation of much of our work—is underappreciated. People want results without the equations.

Sho: What areas should we focus on to advance biomimetics?

Arindam: Nature always solves problems locally first. A cell repairs itself before the organism heals; a forest regenerates patch by patch. Biomimicry should follow that hierarchy—local solutions that scale outward. Start small, refine, then expand.

But we must also think systemically. A doctor who treats only the eye may not understand the knee; our disciplines can be just as siloed. To truly advance, we need a systems-level understanding where specialized knowledge connects fluidly.

Sam: Exactly—hierarchical and systemic at once.

Sho: How did each of you develop your interest in biomimicry?

Arindam: Curiosity. As a child, I flew kites during our month-long kite festival. It taught me physics before I knew the word—how wind, humidity, and temperature affect flight. I watched birds glide effortlessly while I fought the air with string and paper. Later, living alone, I learned another biological lesson—leave a banana peel out, and fruit flies appear as if summoned. How did they know? Those small observations build fascination.

Sam: For me, it grew from studying surfaces and sensing. We began thinking about how touch works in living organisms—the nuance between a soft and a hard touch—and how that might inform imaging and detection.

Sho: What are you working on now?

Sam: We recently submitted a paper to ACS Nano on imaging protein folding using atomic force microscopy. We captured the intermediate states of proteins—moments in their folding process—almost like watching evolution in real time.

Arindam: That project emerged from our "transitional tapping AFM" method, now in the process of patenting. The sense of touch

Arindam Phani and Seonghwan (Sam) Kim
Shoshanah Jacobs

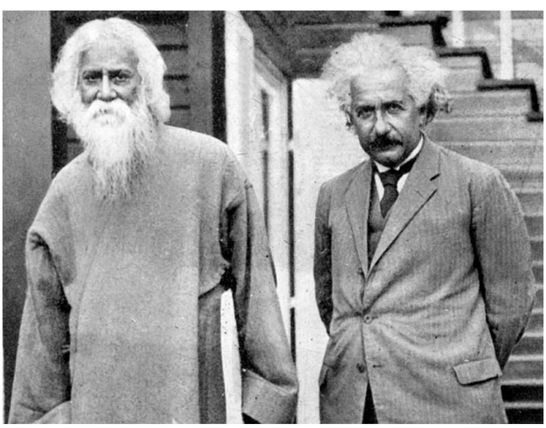
inspires it: by varying pressure, we can map molecular surfaces in different ways. Initially, we applied it to drug molecules, but our protein work showed even more promise. Next, we're turning to DNA to understand how genetic sequences unfold and refold dynamically.

Sho: That's fascinating. What's your favourite biomimetic example of all time?

Arindam: Flight—always. Watching a Boeing 747 land, gliding like a duck on water, still amazes me. Such a massive, heavy machine behaving with biological grace—it's a perfect fusion of physics and inspiration.

Sho: What's the last book you enjoyed?

Arindam: *The Catcher in the Rye*. It reminds me that even in technical work, perspective and emotion matter.



Sho: Who do you admire, and why?

Arindam: Rabindranath Tagore. He wrote constantly—poems, songs, novels, philosophy—an entire universe of thought. His writing mirrors how nature works: continuous, prolific, and profound. Every piece contains enough depth to live inside for a lifetime. He reminds me that creation and reflection are daily acts of discipline.

Sho: What's your idea of perfect happiness?

Sam: (laughs) Retirement. Or early retirement?

Arindam: (laughs) A million-dollar research grant—and five quiet years with my woodworking.

Sho: If you weren't scientists, what would you be?

Arindam: A table-tennis player. But academia is my first love — I think I would have always found my way back.

Sam: I'd still be curious about the unseen—so maybe still sensing, just differently.

Sho: Is there anything else you'd like to add?

Arindam: Yes—one of our next challenges is detecting forest fires early. Our bio-inspired sensors could detect volatile compounds at the ignition stage—giving a 20-minute

Rabindranath Tagore with Albert Einstein in 1930
Photo: UNESCO - UNESCO Gallery, 2015 | Wikimedia Commons, https://en.wikipedia.org/wiki/Rabindranath_Tagore
Next page top: Black Fire Beetle *Melanophila acuminata* (De Geer, 1774)
Photo: Udo Schmidt, 2015 | Wikimedia Commons

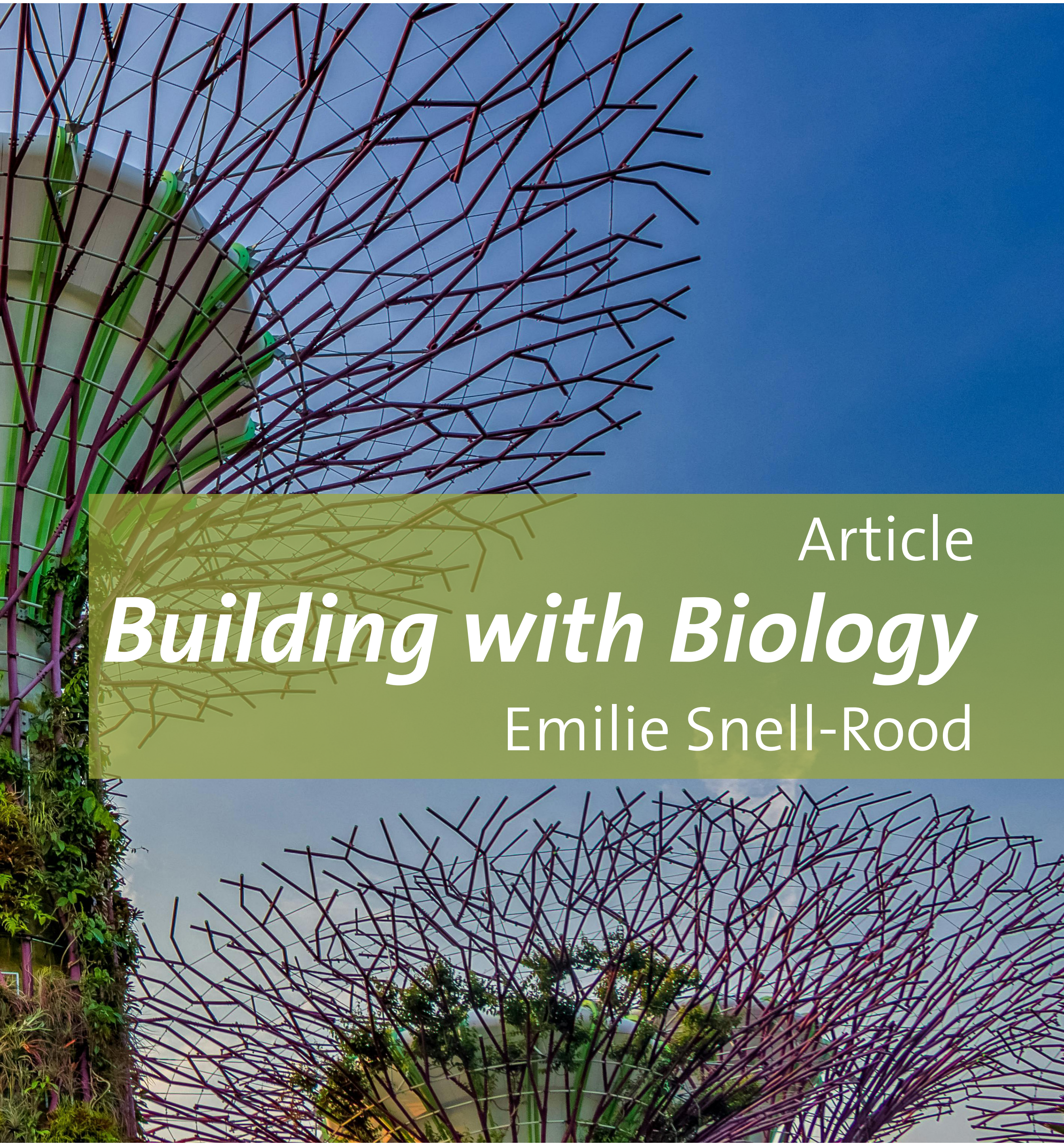
window for intervention. Nature already detects danger faster than we do; we just need to listen. ×

Please also see: https://www.ucalgary.ca/news/schulich-researchers-look-insects-inspiration-developing-nanosensors

Dr. Seonghwan (Sam) Kim is a Professor in the Department of Mechanical and Manufacturing Engineering, Schulich School of Engineering (SSE) at the University of Calgary. He is the founder of the Nano/Micro-Sensors and Sensing Systems Laboratory (NMS3, https://www.ucalgary.ca/labs/nanosensors/home/) at UCalgary to develop point/standoff sensors and sensing systems and to explore novel characterization techniques for nanomaterials, nanocomposites, and biological materials.

Dr. Arindam Phani's work lies at the intersection of experimental condensed matter physics, nanotechnology, and biophysics, and directly supports innovation in biomedical devices, intelligent bio-interfaces, and next-generation adaptive materials. Through real-time probing of fast-timescale fluctuations, he aims to bridge the gap between statistical physics and translational biomedical engineering.

Gardens by the Bay Under the Blue Sky (Supertree Grove, Singapore)
Photo: Nextvoyage, 2018 | Pexels cc



Article

Building with Biology

Emilie Snell-Rood

Building with Biology
Emilie Snell-Rood

Uniting problem solving with biology under the umbrella of "Building with Biology"

Over the last several decades, there has been a growing interest in looking to nature to help solve challenging human problems, from the popularization of biomimicry in the late 1990s to the exponential growth of biotechnology in the 2000s. We have a plethora of bio-based approaches we can employ, including biophilic design, nature-inspired solutions, bioutilization, and bionics. Some of these individual approaches have thrived on their own. However, as we are learning through recent efforts to build a collaborative network at the University of Minnesota, we have much to gain by uniting similar approaches under one umbrella.

The grand challenges faced by society today, from addressing climate change and cleaning our water to feeding the world and curing cancer, require biology. This requirement is not simply about understanding biology, but also taking inspiration from biology, designing with biology in mind, and partnering with biological organisms and systems in the design itself. Here, we explore a union of biological approaches to problem-solving under the broad term "Building with Biology" – a consideration of the union, what we have to gain by such a union, and how we might proceed in bringing these approaches together.

Bringing "bio" problem-solving approaches under one umbrella

Let's review the primary biology-based approaches that we use for problem-solving. Humans have evolved in relationship with biological systems. As part of our natural ecology, **bioutilization** is likely the oldest form of "Building with Biology"; building with wood, stuffing down feathers into clothing, and relying upon the biochemicals of plants for medicine. In these examples, we rely on the unique features and specific functions of biological organisms by using them directly.

However, direct use of biology can deplete the resources that we so desperately rely on. Over the last century, we have increasingly turned to **biomimetic** approaches, where we copy some aspect of how the trait works in our own design. For instance, with VELCRO® we use plastic to mimic how a bur adheres materials, and pharmaceutical companies often learn to synthesize natural products in the lab, meaning we no longer need to extract

A microscopic view of the hook of a Burdock seed | Photo: Alexander Klepnev, 2020 | Wikimedia commons

Libellulidae *Brachythemis contaminata*, male, on *Nelumbo nucifera* leaf (Sacred lotus) with water drops, at the surface of a muddy pond, in Don Det, Si Phan Don, Laos. | Photo: Basile Morin, 2019 | Wikimedia commons the product from nature. In biomimetic approaches, we seek to emulate how a biological trait functions using our own materials in the resulting applications.

While biomimetic approaches do not necessarily require the use of biological or living materials, we often find that designs that integrate biology itself can be more impactful. In the architectural world, **biophilic design** principles embrace the use of biological or natural materials (plants, wood, rocks), forms ("biomorphism"), or processes (moving water or air). People living and working in such biophilic spaces tend to be more engaged and less stressed, presumably because these environments emulate important features of the natural spaces in which we evolved. Here, we are using biology (and nature more broadly) in design as it has positive effects on our wellbeing.

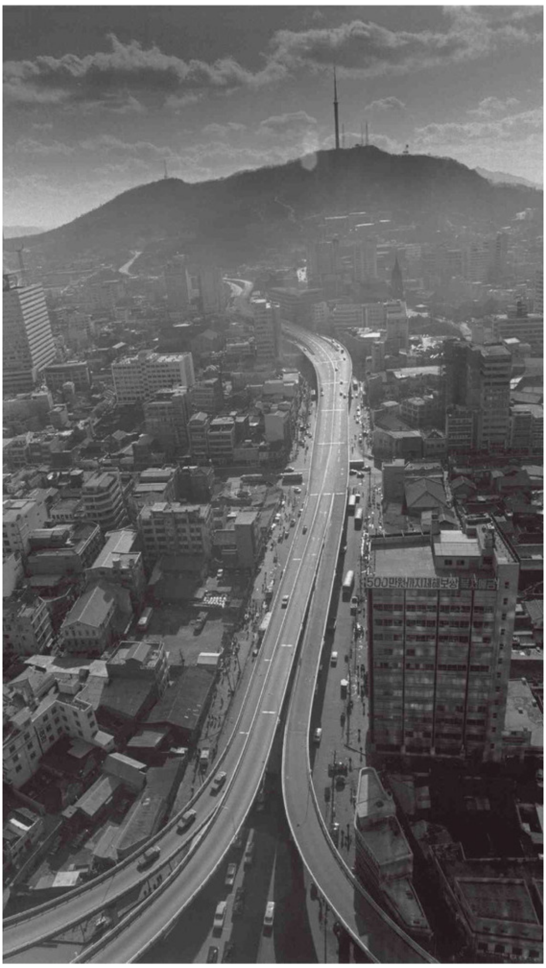
Often, when trying to replicate some biological function in a design, we find that integrating living organisms can be a more feasible option than trying to mimic the biology. This is the premise behind **green infrastructure** or **nature-based solutions** that provide important functions based on ecosystem restoration. Planting a community of interacting plants to slow and

Thick bark and stones used in Neowa (Shingle) roof close to Bukchon Hanok, Seoul
Photo: M. Eggermont, 2025

filter stormwater or capture and sequester carbon is often easier than building a filter or a carbon capture device.

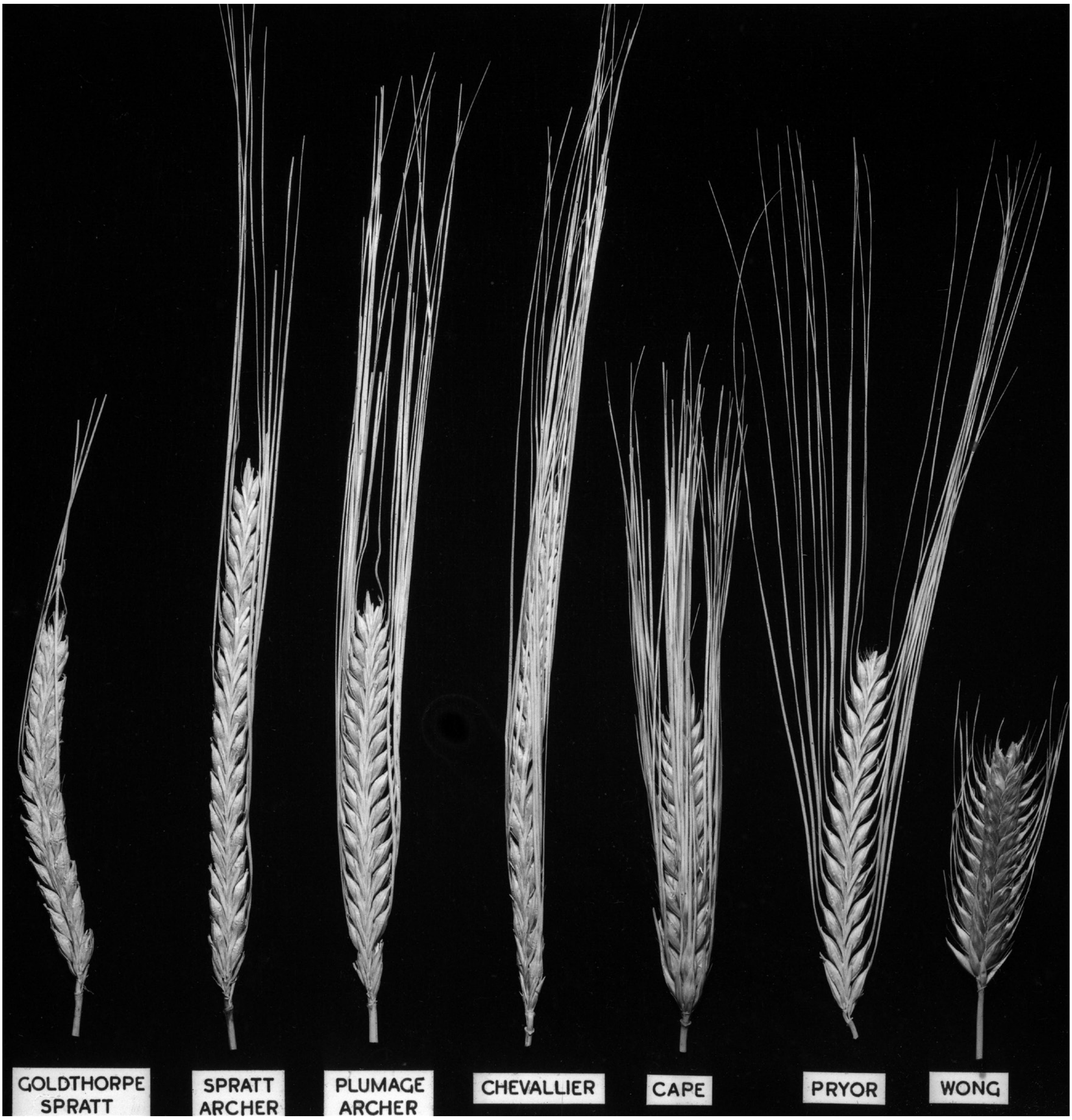
Then what about **biotechnology**? Biotechnology goes a step beyond, using biology, but in a modified way, often through manipulation of the genome (**genetic engineering**), but sometimes through the interface of the living and non-living (**bionics**, in its medical usage) or the synthesis of the living from the non-living (**synthetic biology**).

In all of these approaches, biology plays a central role in the problem-solving



Left: Elevated highway over Cheongye stream in 1972.
Image © National Museum of Korean History via Wikipedia under license KOGL Type 1.
Right: Cheonggyecheon (today), Seoul | Photo: M. Eggermont, 2025

Building with Biology
Emilie Snell-Rood



Seven varieties of barley
Photo: Ron Blackmore/Lincoln University, 1947-66 | Wikimedia Commons

process, but with variation in the history, strategy, and methodology. As a result, these diverse approaches end up scattered across disciplines, from architecture or forestry to biomedical or environmental engineering. Terms such as “bio-inspired design” and “learning from nature” [1] begin to bring these approaches together. The challenge is uniting these approaches under one umbrella, while also maintaining the expertise embodied within the individual specialties.

What we gain by converging people who problem-solve with biology in different ways

Many of the biological approaches to problem-solving have developed independently and are functioning well to tackle grand challenges in their own ways. What do we have to gain by merging them together under one umbrella, apart from a mess of confusing jargon? A central benefit is that we assemble a novel community of problem solvers who share an interest in biology. We have a lot to gain through crosstalk among fields that is facilitated by the bridge that connects us, biology.

When these diverse fields recognize that they all benefit from biology, they can better build the biology-based resources needed to advance the field. Biology is vast and complex, which means it is often expensive in terms of funds and space to house collections, living materials, microscopes, and genomic tools. Investing in biological expertise can provide benefits to a huge range of problem solvers.

Possibly the most impactful benefit of uniting bio-based approaches is that it creates a common method of looking to biology for ideas. Individual approaches, such as biomimetics, are increasingly recognizing a need to diversify the range of potential biological models they use, but this challenge is general across biological approaches to problem-solving. Most existing problem-solving motivated by diversity is driven by a fraction of the available biodiversity on earth. The field of biomimetics tends to look to vertebrates for examples, biotechnology often draws from a set of generic or lab models, and even agriculture depends on a small subset of potential agricultural varieties. We have much to gain by expanding to consider more biodiversity, especially if we are seeking to tailor solutions to new regions and specific climates. But it is challenging to survey the over two million described species on earth for ideas, not to mention the likely 10-30 million additional undescribed species (mostly small things). Fortunately, a general set of

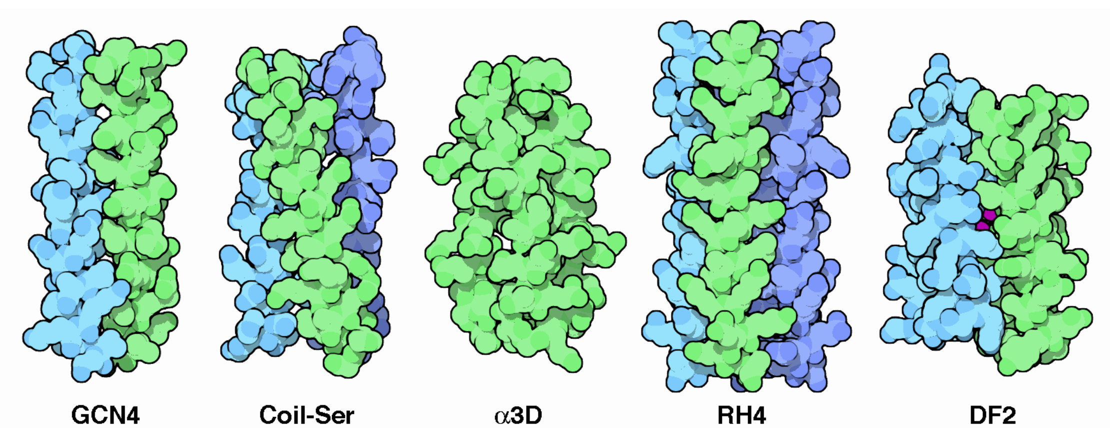
Building with Biology
Emilie Snell-Rood

methods [2] can be used to diversify the list of possible biological models one might explore for solutions, that can be applied from biomimicry to biotechnology. By uniting bio-approaches, we can better design systems of collaboration and interaction that allow problem-solvers to explore biology and biodiversity in partnership with biologists.

Moving forward with "Building with Biology"

How do we effectively unite the researchers, problem-solvers, practitioners, and educators who are interested in problem-solving with biology – what we term "Building with Biology"? We still need the specialized expertise found within the silos of these approaches, and within biology, engineering, and design, but we need a way to create bridges across these fields that are efficient and effective in a time where people have few opportunities for undirected exploration. Investing in networks and centers at individual institutes can be a powerful mechanism to link people under the umbrella of "Building with Biology". For instance, the Biodesign Institute at Arizona State University brings together over 200 researchers that use biology to design solutions.

However, such intellectual infrastructure takes time and funding to build. Smaller efforts that build networks around "Building with Biology" can still yield large benefits. Seminar series and workshops that bring together these fields can spin off new collaborations and projects [3]. Individuals can also use existing tools to



Several examples of designed proteins built from bundles of alpha helices.
Illustration: David Goodsell, RCSB Protein Data Bank and the Scripps Research Institute, 2005 | http://doi.org/10.2210/rcsb_pdb/mom_2005_10

find collaborators across fields. For example, taking a "problem-driven" or "technology pull" approach, engineers and designers can brainstorm organisms that perform similar functions [4] in the natural environment. Armed with these ideas, they can use online tools to find biologists that study those organisms either locally or potentially anywhere in the world.

Biologists can just as easily take a "solution-driven" or "biology push" approach where they first list the various things their favorite organism is particularly "good at." For instance, the butterflies I work on have creative adaptations for reflecting and absorbing light. If I were interested in developing new collaborations around those adaptations, ChatGPT can help me identify engineers or designers that work with light or optics at my institution. Indeed, the AI list is better than the database provided by my institution to find collaborators as it includes an assessment of their likelihood to partner with a biologist based on existing work.

In our recent efforts at the University of Minnesota, we have begun to develop a network of biologists, engineers, and designers interested in problem-solving with biology. Whereas we had only a modest cluster of researchers interested in biomimetics alone (20-30), we have well over 200 who are interested in uniting under the broader umbrella of "Building with Biology." At an initial gathering, it became clear that a major challenge in uniting these approaches is bringing everyone onto the same page in terms of how the diverse approaches work and where they intersect. Our next phase will be offering workshops tailored to either biologists ("what problems might your organism inform") or engineers and designers ("what models in biology might inform your problems"), coupled with more specific efforts to matchmake across fields. Aligning meetings with biological resources on campus, such as natural history collections, creates hands-on opportunities for everyone to start thinking about how biodiversity informs the problem-solving.

We are at an exciting time, at the intersection of fields, where we can benefit from the expertise within disciplines, but use technology to better bridge these fields to tackle our grand challenges through interdisciplinary collaboration. By uniting problem-solving approaches that use biology, we can more effectively harness the creativity and power of the millions of species on earth, and the people taking inspiration from these organisms, to build a more sustainable world. ×

Building with Biology
Emilie Snell-Rood

Acknowledgements
I am grateful for the intellectual interactions with Dimitri Smirnoff, William Weber, Mary Guzowski, and Prasad Boradkar that fostered the development of many of these ideas. The Institute for Advanced Study at UMN provided funding for the Building with Biology Initiative.

References
[1] Gleich, A, C Pade, U Petschow, E Pissarskoi. 2010. *Potentials and Trends in Biomimetics*. https://link.springer.com/book/10.1007/978-3-642-05246-0

[2] Snell-Rood, EC and D Smirnoff. 2025. Biology for biomimetics: II. A tutorial on how to diversify a list of biological models. *Bioinspiration & Biomimetics* ***20*** 062001 https://iopscience.iop.org/article/10.1088/1748-3190/ae0aa2

[3] Guzowski, M, W. Weber, D Handeen, E Snell-Rood, V Interrante. 2025. A Bio-Inspired Approach to Critical Thinking: Integrating Daylighting with a Bio-Inspired Design Process https://design.umn.edu/sites/design.umn.edu/files/2025-05/Mary%20Guzowski%20_%20A%20Bio-Inspired%20Approach%20to%20Critical%20Thinking.pdf

[4] Snell-Rood, EC and D Smirnoff. 2023. Biology for biomimetics I: function as an interdisciplinary bridge in bio-inspired design. *Bioinspiration & Biomimetics* ***18*** 052001 https://iopscience.iop.org/article/10.1088/1748-3190/ace5fb

Professor Emilie Snell-Rood (Department of Ecology, Evolution and Behavior, University of Minnesota) is interested in how organisms respond to anthropogenic environments, and implications for preserving biodiversity. She loves butterflies, bugs in general, birds, plants, pretty much all things biology. In her spare time, she enjoys gardening, running, and spending time with family.

Black and Orange Butterfly (monarch) on White Petal Flower | Photo: Pok Rie | Pexels cc

Arctium minus (Little burdock)
Photo: Douglas Goldman, 2018 | Wikimedia Commons

Article

Turning Bio-Inspired Ideas Into Patents

Brook Kennedy with Anna Bieri

Turning Bio-Inspired Ideas Into Patents

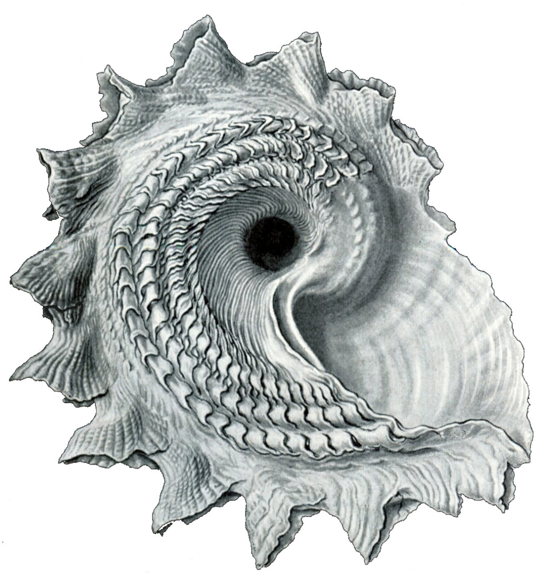
Brook Kennedy with Anna Bieri

In 2025, I was inducted as a Senior Member in the National Academy of Inventors for having authored over 20 patents. In spite of this recognition, I have never benefited commercially from any of my patents. The main reason is that I always invented things in the context of my work, both in industry and in academia. Talking with my students at Virginia Tech about patents, I realized that they frequently hold three major misconceptions:

- "All you need is an idea to be granted a patent"
- Patents alone will protect your invention
- Patents will make you rich.

My most recent patent is US patent 12325208 *Corrugated three dimensional (3D) additive manufacturing*[1] which was inspired by observations of Virginia coast clamshells using a Macronaut, a macro lens that I developed for smartphones (https://zqjournal.org/pdfs/ZQ_issue_19.pdf#page=36). I noticed that many shells had corrugated, interlocking structural layers (right image below). It struck me that clams build shells a layer at a time over years, much like the process of 3D printing, and particularly like fused filament fabrication or Fused Deposition Modelling (FDM®). Could a "clam shell" model help reduce the tendency of layers in a 3D print to shear along the line of layering, especially in a thin wall?

Working with students in computer science and industrial design, we developed

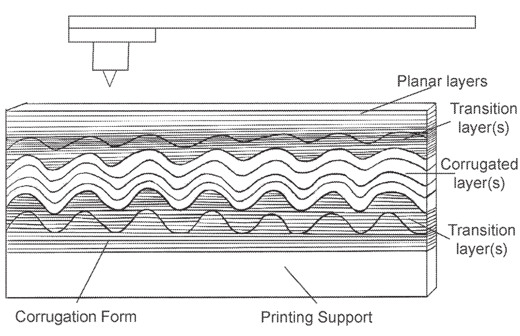


Left: *Astraea heliotropium* | Drawing: Ernst Haeckel, 1904
Right: A close-up photograph of corrugated layering in a clam shell. | Photo courtesy of B. Kennedy

software for 3D printers that allowed us to print ordinary objects using this corrugation method, in one and two dimensions. As expected, the objects were less prone to shearing. However, they were also stiffer overall – something we had not predicted. By simply trying to break the objects by hand (compared to objects made with conventional parallel layers), we sensed that we may have discovered something useful.

Following university protocols, I contacted Virginia Tech's Technology Licensing Office which helps translate research discoveries into commercially viable products. An important first step of this process was to conduct what is called a "prior art search", in which we thoroughly searched for existing public references (publications or patents) that were already out there and similar to our own discovery. To make a long story short, our work seemed sufficiently novel to explore the filing of a patent application. Working with a law firm that specializes in patent law, we drafted a detailed description of the invention and initial claims. The second important step was to understand who might ultimately benefit from our novel 3D printing process. We identified a few companies which develop the specialized 3D printing software that takes a 3D CAD model and "slices" it into printable layers. We also identified 3D printer manufacturers, including those who manufacture large industrial robots that can 3D print houses, such as ABB and Kuka.

In order for an invention to be patentable, it must be "novel, non-obvious and useful."[2] Importantly though, it is not sufficient to simply have a new "idea." Instead, the idea must be translated or "reduced" from thought into a concrete or applied embodiment (such as software or a mechanism) that works or can be used. This is referred to as "reduction to practice," and can be achieved by developing a prototype that demonstrates usefulness and



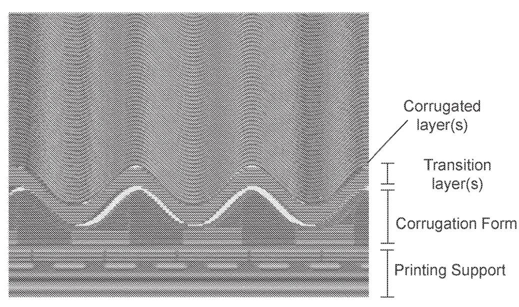


Figure 1 shows a section of an embodiment of a 3D object being one or more corrugated layers. Adapted from US Patent 12,325,2081[1] | Figure 2 shows another view of a section of an embodiment of a 3D object having one or more corrugated layers. Adapted from US Patent 12,325,2081.[1]

feasibility, or through a detailed description that someone having “ordinary skill in the art” can follow (figures 1 and 2). I had earlier patented a mop design with a pivot joint in the center of the handle, helping the user clean under furniture without bending over. The idea of an articulated joint is not itself patentable, only the details of how to implement this particular joint. It took de Mestral thirteen years from his observation of the burdock seed’s attachment principles to developing a viable method of creating the “hook and loop” fastener (figure 3) that was granted a Swiss patent in 1954 and a US patent[3] a year later, with an updated patent[4] in 1961.

Patents include specific claims. A claim “defines the boundaries of an invention, and therefore lays down what the patent does and does not cover.”[5] Claims are difficult to write well. Aside from their technical language, they must protect the invention without exceeding what the invention does or infringing on claims of existing patents.

As universities commonly do in such an instance, we first filed a *provisional patent application*, a quick and relatively inexpensive process that started the patenting process and gave us a year to figure out whether or not to pursue international protection for our invention. We ended up only filing a US patent application, mainly due to cost constraints. During the patenting process, it turned out that another inventor had filed a patent application a few months earlier for a similar use of corrugations, but in their case to make edges of parts look smoother. We spent about four years negotiating with the patent examiner at the US Patent and Trademark Office (USPTO), removing and rewriting claims until the examiner was satisfied that the description of our invention did not intrude on the “territory” of this other invention. Some of our “prior art” search results became “citations” in our patent publication.

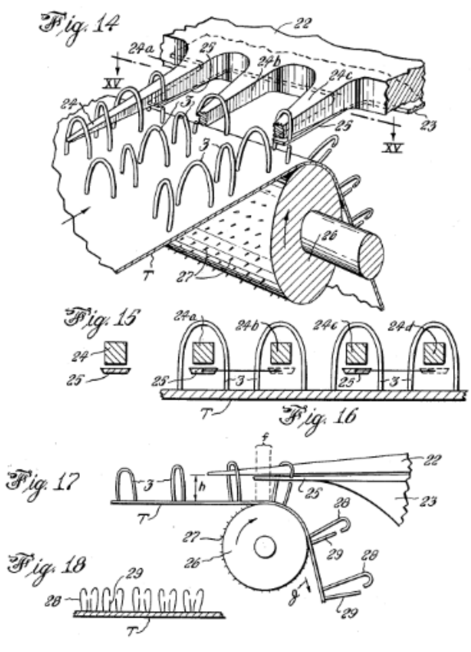
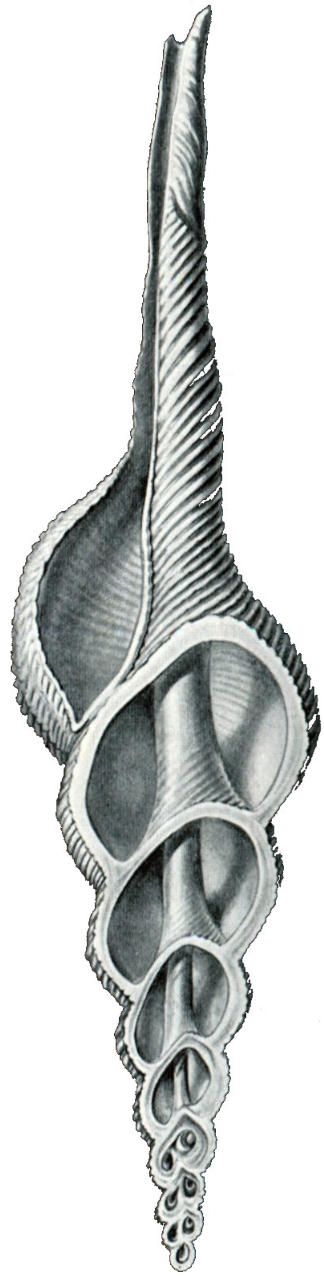


Figure 3 Cutting device and how it operates for forming hooks.
Adapted from US Patent 3,009,235[4]

The patent itself was granted on June 10, 2025 and assigned to Virginia Tech, eight years after we initiated the process.

If a company commercializes goods that infringe on my patent, Virginia Tech would have the legal grounds to send not only a formal "cease and desist" letter but – if unsuccessful – to take further legal action. It is not uncommon for competing companies to design around or redesign their inventions in order to avoid infringement of an existing patent. Similarly, if such a competitor files a patent application, they will have to ensure that the claims will be sufficiently different to pass the examination by the USPTO. Sometimes companies knowingly infringe on a patent with the expectation that its owner does not have the means to pursue the infringement legally.

Virginia Tech owns and licenses some patents that have been very useful and commercially successful, such as Dr. Carl Griffey's barley and wheat varieties that deliver high yield and pest resistance, bringing millions in royalties to Virginia Tech. But many patents never become commercially viable, and many universities – including Virginia Tech – are often insufficiently resourced to market their intellectual property. So far, no companies have approached Virginia Tech to licence my invention. Nevertheless, the patent has been cited by



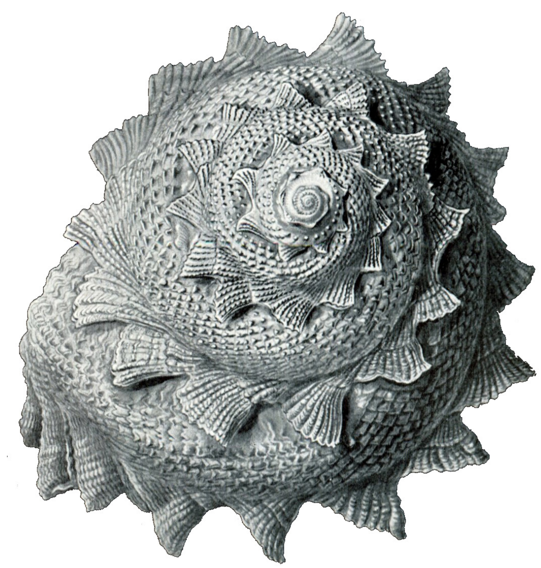
Fusinus colus
Drawing: Ernst Haeckel, 1904

Turning Bio-Inspired Ideas Into Patents
Brook Kennedy with Anna Bieri

Markforged Inc., a metal 3D printer manufacturer, and L'Oréal, the French personal care multinational. Similar to an academic citation, the citation of patents suggest that other researchers and inventors are working in fields closely related to my invention – it is indication that they are aware of the patent but believe that their work does not infringe or the area of application is different.

Patents do not provide a force field protecting your invention until the patent expires. They can be useful for raising seed funding for entrepreneurial ventures by providing credibility – at least the USPTO thinks your invention is unique and valuable. An alternative approach is to just keep producing the next useful invention to stay ahead of the competition.

What part does nature play in the inventive process? The original idea that led to our corrugated layering patent was inspired from clam shells. Often observation and exploration of nature underlie scientific and technological advancement. NASA developed their Technology Readiness Level[6] (TRL) scale in the 1970s to help assess the maturity of technology development, with nine steps from basic research to real-world deployment. Ideas are at TRL 1



Left: Corlayer vase | Photo courtesy of B. Kennedy
Right: *Astraea heliotropium* | Drawing: Ernst Haeckel, 1904, Wikimedia Commons

("Basic principles observed and reported"), while completing the "reduction to practice" phase of the patent process will attain at least TRL 4 ("Component and/or breadboard validation in laboratory environment"). That still leaves five more levels to climb before reaching TRL 9 and becoming a commercially viable innovation.

In spite of the challenges, some bio-inspired patents have been very successful. In 1957, VELCRO® was first manufactured in the USA and took off in 1961 when it was incorporated into the NASA Apollo program. Even though the patent expired in 1978, continued innovation allowed the market size for VELCRO® to grow to about US$1.4 billion in 2025.[7] ×

1. https://patents.google.com/patent/US12325208B2/en
2. https://carsonpatents.com/what-is-reduction-to-practice/
3. https://patents.google.com/patent/US2717437A/
4. https://patents.google.com/patent/US3009235A/
5. https://www.law.cornell.edu/wex/patent_claim
6. https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/
7. https://www.cognitivemarketresearch.com/velcro-market-report

Brook Kennedy is a multi-disciplinary designer and inventor with 24 patents. He also serves as a Professor of Industrial Design at the College of Architecture, Arts and Design at Virginia Tech.

Dr. Anna Marion Bieri is an IP lawyer and researcher. She is the author of *Patents and Professors*, published by Mohr Siebeck.

Gephyrocapsa oceanica
Photo: NEON ja, coloured by Richard Bartz 2007 | Wikimedia Commons

Book review

Biomimicry in Architecture by Michael Pawlyn

Book review

ZQ community review

Reviewed by Hope Ameh, Thomas Boyster, Denise DeLuca, Cornel Schoombee, Janet Stewart, and Emma Winter

The reviewers describe Michael Pawlyn's third edition of *Biomimicry in Architecture* as a well-structured and content-rich book, highlighting its logical flow, diverse content, and compelling message. Several reviewers mentioned the book's thoughtful reorganisation in its third edition, with revisions improving the flow and accessibility of the material which now mirrors the architectural design process.

Chapter 1 provides the context for the book's wider approach to biomimicry by starting with the fundamental question "What is a system?" and covering topics from nutrient flows and Gaia theory to bioregionalism and the history of sewage.

Chapter 2 through 7 cover specific biomimetic applications: materials, structures, water, thermal control, light and colour, and power. One reviewer noted that while these topics might be familiar to readers of previous editions, they are updated with new thinking, science, and examples. Another reviewer described these chapters as seven "design lenses" with implications far beyond architecture, impacting sectors like agriculture, manufacturing, urban planning, and national energy policy.

Chapter 8 “Synthesis": invites readers to reflect on what they have learned and consider the future. It explores how AI, the legal system, and economics can advance biomimicry and pushes for a "bioinclusive culture".

At the end of nearly every section, Pawlyn challenges the reader to consider how the principles discussed can be applied to the built environment and empower readers to participate in the regenerative movement. The book contains valuable supplementary material, including a practice guide for architects, a glossary, extensive notes and references, and a detailed index.

Pawlyn distills complex scientific concepts from biology, chemistry, and physics into engaging explanations without oversimplifying them. He includes a wide array of pictures, diagrams, and real-world case studies. These examples, many of which are new to this edition, illustrate that the ideas are not just speculative concepts but are being actively developed and built, including Grimshaw’s ‘Eden Project’, Oxman’s ‘Aguahoja’ pavilion, and Marks Barfield Architects’ ‘Cambridge Central Mosque’.

Roof of the Tropical Biome at the Eden Project, near St Austell in Cornwall. | Photo: FotoFree, 2024 | Wikimedia Commons

Book review
ZQ community review

Pawlyn incorporates the work of social and environmental philosophers, systems thinkers, and political activists alongside technical experts to frame biomimicry within a broader cultural, legal, and political context and to explore what might yet be. The design lessons have implications far beyond architecture, impacting sectors like agriculture, manufacturing, and national energy policy.

The book is a transformative guide urging an epochal shift toward a bio-inclusive and regenerative design philosophy, moving beyond simple imitation of nature's forms to emulating its underlying processes and systems. The reviewers liked the book's clarity, optimism, real-world case studies, and its call to action for architects and all citizens to think critically about how the built environment can work in synergy with nature.

Hope Ameh: The User Experience and Pedagogical Value

"I observed that the typical format across the book chapters was that the ending paragraph of most sections presented a call to the reader (and by extension, to the built environment) to think of how the message learnt in that section could be translated into design for the built environment. The reader is once again faced with a challenge to think more critically about how nature can be emulated in the design of the built environment."

"There is also a good balance between facts and figures with humour. Some examples include: 'Currently, these experiments are at a relatively small scale (by architectural standards that is – an abalone would take the opposite view)' (pg. 38). .. infusing humour into the book communicates the thoughtfulness of the writer, and his desire to set the reader 'at ease'."

"Clear and concise explanations of key terms are provided ... The book contains a wide array of pictures and diagrams, which makes it easy for visual learners to connect with the chapters."

Thomas Boyster: Architectural Process and Holarchic Structure

"The broadening of the scope of analysis early in a typical architectural process, a phase called predesign, foregrounds the importance of designing as nature as early as possible. Consideration of constraints and potentially malleable context in early space programming enables optimal scoping as a design progresses toward greater specificity, crystallizing from pluripotent origins into a built form which synthesizes the whole in a local context."

“Now beginning with reflections on ethos, the new edition then nests each subsequent section in the context of the broader prior chapter. ... An initial focus on ecosystems and lifecycles opens the conversation to a broader audience. From this foundation, the sequence of subject matters better mirrors the architectural design process.”

“In addition to providing useful parallels to the design process, the integration of topics into a holarchic structure brings the many updated examples together in a mutually reinforcing fashion to communicate the growing progress of the larger regenerative movement. Pawlyn identifies deep roots with historical examples ... [and] contemporary examples showcase greater specificity in their emulations and broader integration of natural design strategies ...”

“Pawlyn could further explicate what frameworks and workflows generate the more pervasively biomimetic projects, such as Exploration Architecture’s ‘Biomimetic Office Building.’ Asking the provocative question ‘how does nature design’ suggests a deeper evolution of the architectural design process itself, which might unlock integral emulation in every aspect of our built environment. While the practice guide to architects appended to the text gestures in this direction, further detail would greatly benefit those architects looking to transform their practice into a biomimetic one.”

Denise DeLuca: The Personal and Philosophical Impact on Practitioners

“When I walk in the woods, I’m often wonderfully overcome with a feeling that things are right and life is good. It is that profound and optimistic, yet practical, feeling that overcame me numerous times as I read the 3rd edition of Michael Pawlyn’s Biomimicry in Architecture.”

“He introduces even the most seasoned biomimicry teachers and practitioners to a slew of new terms, encouraging us to challenge our assumptions, to widen the scope of our thinking, to go beyond asking ‘What would Nature do?’ and ask, ‘What does Nature want us to desire?’”

“From start to finish, it was a joy to hear Pawlyn's voice again.... the welcoming way he makes technical concepts accessible, gently teaching (or reminding) us of the differences between biomorphism and biomimicry, robust and resilient, stiffness and toughness, struts and ties. And more than once he guides us away from the temptation to blindly follow (and repeat) biomimicry lore, by pointing out commonly held misconceptions (including some of my own), explaining what was misguided, and

Cambridge Central Mosque portico in May 2019 | Photo: cmglee, 2019 | Wikimedia Commons suggesting what might have been done better."

"Chapter 1, Aligning with ecosystems, is entirely new — and needed to give us the context for understanding the deeper and wider approach to biomimicry Pawlyn forwards in this edition. As always, he starts at the beginning, in this case by answering the question, What is a system? From there he takes us through nutrient and energy flows, evolution and panarchy, Gaia theory and waste, biosynergy and bioregionalism."

Cornel Schoombee: Simplicity, Dichotomy, and Scale

"A thread that runs through the book is the comparison of 'how humans currently do things' versus 'how nature has done things for millennia'. It's as if the verb 'BUILD' is considered firstly in terms of our human methods of constructing, and then expanded to include the innumerable natural systems, processes, and structures that occur at both micro and macro scales."

"... a picture is painted where humans (and all our very human activities) and the natural world can co-exist in a symbiotic relationship - a bio-inclusive scenario."

"This is a book that informs, excites, and urges every reader to re-examine their world through a new lens of possibilities."

Janet Stewart: Transdisciplinary Application and Actionable Critique

"The 3rd edition builds on that solid base, pushing toward deeper philosophy, more actionable frameworks, more diverse voices, repair/failure stories, more measurement. That makes it even more of a roadmap - not just of 'let's imagine better,' but 'here's how to do better, where, and with whom.'"

"... no single breakthrough will pivot us from environmental disaster. Instead, the path forward is an accumulation of myriad small, locally adapted solutions, woven together in cooperation — just as ecosystems do."

"... a subsequent edition or digital link could offer 'Voices from the field'... Failures & lessons ... Joint policy/design/makers toolkits ... Longitudinal data & performance measurement ... Global diversity ... Emerging technologies that are small-scale and accessible ... Emerging policies on nature's rights."

Emma Winter: Generational Urgency and Critical Reflection on Time

"The 'dualistic separation' between nature and humanity is heavily explored, and how the exclusive mindset is the catalyst for environmental catastrophe is a main theme. It has shaped how we have fabricated our built world, and Pawlyn asks what architecture, with an introspective approach, would look like. He cites the necessity of transdisciplinary work with an evidence-based approach and working alongside the existing economic system to see architecture truly change."

"When discussing how rising temperatures and declining rainfall in tropical sectors will disproportionately affect those communities, he notes that though they have contributed the least to climate change, they are '...among those who will suffer the most from its consequences' (Pawlyn 96)."

"... I noticed that the role time plays has received little attention, which left me reflecting on its importance in shaping change. Whether intentional or not, the response to how we create that necessary epochal shift seems to be '...when enough people decide this is the future they want' with no further deliberation (Pawlyn, 176). ... It suggests that the only way to fix the problem is to let it fester–that the only way to create urgency is to let it become dire. There is no examination of the reality that if we wait for more disparity, for opinions to force change, that it may already be too late." ×

Please also see Michael Pawlyn's talk:
https://www.youtube.com/watch?v=HQR7XZaG2UU

Aguahoja Pavilion, 2018. Cellulose, chitosan, glycerin, acetic acid, polymers and steel base. MIT gift. SFMOMA
Photo: Rob Cordor, 2022 | Flickr cc

Book review
ZQ community review

Hope Ameh is an architectural researcher and biomimicry-driven innovator specialising in integrating nature-inspired design with digital tools to develop climate-adaptive architectural solutions. Using a research-based framework, she abstracts the processes of organisms — such as the resilience of mangroves, the efficiency of the honeycomb or the durability of pitcher plants — and translates them into climate-adaptive design strategies. ORCID profile, LinkedIn profile

Thomas Boyster is a Living Future accredited licensed architect practicing at Wheeler Kearns Architects in Chicago with a master's degree in biomimicry. With experience on projects as diverse as greenhouse dining on an organic farm to a cheese-food factory adaptively reused as a contemporary art museum to wayfinding elements for a forest preserve to single family residences informed by embodied and operational energy, he seeks a holistic integration of biomimicry in architecture as a praxis mundi, regenerating the built environment outwards from built work toward realignment with nature. Other explorations can be found at beWilderWorld.com.

Denise DeLuca is a licensed civil engineer (PE) and holds a master's degree in civil and environmental engineering with a focus on modeling landscape-scale surface and groundwater interactions. As the co-founder of Biomimicry for Creative Innovation and founder of Wild Hazel, she has spent over 30 years studying Nature's innovative systems and strategies and helping others translate them into sustainable designs for buildings and businesses, products and policies. LinkedIn profile

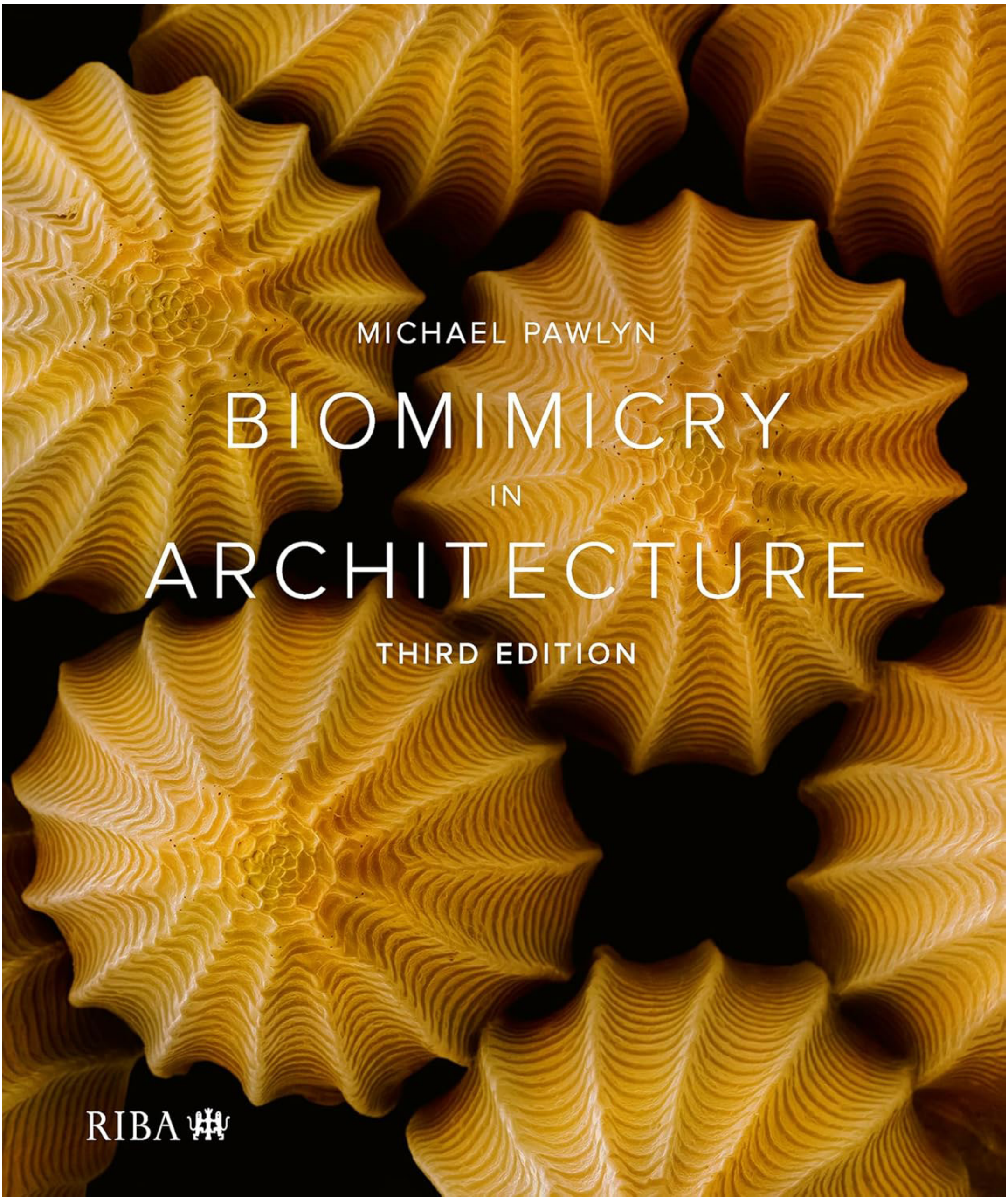
Cornel Schoombee is a registered professional architect based in Pretoria, South Africa. During the first 10 years of his career, he has come to believe that architecture can influence our communities and the natural world in ways that few other professions can. As a young practitioner in the built environment, he is excited to explore how biomimicry can transform the industry - ultimately, how we can learn to create (materials, structures, processes, systems) by emulating the strategies found in the natural world. LinkedIn Profile

Book review

ZQ community review

Janet Stewart is a Toronto-based designer whose 30-year career has spanned every architectural sector - from automotive to animal welfare, housing to healthcare, and hospitality to heritage restoration. A LEED Accredited Professional since 2005, she has navigated architecture's evolution from "energy-efficient" to Net-Zero and Carbon-neutral. Deeply aligned with Michael Pawlyn's view that nature is the best designer, she champions Regenerative Adaptive Re-use as the next frontier. [LinkedIn profile]

Emma Winter is a current student at UC Berkeley, fascinated by the interlinking of art, biomimicry, and new solutions for the future. She is inspired by artists who rethink the relationship between science and creativity, embracing the importance of diverse, multidisciplinary perspectives. She received third place in the Biomimicry Institute's Youth Design Challenge for a water conservation project mirroring vein structures found in plants.


MICHAEL PAWLYN
BIOMIMICRY
IN
ARCHITECTURE
THIRD EDITION
RIBA

ISSN 1927-8314