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Buckminster Fuller at Black Mountain College | Photo: State Archives of North Carolina Raleigh, NC, 1949 | Flickr cc

Editorial

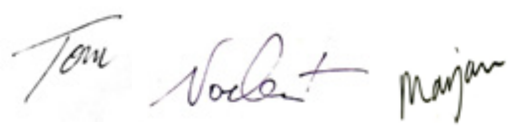
If there is one word that unites the features in this issue of *Zygote Quarterly*, it is “framing”. In our case study, we relate how Don Ingber of the Wyss Institute at Harvard developed his tensegrity theory of cell structural framing. David S. Goodsell, scientist and artist, returns to our pages with more fascinating images of the framework of proteins and viruses.

Photographer Myoung Ho Lee reveals the essential structure of trees by framing them in place with a white background, while physicist Annick Bay describes her work in improving light emitting structures by the use of patterned surfaces learned from the firefly.

Jamie Miller and Michael Helms in their opinion pieces on bio-inspired design write of conceptual frameworks, the former of the need to change viewpoints in order to solve problems more effectively, the latter the need to distinguish the types of bio-inspired design in order to collaborate more effectively. Colleen Unsworth et al. review the current state of development of ontologies in service of better nature-based design: frameworks that blend relational factors to complex databases.

Finally, our Heidi Fischer visits the geographical source of Darwin’s inspiration for his theory of natural selection, one of the most disruptive ideas of our civilization and one that has forever changed the frame in which we view nature.

Please help us better understand what content you like by completing the reader survey at the end of every article. Clicking on the thumbs up/thumbs down symbols takes you to a one-question web survey. Happy reading! ×



Tom McKeag, Norbert Hoeller and Marjan Eggermont

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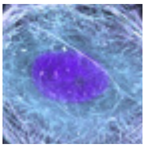
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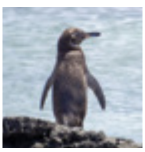
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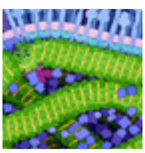
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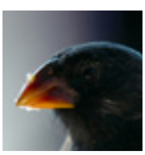
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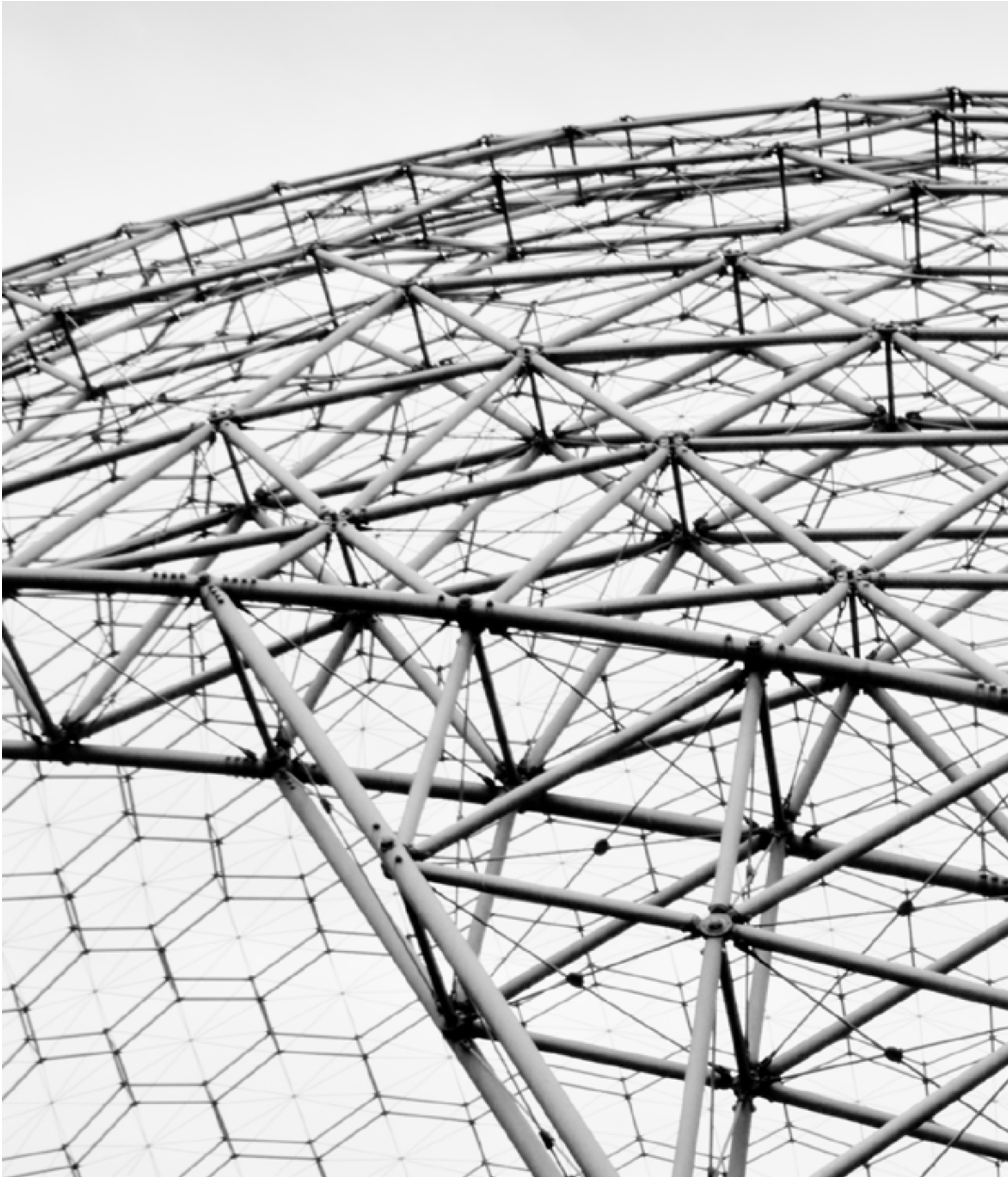
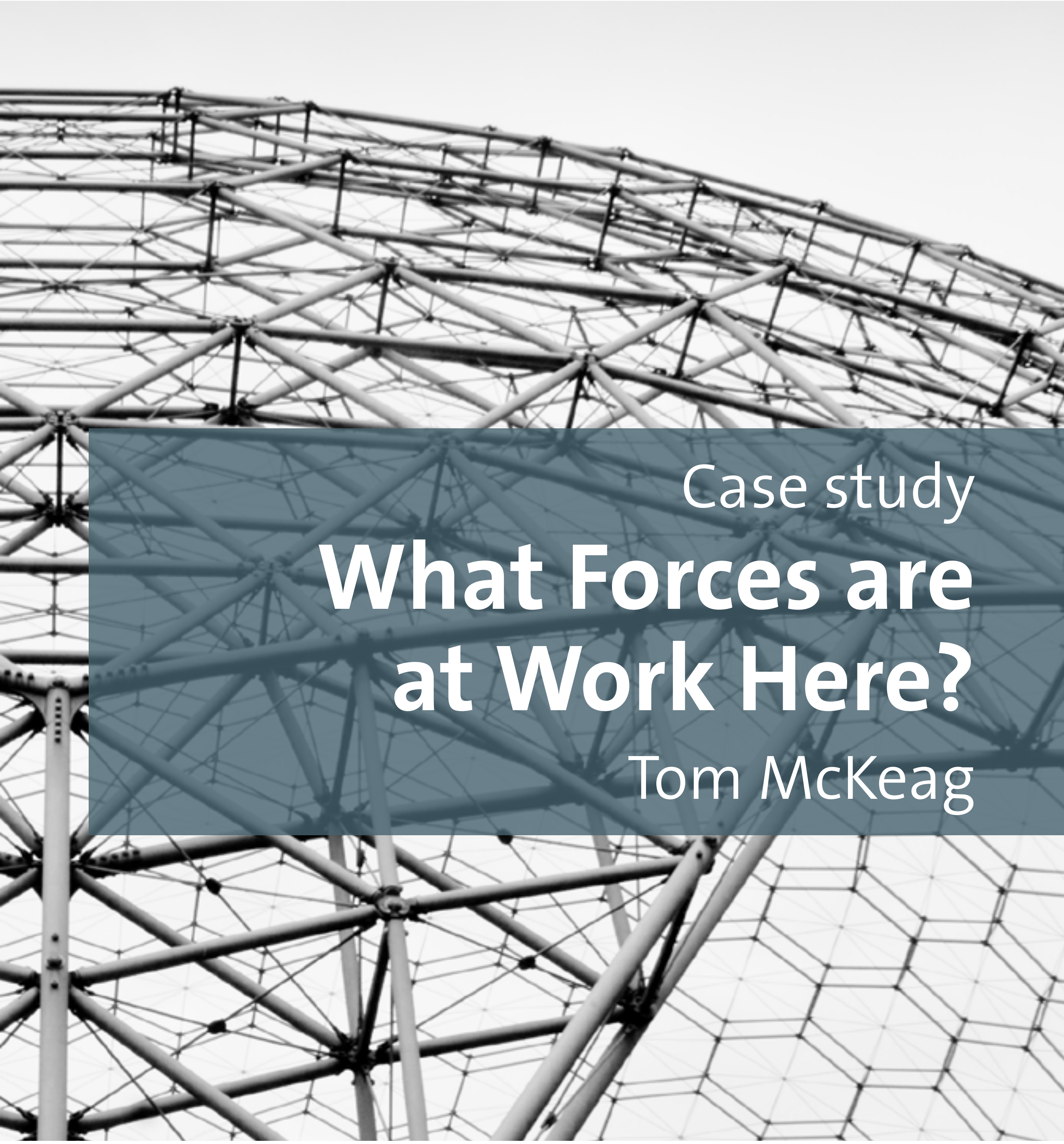


Alaska (Twenty) | ASM Geodesic Dome designed by Thomas C. Howard of Synergetics, Inc in Raleigh, NC
Photo: Green Dawn, 2009 | Flickr cc



Case study

What Forces are at Work Here?

Tom McKeag

What Forces are at Work Here?
Don Ingber and the Theory of Cell Tensegrity

Interdisciplinary Innovation

Bio-inspired Design is interdisciplinary by nature and its pursuit requires a model of shared expertise, collaboration and integration. Biological phenomena cannot be explained without at least a foundational understanding of chemistry and physics, and cannot be measured and analyzed without disciplines like mathematics and genetics. Moreover, applied disciplines associated with individual challenges, from engineering to the social sciences, can add critical insights that rebound to inform later basic, scientific research. This is important; design practitioners, as well as scientists, necessarily need universal models from which to predict, plan and act. These need to be reviewed, debated and refined concurrently with the latest research results and with the widest range of participants.

One well-documented example of this kind of professional cross-pollination has led to a disruptive theory for the mechanical structure of the foundational unit of biology, the cell. This is a tale of BID in reverse, however. In this case, a model from the built world informed a theory of the natural.

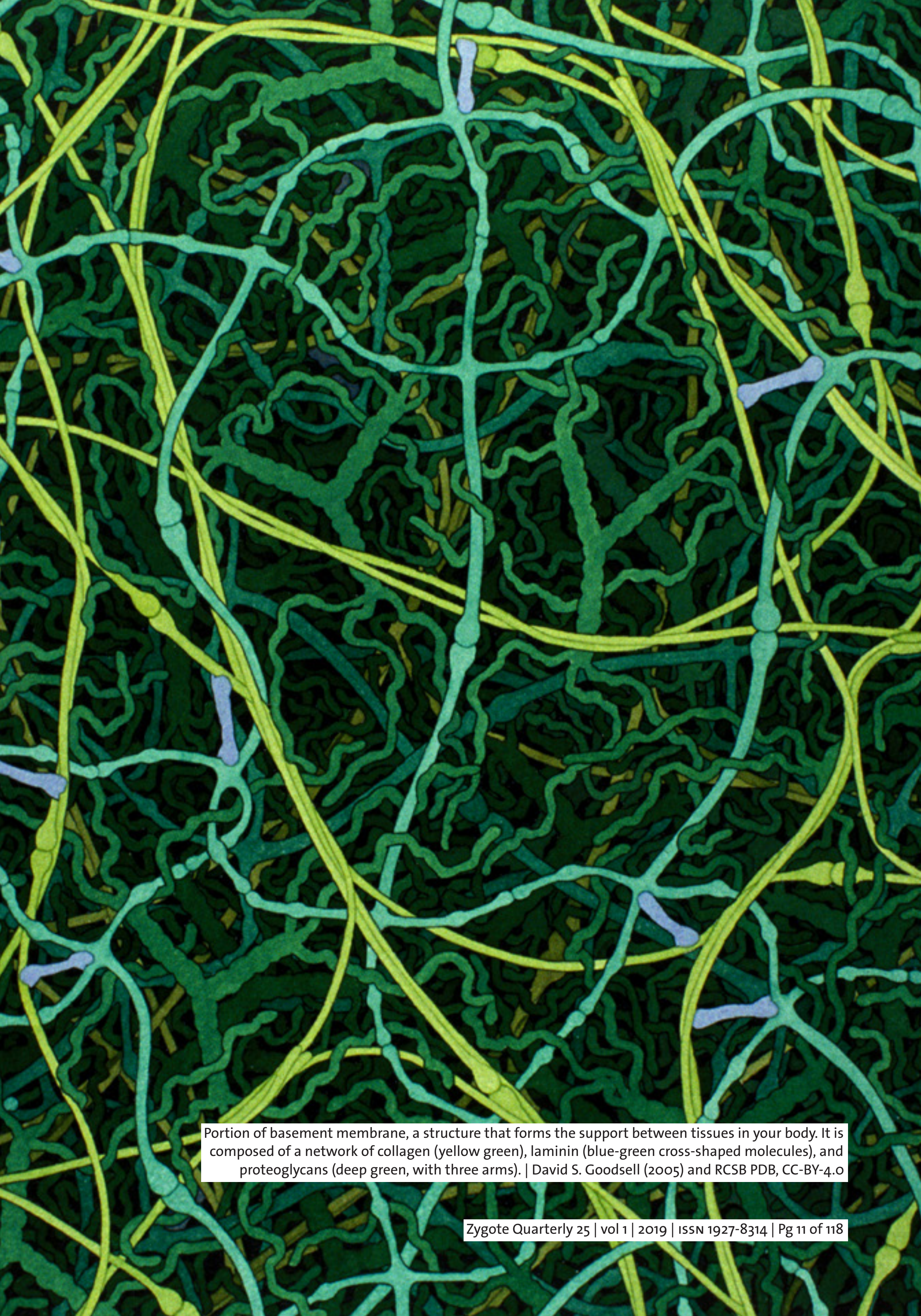
Its acceptance, and the field and organizations that have blossomed from it, have created a feedback loop where discoveries about the nature of the human body at the cellular scale prompted by this paradigm have informed the built world of biomedical engineering.

An Unlikely Source for a Biology Concept

The scanned copy of mechanical type now looks somehow quirky and quaint in the imprecision of the letters of a 1985 paper entitled “Cells as Tensegrity Structures: Architectural Regulation of Histodifferentiation by Physical forces Transduced over Basement Membrane”. It is a physical artifact in a 30-year trail of scientific discovery and debate that has changed the way the world looks at cells and how and why they behave the way they do.

The paper was written by Donald E. Ingber and James D. Jamieson, both from Yale School of Medicine. Ingber was newly ensconced at the Department of Surgery, Children’s Hospital of Brigham and Women’s Hospital in Boston. The paper offered a new perspective for a central theme in biology: How do cells and tissues organize themselves?

Cell differentiation (how cells become specialized in attributes and function);



Portion of basement membrane, a structure that forms the support between tissues in your body. It is composed of a network of collagen (yellow green), laminin (blue-green cross-shaped molecules), and proteoglycans (deep green, with three arms). | David S. Goodsell (2005) and RCSB PDB, CC-BY-4.0

What Forces are at Work Here?
Tom McKeag

morphogenesis (how cells align for the development of shape); and cell growth are three main concerns in evolutionary development, sometimes referred to as evo-devo. As ontogeny (development of an organism) is reminiscent of phylogeny (evolution of a species), these are also key questions within anatomy and physiology. Ingber had been keenly observing embryos and was unsatisfied with the current explanations for the speedy and miraculous embryonic transformations from a single cell he was observing in the lab.

Ingber and Jamieson stated that the current models for cell activity, molecular genetics, molecular messengers and chemical gradients, were inadequate to explain what they were observing in the lab and what was clearly documented, but unexplained, in the literature. Scientists had perhaps been overlooking work from the past that gave more weight to mechanical forces in pattern formation, as well as the role of shape in functional performance and the relationships between and amongst cells and tissues within a system.

"We would like to propose that these physical forces may be informative in nature serving as regulators of gene expression, cell growth, and histodifferentiation through their modulation of cell shape" (1).

Moreover, the authors offered a higher-level explanatory framework for the pattern-forming physical forces: tensegrity. Tensegrity was a concept initially demonstrated in 1948, not by a scientist or an engineer, but by an artist, the sculptor Kenneth Snelson. Snelson's insight was quickly adopted and championed by the famous architect/author R. Buckminster Fuller, circa 1961, who coined the phrase (a conflation of "tensional integrity") and defined the term. Tensegrity structures are those that are stable from the combined effects of continuous tension on their elements, rather than compression. Tension is the physical force one feels at the end of a leash on a straining dog; compression is the force one uses to squash a bag into a garbage can.

In Snelson's elegant structures, a combination of rods and cables create a balance of stiff elements that resist compression locally, and flexible elements that are tuned tightly in tension. As Ingber has written, however, these stable structures do not have to contain rigid elements, but merely two types that differ in the degrees of their elasticity or ability to regain their shapes after being under a tension or compression load.

The architect Fuller went on to explore the building principles of this phenomenon,

Needle Tower II - Kenneth Snelson (1969) | Kröller-Müller Museum | Photo: Marco Derksen, 2013 | Flickr cc and developed his system of geodesics, or minimal pathways to constrain movement; the fundamentals of turning a mechanism (parts that move) into a stable structure (parts that do not). This concept is quickly demonstrated at any scale of "stick" building: a square of joined sticks is not stable and "racks" (revealing it as a mechanism) until an additional diagonal cross piece is added, thus creating two stable triangles (now stabilized into a structure). Fuller developed his most formal definition of tensegrity in his book *Synergetics*.

"Tensegrity describes a structural-relationship principle in which structural shape is guaranteed by the finitely closed, comprehensively continuous, tensional behaviors of the system and not by the discontinuous and exclusively local compressional member behaviors" (2).

The human body structure has often been held as a tensegrity model, with bones comprising the rigid struts, and muscle and sinew the tensioning cables. Fuller's geodesic domes and tetrahedral space frames are also examples ("Bucky, geodesics, and biomimicry" by Jay Baldwin: https://zqjournal.org/editions/zq02.html p. 36). It was at the cellular scale, however, that this concept was most intriguing to Ingber.

The "Aha!" Moment

In 1975 Donald Ingber was a 19-year old molecular biophysics and biochemistry student at Yale with an interest in art. One day in sculpture class, he and his classmates were given sets of wooden dowels and fishing line and told to make some objects according to a simple rule: none of the stiff dowels within their sculptures could touch each other. One of the students knew of the work of Kenneth Snelson and Buckminster Fuller and clued his fellows into how they could make a wide variety of tensegrity models.

Ingber had just been working in the lab culturing cancer cells and in the course of his work had observed how easily the cells changed shape from flat to round depending on their surroundings while still maintaining their overall integrity. He remarked on this to his supervisor and told him they were exhibiting tensegrity. After explaining the source of his insight he was told never to mention it again. Undeterred, Ingber went on to write his thesis on the topic. For this thesis he built many models to test and illustrate his ideas.

The Prevailing Paradigm

A quick review of the human cell is in order here, with first a reminder that not all cells are created equal. Eukaryotic cells, those of plants, animals, fungi and unicellular organisms, have membrane enclosed organelles (including a nucleus) and perform more complicated functions than the prokaryotic cells of bacteria. Within the eukaryotic cell are the following parts: outer membrane, nucleus, and various organelles (endoplasmic reticulum, Golgi apparatus, lysosomes, mitochondria, and secretory granules) suspended within the gel-like cytoplasm. Also, within this cytoplasm are microfilaments and microtubules which have been less studied and understood.

The prevailing paradigm for cell structure in the late 1980s and early 90s could be summarized metaphorically as a 'tensed balloon filled with molasses or jello' (3) The nucleus, cell membrane and organelles were where all the important activities occurred, and the cytoplasm in between was seen by many as so much homogenous liquid space.

Most science and engineering researchers had posited that the dense

Monadnock Tensegrity
Photo: Andrew Scott, 2017 | Flickr cc

sub-membrane cortical network of filaments in a cell took the full load of externally applied stresses to the cell and did so equally along the entire periphery (4).

The cytoplasm of a cell has been demonstrated, however, to be neither homogenous nor secondary in functional performance. Within it is an intricate structure network forming a cytoskeleton with important jobs to perform. Microtubules, and microfilaments serve as both internal structure for cell integrity and pathways for organelle and enzyme transfer for biochemical reactions. These are not static structures and respond to external stresses by initiating corrective chemical processes.

Additionally, much of post-war molecular biology education had been dominated by the study of chemistry and Ingber thought it was curious that shapes and physical forces were not given more attention. The function of these three-dimensional molecular objects had been clearly demonstrated to be partially determined by shape. At the cellular and molecular level, he believed that mechanical forces played a much larger role in biological processes.

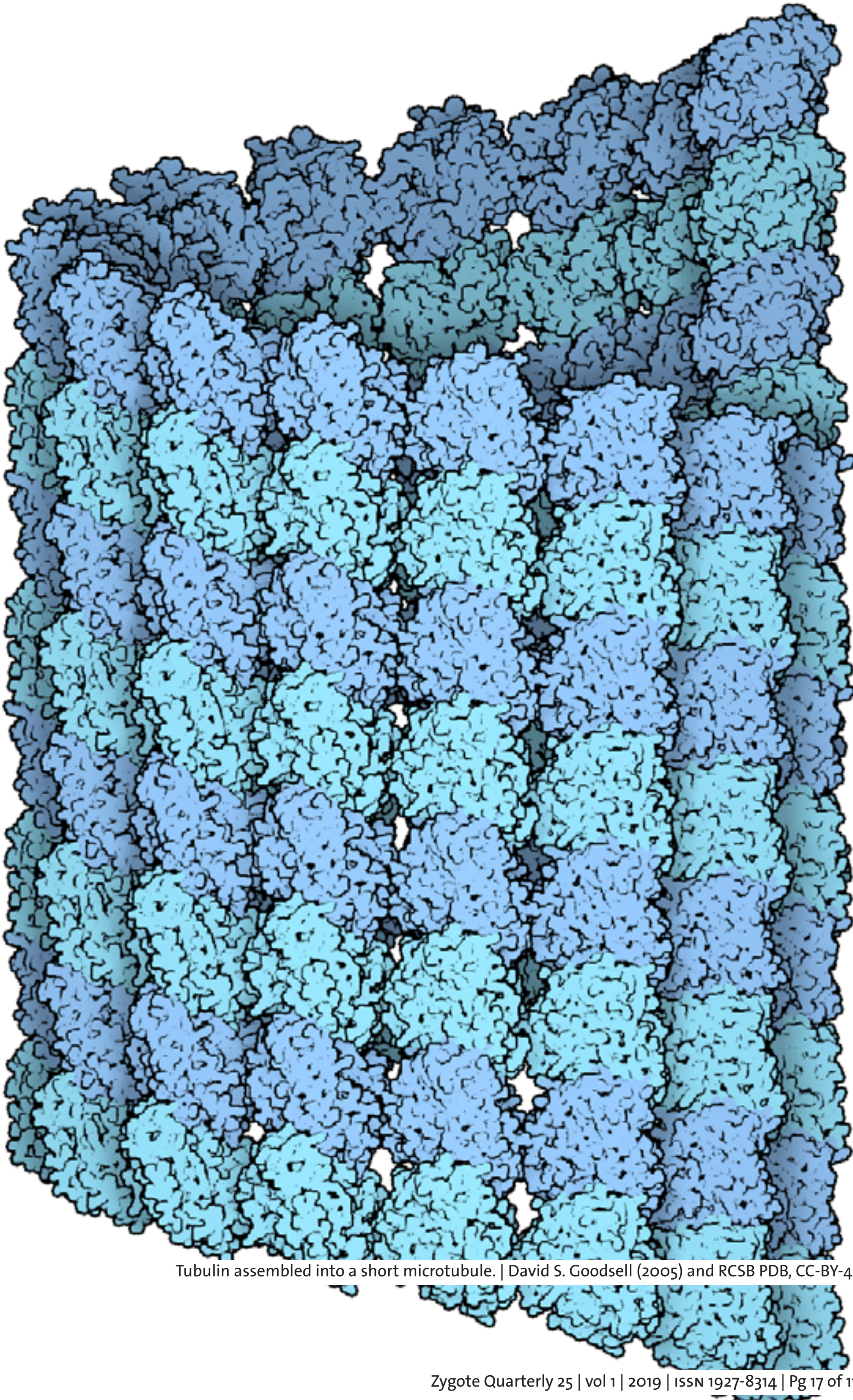
The New Theory

Ingber adopted Fuller's complete definition of tensegrity in that it should comprise two structural concepts, that of stability through tension (prestressing) and geodesics, or minimal force pathways. He proposed that the entire cell is a prestressed tensegrity structure, with the cytoskeletal microfilaments and intermediate filaments providing the tensioning and the microtubules and adhesions from the extracellular matrix (ECM) providing the resistance to compression that counterbalances the tensioning. Ingber also noted that filaments can have dual functions and swing from tension to compression-bearing roles. The contractile actomyosin apparatus is believed to be the mechanism that activates the tensional prestressing that stabilizes the cell.

The complexity of this "structural homeostasis" within the cell does not end with these components and forces, according to Ingber and others. Osmotic forces, the polymerization of filaments, and cell distension through adhesion to the ECM produce additional tensional stresses. Intermediate filaments that interconnect microtubules and microfilaments at many points serve to stiffen the matrix, and this matrix is in turn connected to a highly elastic cortical cytoskeletal network directly beneath the plasma membrane.

The Debate

Nearly thirty years of debate within the scientific community has followed the first



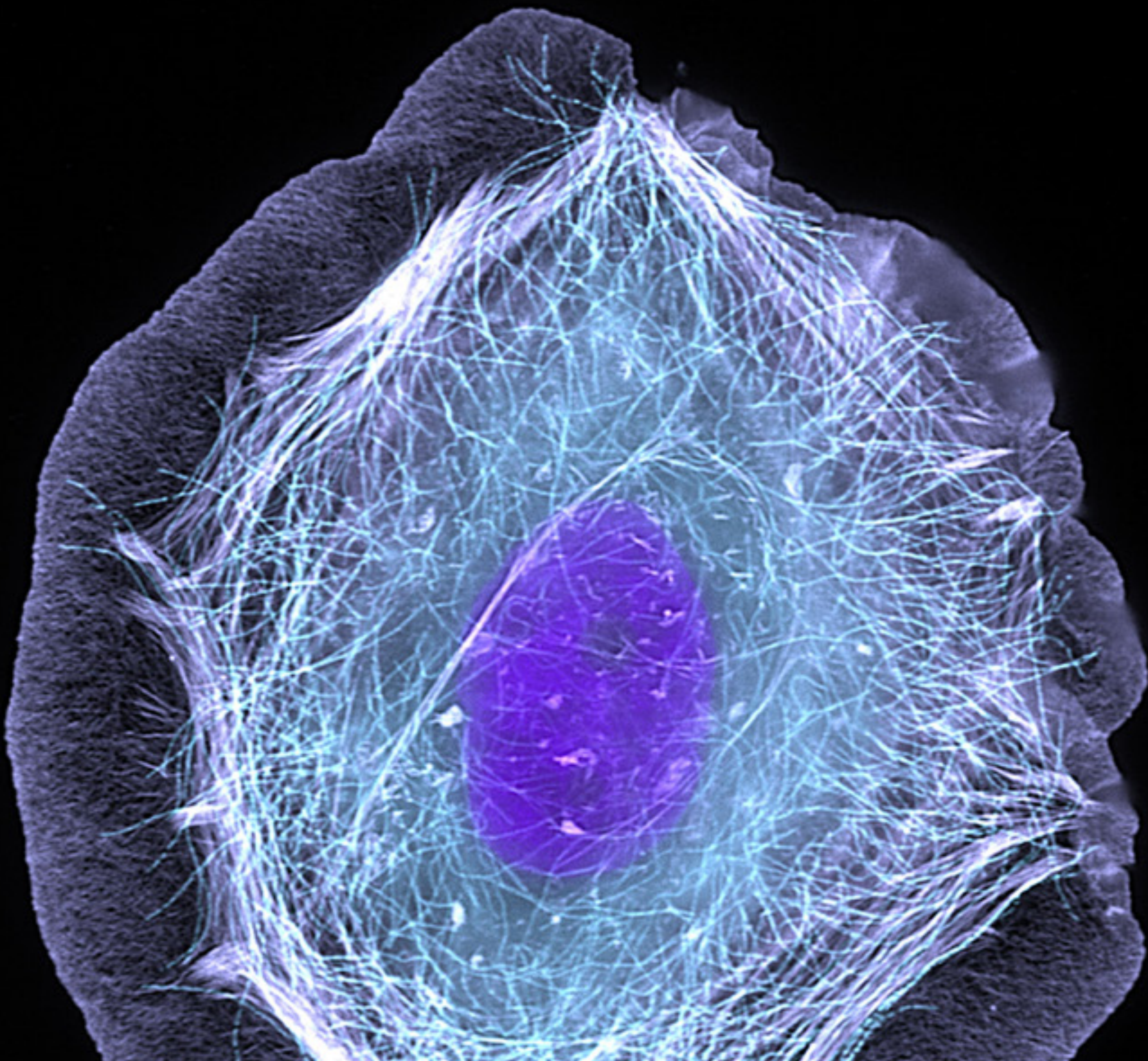
Tubulin assembled into a short microtubule. | David S. Goodsell (2005) and RCSB PDB, papers on this subject and the process has comprised a rigorous but unpredictable combination of new discoveries and techniques, collaborations and insights.

In 1993, Ingber submitted a commentary to the *Journal of Cell Science* in which he outlined his cellular tensegrity model. He offered that it would explain the range of behavior and activities of a cell being observed: shape, movement and even responses. Much was still unknown about the cytoskeleton, but he laid out the suggestive evidence bit by bit and made a compelling case for a mechanical theorem that seemed to address many scale behaviors seen to date. Most importantly, the paper changed the frame of reference for research in cell structure, which would now include, irrevocably, the principles of tensegrity (3).

In 2000, many researchers had applied the tensegrity model to cell and tissue architecture and had demonstrated its plausibility in explaining complex mechanical forces in viruses, cells, tissues and organs of animals and plants. The idea was still being challenged strenuously enough that the editors of the *Journal of Applied Physiology* published Ingber's summation of his views under the feature title "Controversies in Physiology" in a written debate with proponents of the viscous cytosol model, Heidemann et al from Michigan State University (5).

The main difference in the two views of cell mechanics was this: the cellular tensegrity model held that the intricate network of cytoskeleton components within the cytoplasm of a cell, a cortical actin-ankyrin-spectrin lattice, constituted an independent and prestressed structure which allowed the cell to absorb and adjust to outside mechanical forces. This adjustment, like that of all tensegrity stuctures, meant the whole lattice would shift as a system according to force and direction with asymmetric but stable results. The viscous cytosol model held that outside force placed upon the cell would result in a continuous absorption of this force equally and continuously along the cell membrane.

Key to proving one theory over the other, according to Ingber, was demonstrating a transfer of force to a remote part of the cell (action at a distance), and he also offered proof of prestressing citing studies that removed the contractile capability of the cytoskeleton and thereby reduced the cellular shear modulus (resistance to shear force, a measure of cell stiffness). In summary he argued that the cellular tensegrity model was the only one extant that provided an explanation of the complexity, multimodality and hierarchical nature of cells, and from



Skin cell | Photo: ZEISS Microscopy, 2014 | Flickr cc

What Forces are at Work Here?

Tom McKeag

Three types of filaments that make up the cytoskeleton: a microtubule (the largest), an intermediate filament (the knobby one), and two actin filaments (the smallest ones). The large blue molecules are ribosomes, busy in their task of synthesizing proteins. The large protein at bottom center is a proteasome.

mechanistic principles offered predictive power to illuminate complex behavior at many linear scales.

In 2003, Ingber returned again to the ramparts to outline the growing empirical basis for his theorem. In a redux piece to his 1993 article in the *Journal of Cell Science* he revisited the concept within the context of a decade of progress in the study of cell structure and mechanoregulation. By now he could clearly state that the cytoskeletal lattice both generated and resisted mechanical loads and therefore cell shape distortion, that they aided the movement of organelles and had a role in aligning enzymes and substrates associated with critical biochemical processes. These chemical activities were, in turn, altered by changes in cell shape.

Ingber laid out the past decade's evidence for what he considered three key proofs of his concept: that cells behave mechanically as discreet networks, not as a continuum; that cytoskeletal prestress is a major determinant of cell deformability; and that microtubules act as local compression elements acting in concert with ECM anchors to counterbalance the tension elements of the cystoskeletal lattice.

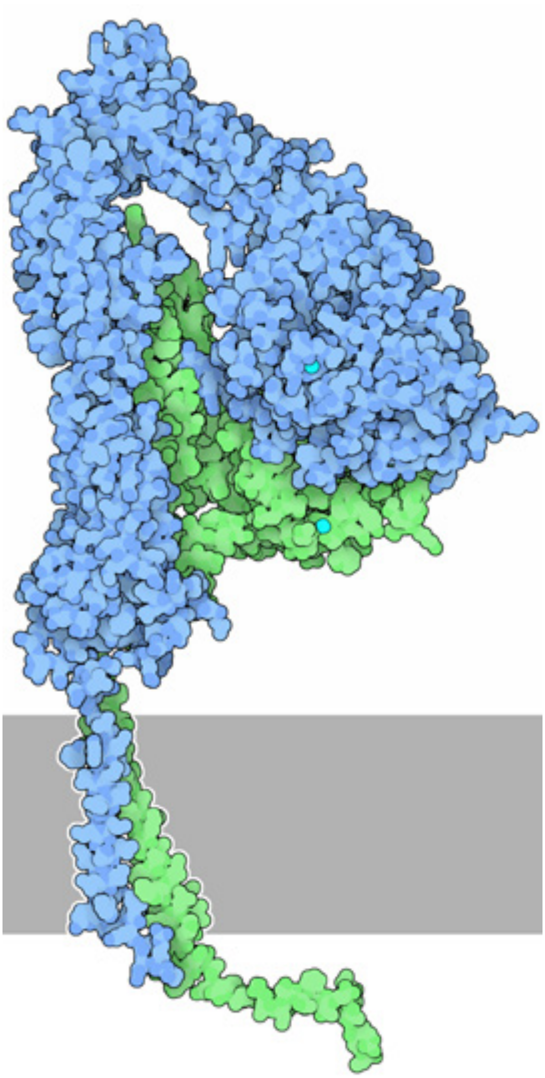
Although much had been learned about the microstructures within cytoplasm to suggest a structural role, a predictive model for in vitro mechanical behavior was still lacking. He called upon the scientific community to continue the work that was needed to solidify this concept into a universal theory.

"We must therefore search for a model of the cell that will allow us to relate mechanics to chemistry at the molecular level and to translate this description of the cell into mathematical terms. The former will permit us to define how specific molecular components contribute to complex cell behaviors. The latter will allow us to develop computational approaches to address levels of complexity and multi-component interactions that exist in living cells but cannot be described by current approaches. The long-term goal is to understand biological processes responsible for cell behavior as integrated, hierarchical systems rather than as isolated parts" (6).

The Impact

What has followed has been decades of scientific debate, refinement and increased collaborative and reinforcing study of this now generally accepted paradigm. Ingber's work has contributed to the development of whole new area of study in which mechanical forces have been demonstrated to influence bio-chemical reactions and gene expression: mechanotransduction.

What Forces are at Work Here?
Tom McKeag



Inactive conformation of integrin

Ingber and his colleagues have determined that living cells use tensegrity architecture to stabilize their shape and cytoskeleton, that cellular integrins function as mechanosensors on the cell surface, and that cytoskeletal tension is a fundamental regulator of many cellular responses to mechanical cues. (7)

Ingber's cellular tensegrity theory has informed the fundamental question of how life forms and organizes itself and led to the prediction that changes in extracellular matrix structure and mechanics play a fundamental role in tissue and organ development.

The story of the cellular tensegrity paradigm, and the scientific search and debate that continues to animate it as a living process, is also an object lesson in interdisciplinary innovation. The bounding of traditional academic lines, the application of established principles to new disciplines, the use of all crafts, expertise, and insights, the inspiring of new and varied lines of inquiry, and the dogged investigation of all legitimate technical questions are found here, and worth studying closely. ×

Footnotes

1. Ingber, D. E., and J. D. Jamieson. "Cells as tensegrity structures: Architectural regulation of histodifferentiation by physical forces transduced over basement membranes." pp. 13-33, *Gene Expression during Normal and Malignant Differentiation*, Academic Press, Inc., London (1985). ISBN 0-12-059490-0

2. Fuller RB. *Synergetics*. New York: Macmillan, 1975, p. 372– 434.

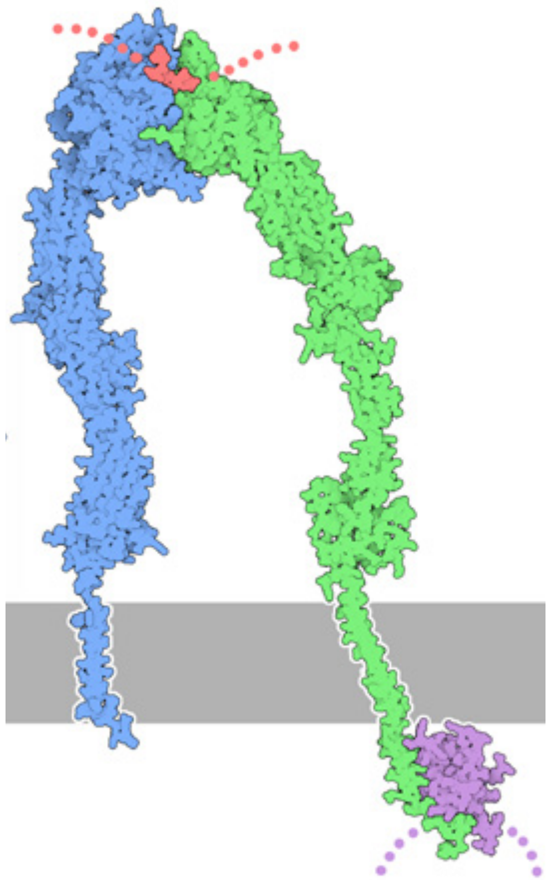
3. Ingber, Donald E. "Cellular tensegrity: defining new rules of biological design that govern the cytoskeleton." *Journal of Cell Science* 104 (1993): 613-627.

4. Heidemann, Steven R., et al. "Direct observations of the mechanical behaviors of the cytoskeleton in living fibroblasts." *The Journal of Cell Biology 145*.1 (1999): 109-122.

5. Ingber, D. E., et al. "Opposing views on tensegrity as a structural framework for understanding cell mechanics." *Journal of Applied Physiology 89*: 1663–1678, 2000. https://doi.org/10.1152/jappl.2000.89.4.1663

6. Ingber, D. E. "Tensegrity I. Cell structure and hierarchical systems biology." *Journal of Cell Science 116*, 1157-1173 © 2003 The Company of Biologists Ltd doi:10.1242/jcs.00359

7. Ingber, D. E. "Tensegrity and mechanotransduction". *Journal of Bodywork and Movement Therapies 12* (3): 198–200. doi:10.1016/j.jbmt.2008.04.038. PMC 2614693. PMID 19083675.



Hypothetical model of the open, active form of integrin, with a fibrinogen peptide in red and a talin domain in magenta.

Myoung Ho Lee
Tree...#3, 2012

Portfolio

Myoung Ho Lee

Portfolio
Myoung Ho Lee

"Mirages, or billboards, portray what is desired, in theory. By advertising what is readily visible in nature, Myoung Ho Lee's stagings question the daily hierarchies of seeing, slyly conflating Korea's tranquil landscape tradition with the bold style of studio portraiture perfected by Richard Avedon. But unlike Avedon—who plopped subjects into white backgrounds to relieve them of context, muddling ideas of neutral looking—Lee occasionally leaves traces of each spectacle's production within the frame. Backdrops are wrinkled and shadowed... Totems of humankind's giddy disregard for nature, the towers' presence sobers up the artist's wanderlust aesthetic, a reminder of the threats that loom over a tree's gorgeous symmetry, over the very existence of a season." — Zack Hatfield, *Artforum*, 2017. Myoung Ho Lee is an Assistant Professor in the Department of Photography/Film at Kyung-Il University, Gyeongsan, Korea.

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

Unlike other artists, I have started my artistic career with a thorough plan from the beginning until the end about which works I want to show and how I want to present them. I even have a principle and system to name my projects and series. For example, "Tree Series" is when I look for objects surrounding me, and "Tree... Series" is when I look for objects away from my surroundings. It is related to what we first learn about the basics of geometry from school, dot, line and face. So, we can guess "Tree...... Series" or "Tree......... Series" as well? Plus, it can be a big transition: the relationship

Myoung Ho Lee
Tree...#8, 2015

between object and observer changes from "one to one" to "one to many". If we look at "Tree... #7" or "Tree... #8", we can find this from the comparison of other works.

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

To be precise, it is me 'seeing well', not 'seeing differently.' I believe it is a key to see things around the world as they are. We often see things differently because of internal and external reasons. I feel all the problems in the world begin from it. Everything should go well if we see and feel things as they are. It is what I try to do with my photography and art.

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

There is some mixture of things, but if I have to pick one it is meditation. I know that external information and stimulation are important as a contemporary artist. However, my work is mainly exposing essentials over change of era, so deep meditation(contemplation) is a key point of my work.

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

I have worked on two different categories. One is work as fine art, another is work to apply the concept and form of my work to society. The first one has 3 categories, which are "Tree", "Mirage" and recently work "Nothing but". The second one is to find a way to contribute to the society. These days as a Cultural Heritage Administration honorary ambassador, I have worked on cultural heritage with my concept and form as fine art.

What is the last book you enjoyed?

It is Carl Sagan's *Cosmos*, which is so famous that I am reading it again. It is a very artistic book, which has all the ambivalent factors such as fiction and nonfiction, logic and illogic, and reason and sensibility. When we think of the fact that art itself includes artistic meaning as well as technology, this book might be an art book and a scientific book at the same time. I even think my work resembles the book.

What’s your favorite motto or quotation?

In Korea there is a saying ‘Il-hee-il-bee’. It means alternation of laughter and tears. In other words, even if there are ups and downs in life, you should have a faith in your own philosophy. It means so much to me living as an artist. Bad things and good things can happen from inside and outside. Whenever anything happens it is important for me to keep calm and accept emotion and condition to create consistent work. ×

We would appreciate your feedback on this article:

Myoung Ho Lee
Tree...#7, 2014
© Myoung Ho Lee, Courtesy Yossi Milo Gallery, New York

Myoung Ho Lee | *Tree #14*, 2009 | © Myoung Ho Lee, Courtesy Yossi Milo Gallery, New York

Myoung Ho Lee | *Tree #6*, 2008 | © Myoung Ho Lee, Courtesy Yossi Milo Gallery, New York

Myoung Ho Lee | *Tree #9*, 2006 | © Myoung Ho Lee, Courtesy Yossi Milo Gallery, New York

Myoung Ho Lee | *Tree #8*, 2007 | © Myoung Ho Lee, Courtesy Yossi Milo Gallery, New York

Myoung Ho Lee | *Tree #3*, 2006 | © Myoung Ho Lee, Courtesy Yossi Milo Gallery, New York

Myoung Ho Lee | *Tree...#6*, 2013 | © Myoung Ho Lee, Courtesy Yossi Milo Gallery, New York

Myoung Ho Lee | *Tree #10*, 2006 | © Myoung Ho Lee, Courtesy Yossi Milo Gallery, New York

Myoung Ho Lee | *Tree #1*, 2006 | © Myoung Ho Lee, Courtesy Yossi Milo Gallery, New York

Myoung Ho Lee | *Tree #12*, 2008 | © Myoung Ho Lee, Courtesy Yossi Milo Gallery, New York

River of Blue
Photo: Dag Peak, 2003 | Flickr cc

Article

Perspectives on "Stories from the trenches"

Jamie Miller
& Michael Helms

Perspectives on "Stories from the trenches"
Jamie Miller& Michael Helms

The "Stories from the Trenches" series followed several examples of biomimetic innovation from ideation and proof-of-concept (https://zqjournal.org/editions/zq21.html p. 38), through business model generation and market entry (https://zqjournal.org/editions/zq22.html p.8), and across the Valley of Death to commercialization and scale-up (https://zqjournal.org/editions/zq23.html p.22). We wanted to include other voices on engaging the business community and 'making biom* real'. Dr. Pete Foley, Margo Farnsworth, and Dr. Arndt Pechstein provided their insights in ZQ24 (https://zqjournal.org/editions/zq24.html p. 40). This issue brings the unique perspectives of Jamie Miller and Dr. Michael Helms. - Ryan Church, Rachel Hahs, and Norbert Hoeller

"Where Do We Want to Be When We Grow Up?"

By Jamie Miller

I want to see biomimicry as the governing paradigm in design. Tapping into biomimicry thinking can help us create urban infrastructure that is in harmony with nature, breaking down the barriers we have created between natural and built environments. In ten years, I picture buildings that breathe like lungs, in cities that fully implement circular pathways to eliminate waste and reduce raw material inputs, that are built from the bottom up, implement distributed governance, and incorporate technology that strives to mimic and integrate with natural processes. And with today's creativity and tomorrow's technologies, I have little doubt that these ideas could become real.

What Stands in Our Way?

We fear the unknown, and for much of our history, we feared the complexity of nature. Even when new knowledge becomes available, it can be hard to integrate it with our existing knowledge. We have become comfortable with the status quo and can unconsciously block information that might be counter to our beliefs. Plus, it is difficult to inspire change when our lives are good. We project our past technological successes into the future without recognizing the undesirable consequences. We repeatedly use the same thinking to solve problems, an approach Einstein tells us is futile. We have created artificial environments which protect us from uncertainty by isolating ourselves from nature.

Skylights | Photo: Auddess, 2009 | Flickr cc

Perspectives on “Stories from the trenches”

Jamie Miller& Michael Helms

The Newtonian paradigms of separation and isolation give us the illusion of control, but it is becoming increasingly clear that we are creating conditions that increase uncertainty. Our dependence on fossil fuels is creating large energy gradients that nature needs to dissipate. One pathway is through increasingly frequent and severe weather events that are further exacerbated by growing greenhouse gas emissions. We forget about the services nature provide, the carbon it can sequester, and most importantly, the ideas it can foster for true sustainability.

We need the courage to adopt a new paradigm and the creativity to use that paradigm to safely disrupt the way we currently do things.

How Can We Get There From Here?

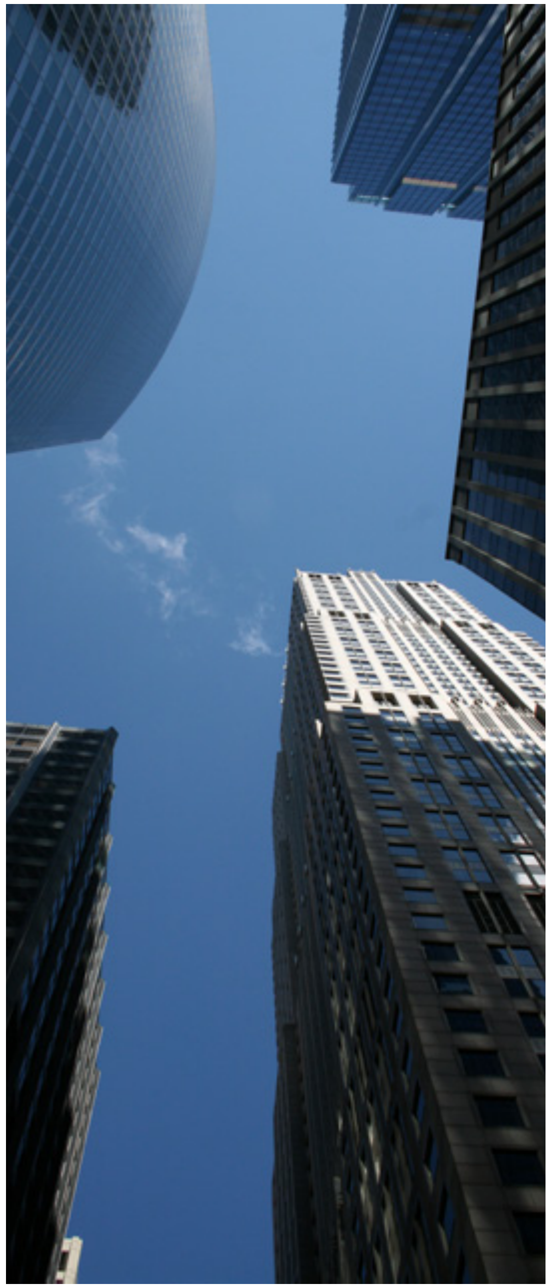
We need to engage youth who have the courage and are open to change because they are less vested in our existing paradigms. We need to apply our creativity not just in developing new ideas, but also to get these ideas implemented by integrating existing technologies, identifying opportunities for delivering marketable solutions, and working with business people with deep skills and expertise in the fields we are trying to change. We need to act like weeds constantly looking for opportunities.

We need to become better storytellers, learning the language of nature to help innovators and entrepreneurs understand urban systems from an ecological perspective to expand existing paradigms and identify novel insights. How are our systems and natural systems similar and how are they different? Even though we are natural beings, why are there such glaring contrasts between the natural world and our technological world?

When we recognize that nature embodies sustainable ideas, and we learn to speak this language that can help us harness these ideas, we must commit to practice. We need to tackle bigger issues by exploring the application of biomimicry to systems. We need to inspire bottom-up disruptive technologies. How can small-scale biomimicry interventions create new paradigms, the way Uber has revolutionized transportation? We need creative ways of integrating existing technologies to reduce costs and risk by building and strengthening relationships that can drive systemic change, such as Encycle’s (https://www.encycle.com/) approach to improving efficiency and effectiveness in the energy sector.

If we are going to have true impact on today's wicked problems, like climate change, we will need to evolve. We will need to evolve our thinking, to stop arguing over semantic differences, and evolve our systems through action. ×

About the author: Jamie Miller is founder of Biomimicry Frontiers, an award-winning integrated consultancy of landscape, architecture, and product design. He was trained by Janine Benyus (the author of *Biomimicry: Innovation Inspired by Nature*) and has been building biomimicry in Ontario through his consulting, lectures, and workshops since 2007. Jamie taught the biomimicry program at OCAD University, during which he earned a PhD degree in engineering that focused on applying systems-level biomimicry to urban infrastructure resilience. More recently, Jamie has founded the Biomimicry Commons, an incubator and disrupter studio for creating action-oriented solutions to climate change. https://biomimicryfrontiers.com/



Glass, concrete, steel, sky
Photo: Dare2Dream, 2007 | Flickr cc

Perspectives on "Stories from the trenches"
Jamie Miller& Michael Helms

Deep Biologically Inspired Design and the Need for Industry-Academic Partnerships

By Dr. Michael Helms

The processes of biomimicry, bio-inspired design, bionics, etc., collectively referred to as biom*, encompass a host of different approaches with a single underlying philosophy – biological systems can inspire us to think differently about designed systems. One way to estimate the impact of this philosophy is the frequency with which key terms appear in new patent filings and funded research proposals. Extending Bonser & Vincent's patent analysis of the US patent database through 2017 (Figure 1), we see a continued exponential rise in the number of biom* related patent filings.

Lepora et al. further support the rapid growth of biom* related research by analyzing annual publication data, which shows a similar exponential growth curve.

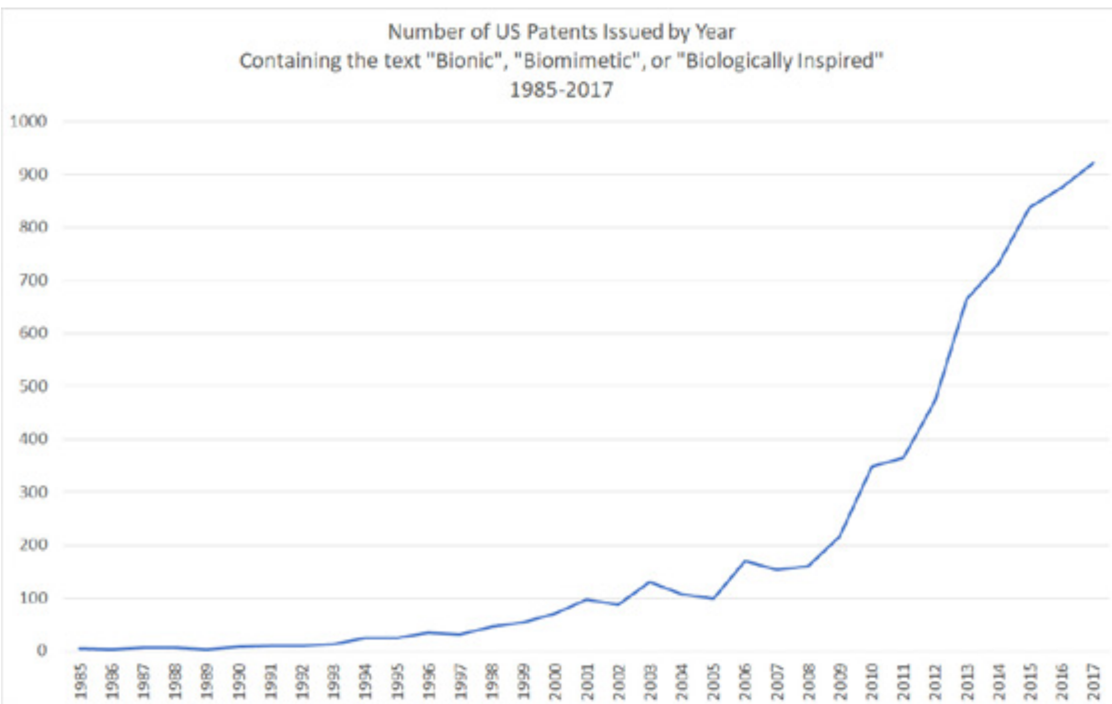


Figure 1 US Patents Related to Biomimetics by Year

Conducting a biom* terminology analysis on the National Science Foundation funding database (Figure 2) we see a similar rapid increase in funded research that peaks in 2010 – a research "gold rush" – followed by a dip, and now a smoother, more sustained level of funding in subsequent years. From my experience working with industry R&D organizations at PatternFox Consulting, it appears that industrial R&D departments at a select few U.S. companies and government organizations are also making investments in developing their internal capabilities with respect to biom*. These investments range from forming special interest groups to identify, formalize, and communicate best practices within their organizations, to providing seed funding for bio-inspired design projects inside the company, to multi-year cooperative research projects with university partners.

On the flipside, as I engage with industrial R&D organizations, especially manufacturers, I hear a slightly different

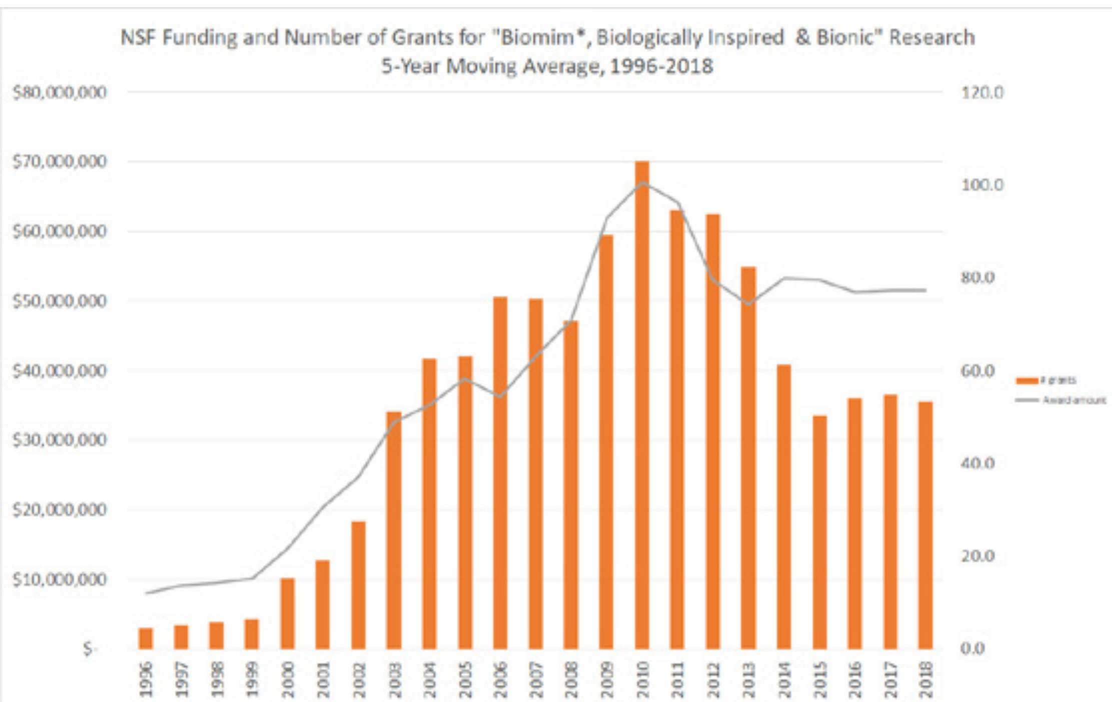


Figure 2 NSF Funding And Grants Related to Biomimetics by Year
Source: https://www.nsf.gov/awardsearch/

story in which biom* is not being so readily and enthusiastically embraced. For example, I recently conducted a workshop at the annual meeting of the Innovation Research Interchange (http://www.iriweb.org/) where we asked a group of research executives and directors how many of their organizations were actively pursuing biologically inspired design strategies. Only three out of the roughly 50 participants responded affirmatively, suggesting a large gulf between the aspirational goals of industry thought leaders, and actual experience. Of those three, one was beginning to understand the process and had no active projects, the second had experience with multiple projects that looked to biology as a potential source of inspiration but ultimately went a different direction, and the third was a pharmaceutical executive for whom biologically inspired design was a specialized process somewhat unique to the drug industry. When pressed, we learned that several additional organizations worked with external organizations to provide bio-inspired design services in the past, but the results were relegated to a shelf to collect dust after an initial period of excitement and a short engagement. Our discussions with other large industrial R&D organizations revealed a dismal pattern. Except for aerospace and defense organizations, the biom* "innovation" cycle typically is this: excitement and engagement, followed by ideation sessions, followed by a period of stagnation and confusion, and then ultimately dismissal of the ideas and the process.

To provide a bit of perspective, among the different flavors of biom*, I focus on what Lenau terms biologically inspired design (BID). Lenau characterizes BID as being particularly focused on the design process for transferring biological mechanisms to drive innovation. This is distinct from other biom* processes such as biomimicry, bionics, and bioreplication, each of which, according to Lenau, have their own slant on the process. I am also focused on bringing BID to large industrial R&D organizations, which I recognize represents only a fraction of the biom* ecosystem. My goal is to adapt what we know BID has accomplished in academic and small government funded labs to these larger R&D counterparts. What I have seen thus far in industry suggests that there are two different BID processes at play in the industrial R&D ecosystem, which I will call inspirational BID and deep BID.

Inspirational BID and deep BID

Inspirational BID is designed to break designers out of traditional ways of thinking, increase creativity metrics such as quantity and variety of design, and provide designers and engineers with a new lens for examining problems. Inspirational BID can take place in an afternoon workshop, or over the course of a month or two. Inspirational BID often uses case studies, design ideation exercises, hands-on engagement with biology, and scientific articles to provide exposure to the possibilities and potential of BID. Clients typically leave with a collection of new ideas and problem approaches, a renewed connection to nature, and a new tool in their designer toolkit. Inspirational BID provides biom* practitioners with a method for demonstrating the promise of BID, while providing a low barrier to entry, and requiring little specialized knowledge.

Deep BID, by contrast, focuses on converting bio-inspired design concepts into technical engineering designs and working prototypes. Deep BID relies on systematic engineering design processes to apply technical and scientific understanding of both the problem domain and the biological source material to create specifications for designs. Deep BID projects take place over the course of six+ months, require six figure R&D investment, and advanced technical capabilities in terms of both infrastructure and human resources. Deep BID translates technical engineering principles of biological systems into validated engineering specifications, providing biom* practitioners with sound engineering justification for continued investment in developing these technologies and products. Deep BID requires much higher time, human resource, and capital commitments from an organization, as well as interdisciplinary expertise.

While these activities are vastly different undertakings, they are rarely distinguished. Additionally, the end point of one is not the starting point of the other. That is, there is a chasm between inspirational BID and deep BID that most clients cannot cross on their own. In some respects, inspirational BID is no different than any other conceptual design process in that the leap from conceptual design to prototype is fraught with challenges and pitfalls. However, unlike other design processes, borrowing from the domain of biology has its own unique set of challenges that layer onto the already difficult process. These difficulties can include: an incomplete understanding of the underlying biological source of inspiration; radically different manufacturing processes and materials; orders of magnitude difference in performance scale; and environmental factors and interactions. It is incumbent on the biom* community to develop methods and expertise to

Feathers | Photo: Meyers Lab, 2018 | Jacobs School of Engineering | Flickr cc

assist clients in overcoming these unique obstacles.

To be clear, I believe inspirational BID and deep BID are both valuable and important for the long-term success of BID. I fear that without being clear in their distinction, the biom* community is confusing and ultimately disappointing industry. As a community we tend to point to the results of deep BID, but we begin with inspirational BID without understanding and communicating the path forward. In addition to the not insignificant challenge of communication and expectation setting, I believe we also have a delivery problem. While the community has a ready supply of excellent inspirational BID practitioners, I have not seen any stand-alone organizations in the industrial R&D ecosystem capable of systematically and repeatedly making the leap to deliver a deep BID prototype. The reason for this is simple; biology is too diverse and too much is still unknown about many biological processes. No single organization can deliver on the generalized promise of BID, because no organization can afford to house that breadth of expertise.

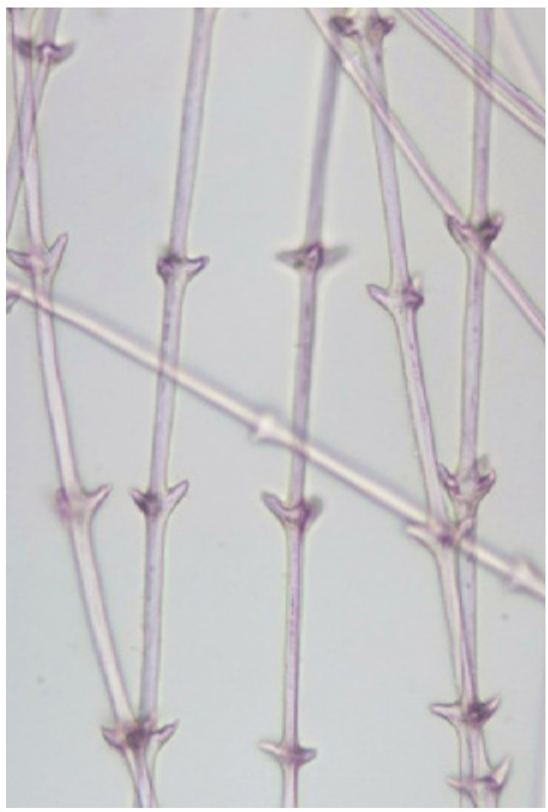
Deep BID and the "Valley of Death"

The "Valley of Death" represents the gap between university research and industrial application of that research. Whereas university researchers focus on developing new knowledge, they are not incentivized to develop manufacturable products. Likewise, industry lacks the funding and risk tolerance to take a university research product through to manufacturability. While some of the more promising breakthroughs bridge the gap, most research sits on the university shelf or buried in a dissertation. This is especially true for biological research that was never intended to be used for purposes of engineering innovation. There exists within the stacks of academic research a treasure trove of untapped "biological intellectual property", growing at an exponential rate.

There is a second valley of death: the chasm between the biologically-inspired conceptual design and the realized prototype of that design. Crossing this gap requires the deep technical problem expertise that can only be found in an industry lab, combined with the ability to research and prototype biologically-inspired designs. It would be impractical for most organizations to maintain the talent and facilities required to do both. The way PatternFox and others address the problem is to facilitate industry-university partnerships for the targeted development of specific bio-inspired designs. In many cases the Intellectual Property (IP), equipment, and human resources already exist. Of course, such open-innovation is nothing new. Many such university-corporate partnerships already exist and provide great examples of the potential of this model. I believe for the biom* community, this model is not only particularly useful, but currently the only way to deliver generalizable BID services to industry because of the complexity of biology and the research and tools required to deliver BID prototypes.

Although useful and necessary, this model is far from a panacea and comes with its own challenges, not the least of which are publication and IP rights. Moreover, partnering with the university ecosystem broadly and staying current on available capabilities may be difficult or impossible for individual design practitioners. This is where centralizing organizations like University of Akron's Biomimicry and Innovation Research Center (BRIC) and Georgia Tech's Center for Biologically Inspired Design (CBID), and clearing houses like AskNature, can be great assets. Such groups can connect inspirational BID practitioners to deep BID capabilities, marrying the promise of inspirational BID to the capability to deliver on that promise. Within the context of the large industrial R&D ecosystem, I believe proper framing and expectation setting when we begin engaging in biom*, coupled with extending individual capabilities to deliver deep BID capabilities through open-innovation partnerships, will increase the momentum of the biom* movement within that ecosystem and help us realize the benefits of what we all know is possible. ×

We would appreciate your feedback on this article:



Barbules of the feathers of the sacred dove (*columbidae*) – Transmitted Off Circular Polarized Light Illumination
Photo: Ernest Russell Crutcher | cc | asknature.org

Perspectives on "Stories from the trenches"
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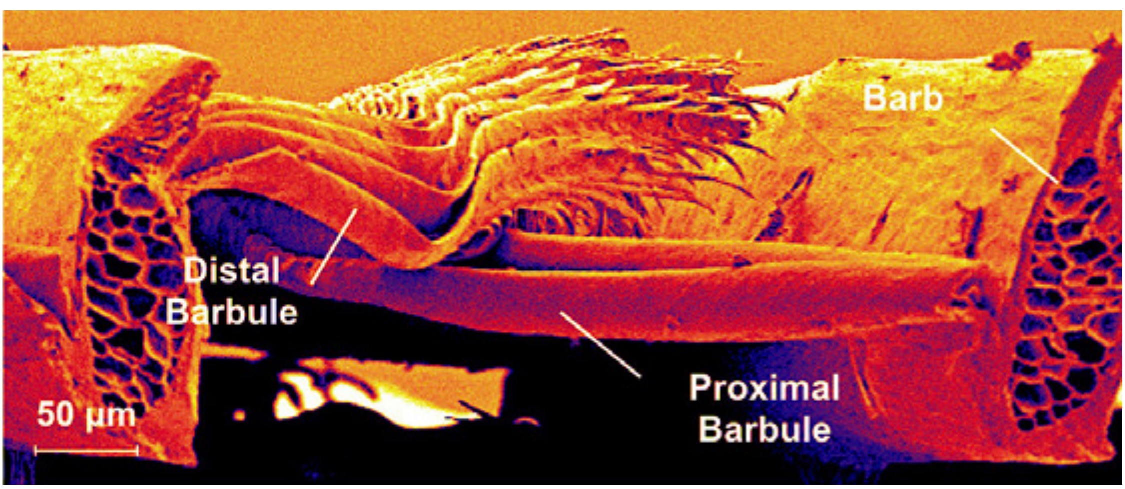
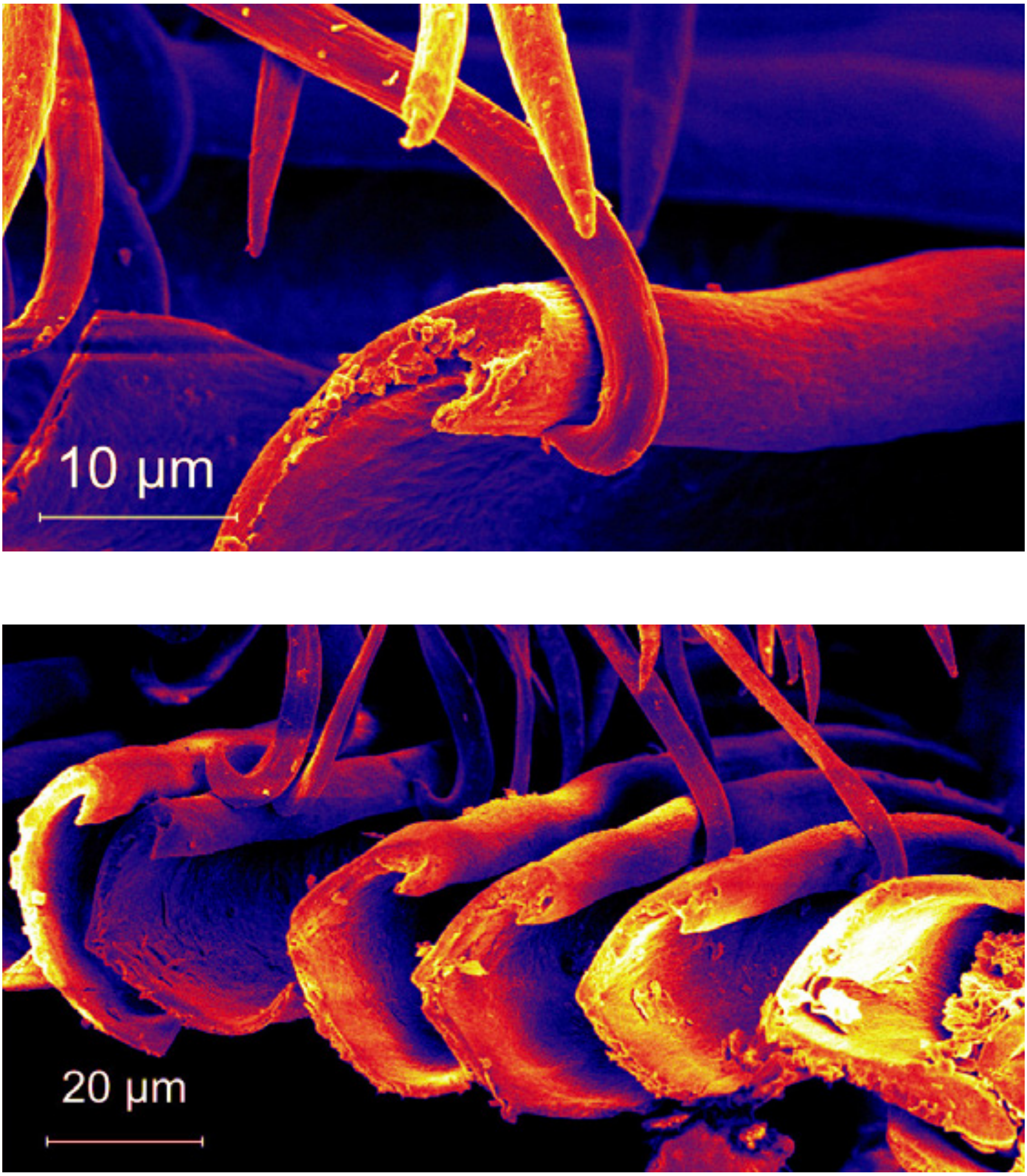
About the author: Dr. Michael Helms is a Research Scientist at the Georgia Institute of Technology, and Co-founder of PatternFox Consulting (http://patternfoxconsulting.com/). He received his Ph.D. in Computer Science from the Georgia Institute of Technology, where his research focused on improving design creativity. In addition to teaching biologically inspired design and cognitive science at Georgia Tech, Michael has over 40 peer reviewed publications in the field of biologically inspired design. Michael's recent work focuses on understanding how existing biologically design methods can be applied in industrial settings to increase design innovation and better manage uncertainty.



Barb and barbules
Photo: Jacobs School of Engineering, Meyers Lab, 2019 | Flickr cc



Barb and barbules
Photo: Jacobs School of Engineering, Meyers Lab, 2019 | Flickr cc

Marine Iguana
Photo: Michelle Fehler, 2018

The Science of Seeing

Nature, Where Art Thou?

Adelheid Fischer

Nature, Where Art Thou?

Adelheid Fischer

In February 1535, Fray Tomás de Berlanga, the Bishop of Panama, set sail down the western coast of South America. He was on a royal errand, sent by King Charles V of Spain to investigate territorial disputes in Peru. For the first seven days of the voyage, fair winds allowed de Berlanga's vessel to make good time. But when it entered equatorial waters, the winds died, and the ship succumbed to strong currents that carried it into deep ocean waters some 600 miles off the coast of present-day Ecuador. The crew grew uneasy, having packed only enough provisions for a two-week voyage. On March 10 they spotted islands on the horizon. After making landfall on one of them, however, their hopes were quickly dashed. They encountered parched fields of volcanic rock, "so many that it seemed at some time God had showered stones," de Berlanga wrote in a subsequent report to the king. Nowhere, he added, did the land "have the virtue to create [even] a little grass." To slake their thirst, the desperate men squeezed the pads of prickly pear cactus to harvest liquid that de Berlanga described as "slops of lye"; yet the men "drank it as if it were rose water." By the time the crew located a supply of potable water on a second island, two men and ten horses had already died of dehydration.

De Berlanga and his crew are thought to have been the first humans to set foot on the isolated archipelago that later became known as the Galápagos Islands. Although the bishop noted the presence of fantastical animals such as seals, giant tortoises and iguanas, he failed to be impressed. He concluded that the islands were "dross" and "worthless," writing that even the birds (never having encountered humans and therefore lacking a fear of them) were "silly" since "they do not know how to flee and many are caught in hand."

Fast forward nearly 500 years, and de Berlanga would have been shocked to learn that the volcanic outcrops he stumbled upon would become one of the most coveted tourist destinations in the world. What would he have made of today's Galápagos Islands?

I pondered that question this past fall as I strolled Puerto Ayora, a small town on Isla Santa Cruz, the second largest in the Galápagos archipelago. Lining the main street were art galleries, boutique hotels and cafes selling espresso and Ecuadoran chocolate. The street was chockablock with souvenir shops shoe-horned into even the narrowest slots. Especially popular with tourists was the Charles Darwinabilia: T-shirts featuring the big-bearded 19th-century scientist in a suit and cravat

Galapagos Oystercatcher (detail) | Photo: Michelle Fehler, 2018

Lava Galapagos | Photo: Michelle Fehler, 2018

Blue-Footed Booby | Photo: Timothy Finley, 2011 | Flickr cc riding cowboy-style on a bucking tortoise or nuggets of pop psychology mined from Darwin's writings on evolution: "To change is difficult. Not to change is fatal." One of the most popular and ubiquitous slogans, however, was cooked up not by Darwin in a respectable English drawing room but, in all likelihood, by some tipsy island promoter on a bar stool: "I Love Boobies" (a reference to the popular blue-footed booby, a marine bird that draws oglers from around the globe). It adorned everything from coffee mugs and key chains to baseball hats.

De Berlanga would have been mystified by the fact that people flock to the Galápagos with the sole purpose of plopping down perfectly good money to see boobies and other "silly" animals—people like me and my two co-faculty from Arizona State University. This past fall we visited the islands for eight days with a class of 24 graduate students in architecture and design. Our goal was to gather research for the design of a wellness center for the island's elders, most of whom homesteaded the remote archipelago decades ago. As part of our design preparation, we interviewed island residents, healthcare workers and architects. But our research also consulted Galápagos ecologists who took us snorkeling with parrotfish and penguins, hiking into upland forests and nearshore cactus stands and pacing volcanic islands that were every bit as rock-bare and sun-shot as those that de Berlanga decried. We wanted to understand firsthand how the plants and animals prospered in this place and how we might use their strategies to foster sustainable innovation in the design of new structures and systems.

We chose the Galápagos Islands as the focus of our biomimicry studio because it is one of those places you visit for no other reason than to see "nature." Oddly, while nature tourism is one of the main economic engines of the Galápagos, the archipelago does not host an exceptionally robust number of species, mostly because the islands are geologically young and located far from the mainland. The archipelago, for example, is home to only six species of native mammals, including rice rats, the Galápagos fur seal and the Galápagos sea lion. But this isolated Pacific Ocean outpost boasts some of the highest rates of endemism on the planet; that is, many of the plants and animals that call these islands home are found nowhere else in the world. For example, of the archipelago's twenty-two species of reptiles, twenty are endemic. Eighty percent of the land birds are limited to the Galápagos as are 30 percent of the plants. More than 20 percent of the marine species are endemic including

Galapagos Sea Lion | Photo: Michelle Fehler, 2018

Nature, Where Art Thou?
Adelheid Fischer

the Galápagos penguin, the only species found in the Northern Hemisphere.

In other words, the archipelago abounds in organisms that have developed local solutions to place-based challenges—boom-and-bust food cycles, freshwater scarcity, rocky environments drenched in solar radiation or high concentrations of salt. “So what does nature do when it meets challenges and opportunities? writes Dutch biologist Menno Schilthuizen. “It evolves. If at all possible, it changes and adapts. The greater the pressure, the faster and more pervasive it does so.” As Darwin sagely observed, the inability to change is often fatal. The plants and animals that we see today then are not simply survivors, but evolutionary entrepreneurs. They developed the capacities to exploit sparse conditions and overlooked opportunities, enabling them to ride the dramatic peaks and troughs of oscillating

Marine Iguana
Photo: Michelle Fehler, 2018

change that characterize life on these remote Pacific islands.

Take the marine iguana (*Amblyrhynchus cristatus*), the only lizard in the world that ventures out to sea for its food. One glance around the animals' arid near-shore habitat, and you realize that food here is not overly abundant. At some point in its ancestral past, *A. cristatus* likely found itself vying for scant resources with its neighbors. With an eye on the land and another on the sea, one of these snaggle-toothed T-Rex wannabes may have dipped a toe or two into the sea to sample some of its succulent green algae. In time they began to undertake prolonged dives for their meals, especially the males which have become champions of the deep. So impressed, for example, was the crew on board Darwin's Beagle with the ability of the iguanas to remain submerged for long periods of time that one of them tied a weight to an animal and threw it overboard. After an hour, Darwin wrote, it was hoisted back on deck and, to the astonishment of all, was "quite active," he wrote. But to be successful in these amphibious forays, *A. cristatus* had to resolve numerous challenges, including the ingestion of excess salt. The species evolved an especially ingenious solution to this deadly problem: a salt-collecting gland located conveniently above their eyes that enables the animals to periodically clear sea salt from their bodies by sneezing it out through nearby nostril channels.

Selection pressures also caused Galápagos tortoises to change and adapt. Those that evolved in the lusher, more well-watered reaches of highland forests developed closed, dome-shaped carapaces that helped them bulldoze their way through thick vegetation. In the drier lowlands where vegetation was more

Galapagos Tortoise | Photo: Michelle Fehler, 2018 sparse, saddleback designs evolved. These flatter carapaces were shaped like saddles with a large opening in the front that allowed the exceptionally long necks of these arid-zone tortoises to reach up into the branches of tree-form cactus and nip off their succulent pads, flowers and fruits.

But if you had to award a prize for most creative adaptation, the winners would likely be the archipelago's thirteen species of endemic finches. These birds are descendants of *Melanospiza richardsonii*, a species from St. Lucia in the Caribbean. Over generations, the finches have evolved beak designs that allow them to exploit different food sources. Some feed exclusively on seeds, others on flowers and leaves. Others became more entrepreneurial in their food choices. Some finches have learned to use tools, stabbing twigs into the holes of dead trees and then feasting on the impaled prey. Others obtain their meals by becoming vampires and drinking the blood of seabirds or gleaning ticks from the bodies of tortoises.

The legendary tameness of the animals which so impressed early visitors like de Berlanga and Darwin still persists, making it possible for visitors to carefully observe them. During our stay, we tiptoed around marine iguanas sprawled in the middle of downtown sidewalks, sopping up warmth from the concrete in preparation for one of their frigid ocean dives. We stood on the sidelines as tortoises lumbered across fields of grass and melted into mud wallows like a bone-tired man easing his aching body into a tub of warm water. At breakfast, in mid-conversation, our forks poised mid-air, we watched as finches filched breadcrumbs from our plates.

These close encounters were startling and inspiring for the biomimicry studio participants. The shape of the tortoise shell, for example, provided the architecture students with an idea for a beautiful, low-tech and inexpensive construction technology: creating building forms by casting concrete over earthen mounds. Their design proposal—a series of low, shell-like structures combined with the gentle undulation of excavated wallows in the landscape—mimicked the shape of the resident tortoises and their own style of ecosystem engineering on the site. The final design—an intentional blend of tortoise and human earth-moving—promised to serve the needs of both reptiles and people.

The students came away from their visit to the Galápagos with a useful and pleasing bio-inspired design. In the process, they were transformed. They watched a tortoise the size of a wheelbarrow go about its business in the wild. They waded into the

Darwin Finch | Photo: Michelle Fehler, 2018

Sally Lightfooted Crab | Photo: Michelle Fehler, 2018

sea as a school of baby white-tipped sharks swam around their ankles. They strolled through cactus forests every bit as strange and fantastical as storybook drawings by Dr. Seuss.

But these memories came at a price. Everywhere we looked, we found evidence that the Galápagos Islands were straining under the weight of visitors just like us. Most of the supplies that support tourists as well as residents, for example, are shipped from the mainland, everything from cereal, drinking water and cement mix to restaurant chairs, chocolate bars and "I Love Boobies" coffee mugs. Although the government limits the number of berths on tourist ships to prevent "overtourism," land-based visitation is unregulated. And pressures are growing. For example, studies by the Charles Darwin Foundation, a nonprofit organization that promotes wildlife research and conservation, point out that the number of hotels in the Galápagos climbed from 65 in 2006 to 317 in 2017. The infrastructure that supports such increases in visitation—basic, big-ticket items such as roadway construction, trash management and sewage treatment—is inadequate. With the greater numbers of well-meaning wildlife watchers has come more pollution, more fossil-fuel consumption, more invasions of nonnative species and greater disturbances of native ones.

All of this has led me to ask this question: Can we study nature's adaptations closer to home, I mean, really close like in our basements and backyards, our abandoned city lots, our roadway swales? Do we have to travel to nature destinations like the Galápagos to witness what biologist Schilthuizen calls "the power of evolution and the relentless adaptability of the living world?"

Experts in the emerging field of urban evolution say no. They point to selection pressures in urban areas that are as strong as any found in the Galápagos, and these pressures are forcing plants and animals to evolve in ways that are every bit as interesting. In his book *Darwin Comes to Town: How the Urban Jungle Drives Evolution*, Schilthuizen describes how the urban heat island, for example, is causing changes in the evolution of city ants vs. their country cousins or how the mosquitoes that live in the London Underground are not only a different species from above-ground mosquitoes, but they also are genetically different from from one subway station to another. Urban evolution research is alive and well even in the Galápagos. Scientists studying Darwin's finches since the 1970s, Schilthuizen writes, have observed that the “division between large and small-beaked Darwin’s finches has begun to disappear in Puerto Ayora.” The cause, he says, are the birds’ new “fast-food habits” in which they “land on tables and feast on the morsels left by diners.”

“While we all have been focusing on the vanishing quantity of unspoiled nature, urban ecosystems have been evolving behind our backs, right in the cities that we have been turning up our naturalist noses at,” Schilthuizen charges. “While we have been trying to save the world’s crumbling pre-urban ecosystems, we have been ignoring the fact that nature has already been putting up the scaffolds to build novel, urban ecosystems for the future.”

What inspiration could we find if we packed our bags and stayed at home instead? ×

We would appreciate your feedback on this article:

Galapagos
Photo: Catherine, 2007 | Flickr cc

Insulin action
David S. Goodsell (2016) and RCSB PDB,

Portfolio
David Goodsell

Portfolio
David Goodsell

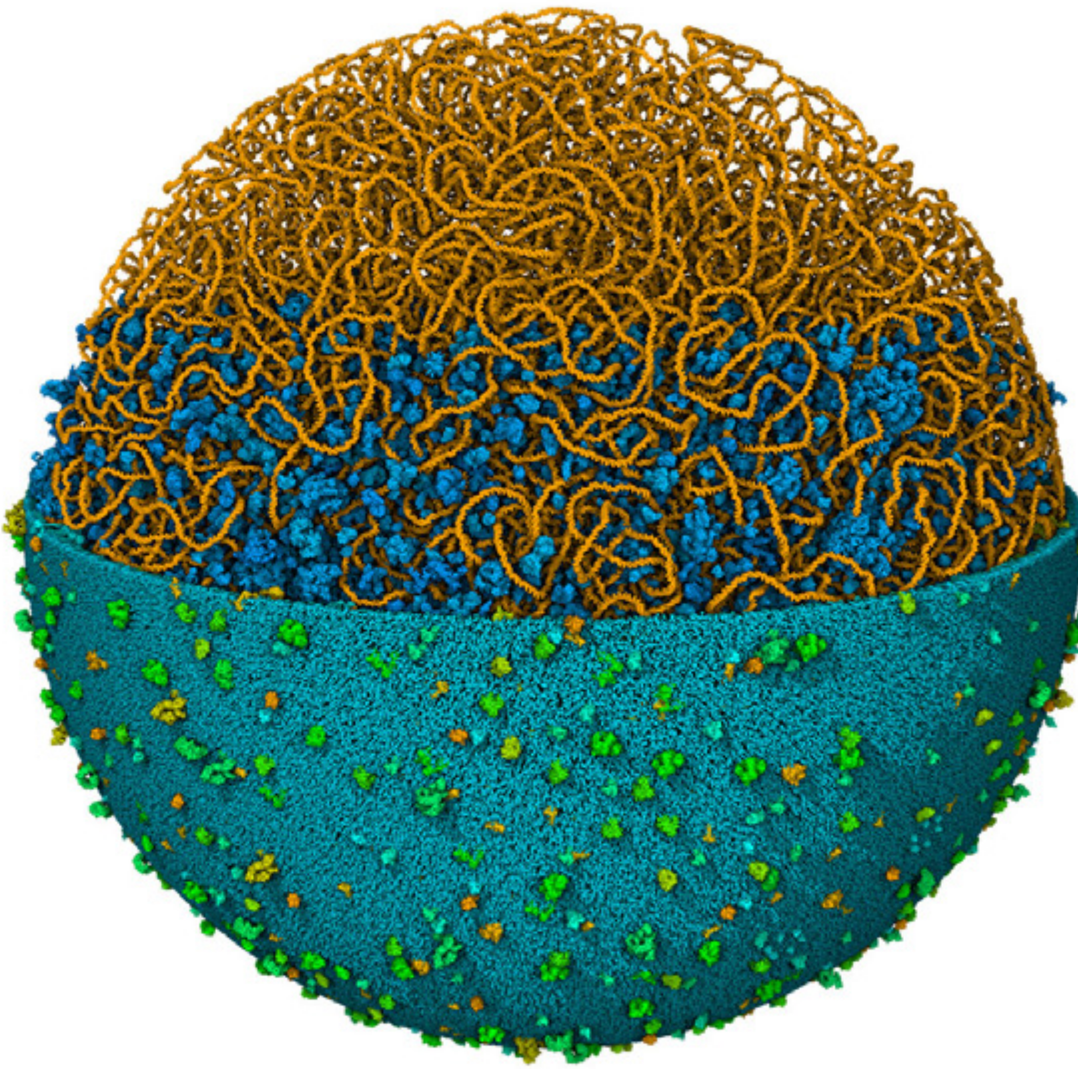
David S. Goodsell, Ph.D., is an associate professor in the Deparment of Integrative Structural and Computational Biology at the Scripps Research Institute in La Jolla, CA, with a joint appointment at Rutgers University in Piscataway, NJ. He is especially known for his watercolor paintings of living cells. Originally trained as a structural biologist, Goodsell has developed a signature style of scientific drawing. He started painting early in his childhood. While in college, he majored in both chemistry and biology but not in art. In graduate school, Goodsell became interested in scientific illustration while writing molecular graphics programs to visualize protein and DNA structures. During his postdoctoral years, Goodsell further honed his skills as both a scientist and an artist. Goodsell's illustrations are published monthly in the RCSB Protein Data Bank, an archive of protein structures. His illustrations are used in many biology textbooks and scientific publications. He is the author of several books including *Bionanotechnology: Lessons from Nature* (J. Wiley and Sons, 2004), *Our Molecular Nature: The Body's Motors, Machines, and Messages* (Springer-Verlag, 1996), and *The Machinery of Life* (Springer-Verlag, 1993)

Can you tell us about your activities since we last spoke to you in 2012?

We've been working hard on a project to create 3D models of the molecular structure of cells and viruses, building on my work on painted cellular landscapes. We've developed two general approaches. The program CellPAINT allows people to create images similar to my paintings, using an interface that is much like a digital painting program. You can draw in membranes and DNA, and pick proteins from a palette and drop them where you want. Try it out at http://cellpaint.scripps.edu.

We've also been working on a more scientific approach with programs in our CellPACK suite. These allow scientists to create detailed models based on experimental data from proteomics, EM tomography, and structural biology (see image on the right).

David Goodsell



Model of a mycoplasma cell, created with CellPACK and associated software by David S. Goodsell and Ludovic Autin (2018). The membrane is shown at the bottom, and is clipped away at the top to show the DNA (orange) and soluble molecules (proteins, ribosomes, etc, in blue).

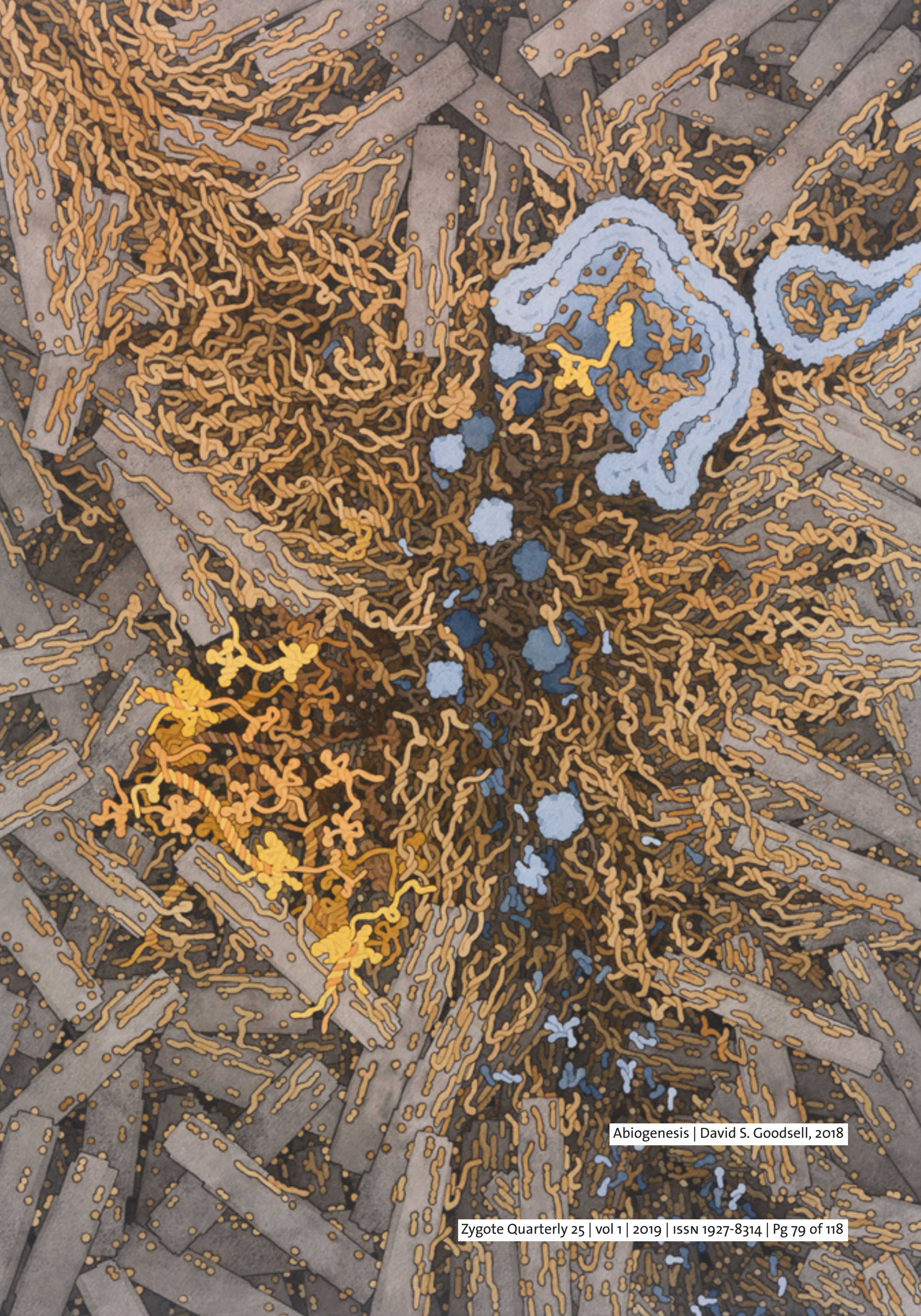
Portfolio
David Goodsell

Any recent exciting projects you want to tell us about?

I had the opportunity to spend a month painting at the Djerassi Resident Artists Program, summer of 2018. I focused on creating two large paintings of the origin of life. "Abiogenesis" (see image on the right) shows some of the mechanisms for the early development of self-replicating RNA and small lipid vesicles, and "Last Universal Common Ancestor" (pp. 80-81) shows one conception for the primordial cell that gave rise to all modern life on Earth, caught in the process of dividing. ×

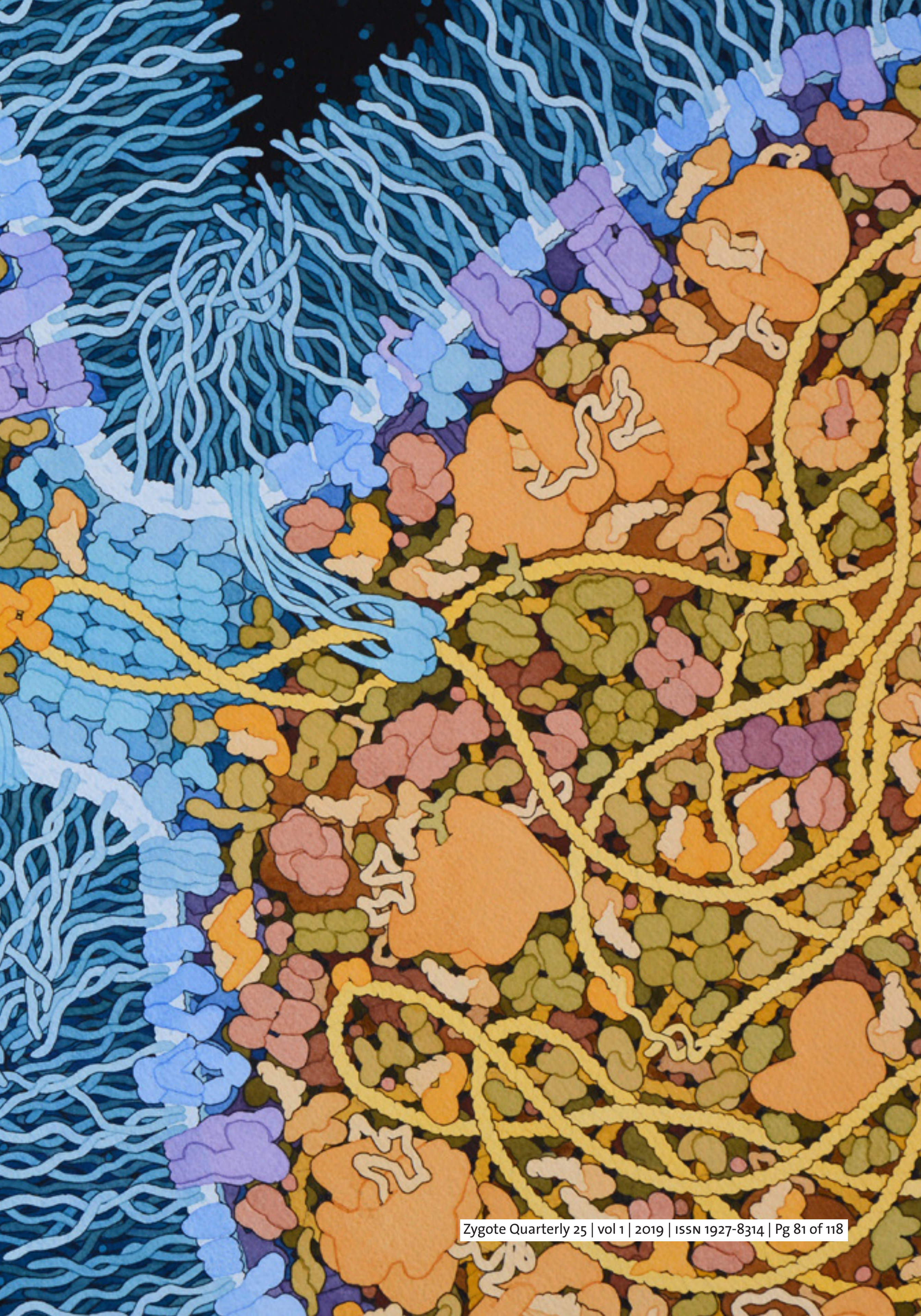
We would appreciate your feedback on this article:

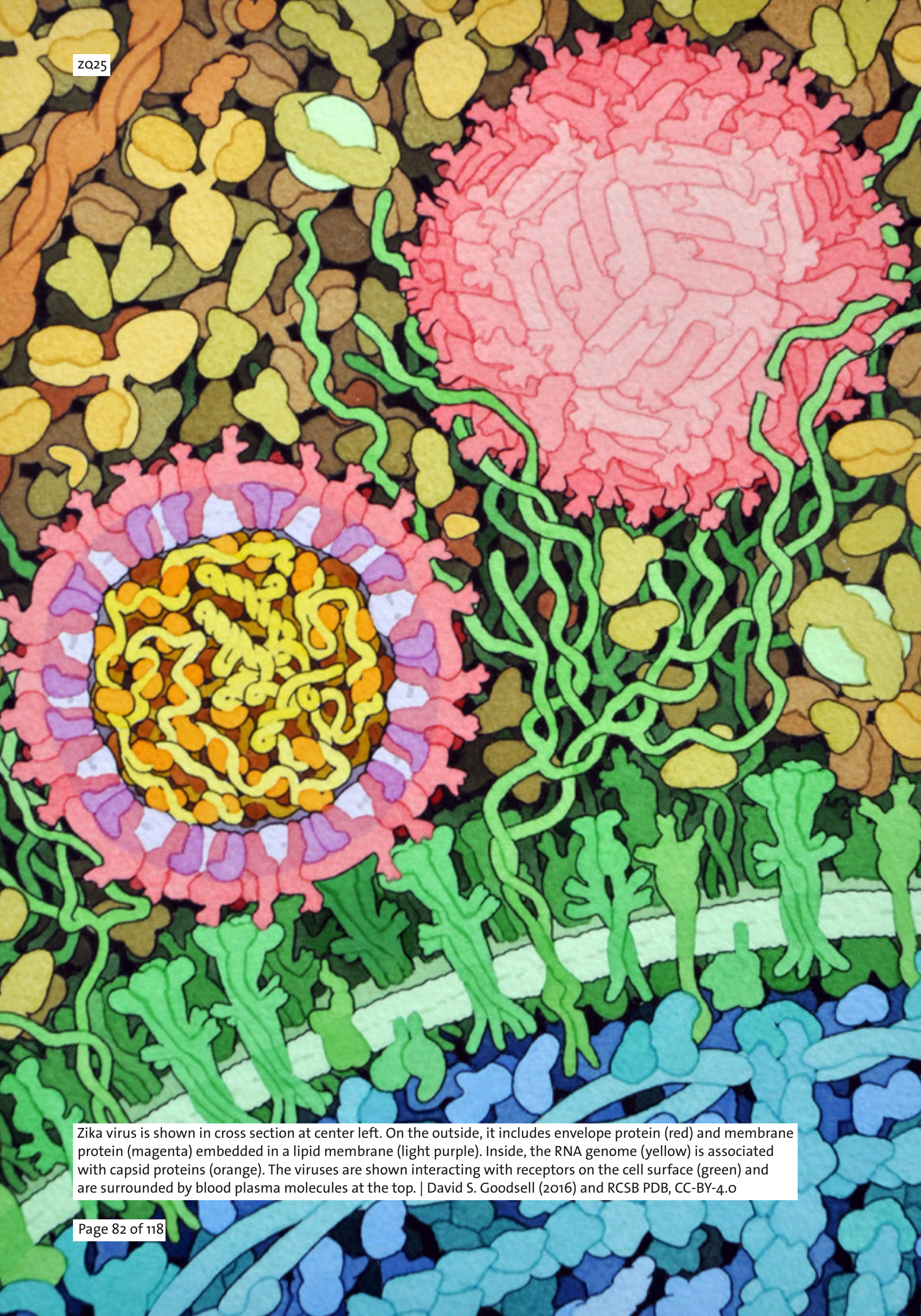
David Goodsell's paintings reveal the incredible beauty of the living cell
https://www.youtube.com/watch?v=2ZSoknG7wfo



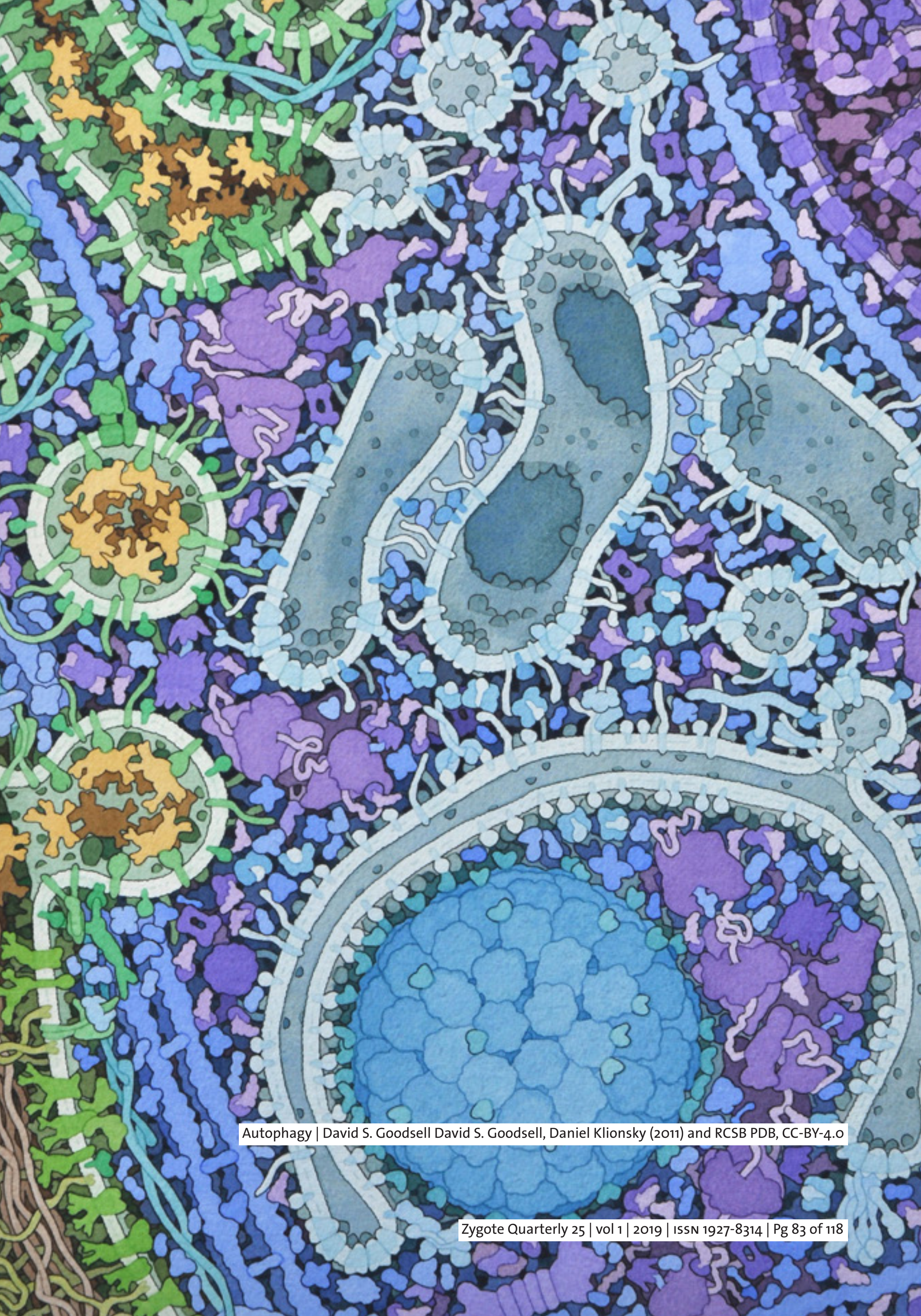
Abiogenesis | David S. Goodsell, 2018

Last Universal Common Ancestor | David S. Goodsell, 2018



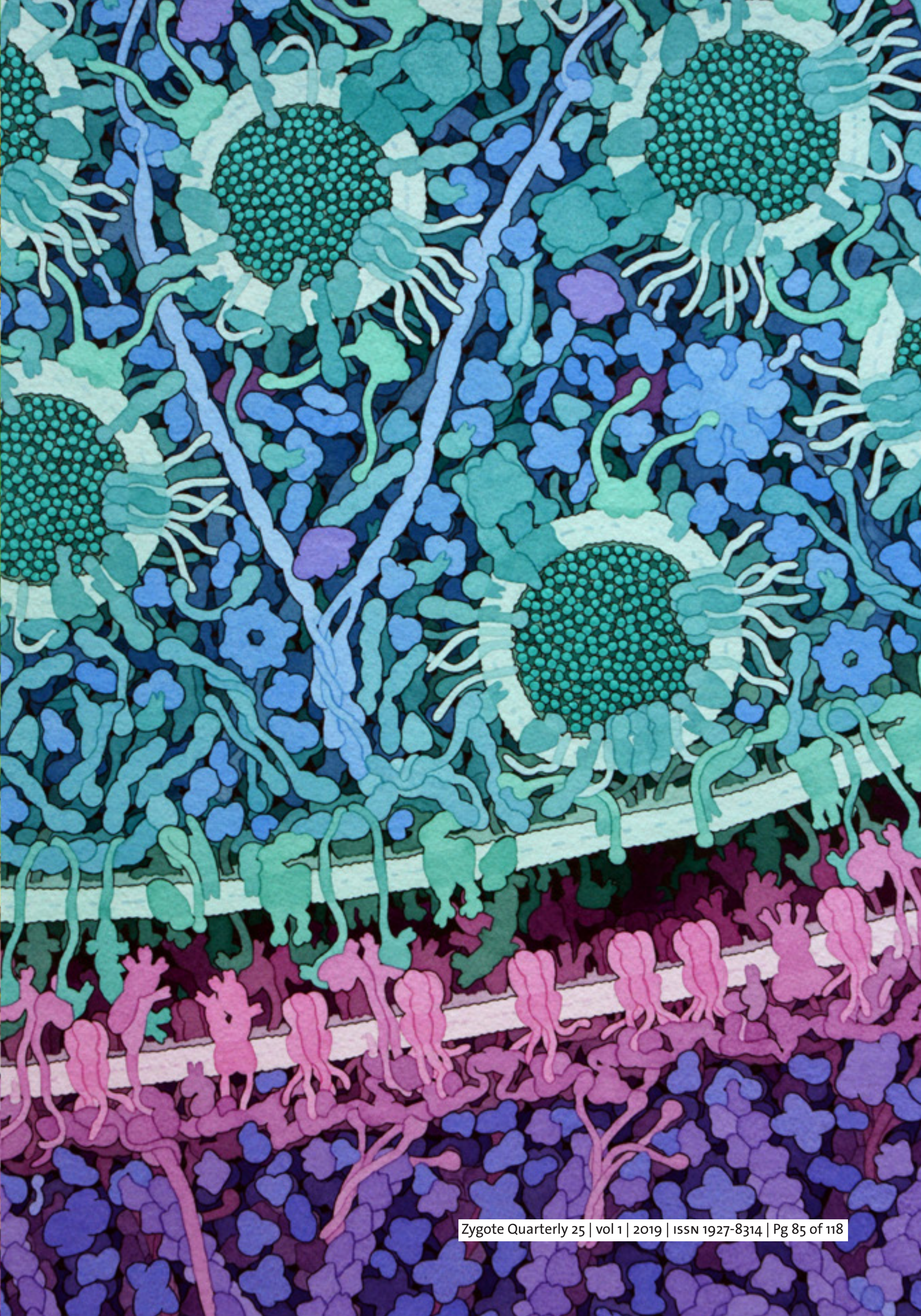


Zika virus is shown in cross section at center left. On the outside, it includes envelope protein (red) and membrane protein (magenta) embedded in a lipid membrane (light purple). Inside, the RNA genome (yellow) is associated with capsid proteins (orange). The viruses are shown interacting with receptors on the cell surface (green) and are surrounded by blood plasma molecules at the top. | David S. Goodsell (2016) and RCSB PDB, CC-BY-4.0



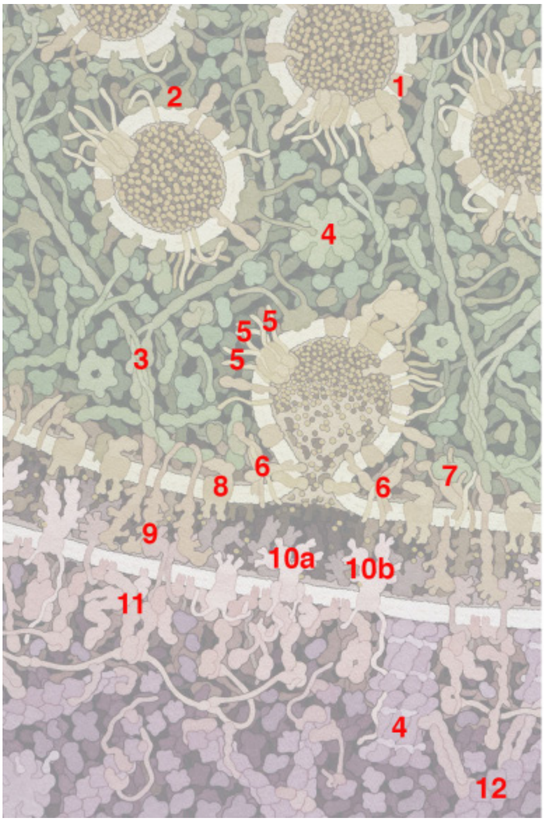
Autophagy | David S. Goodsell David S. Goodsell, Daniel Klionsky (2011) and RCSB PDB,

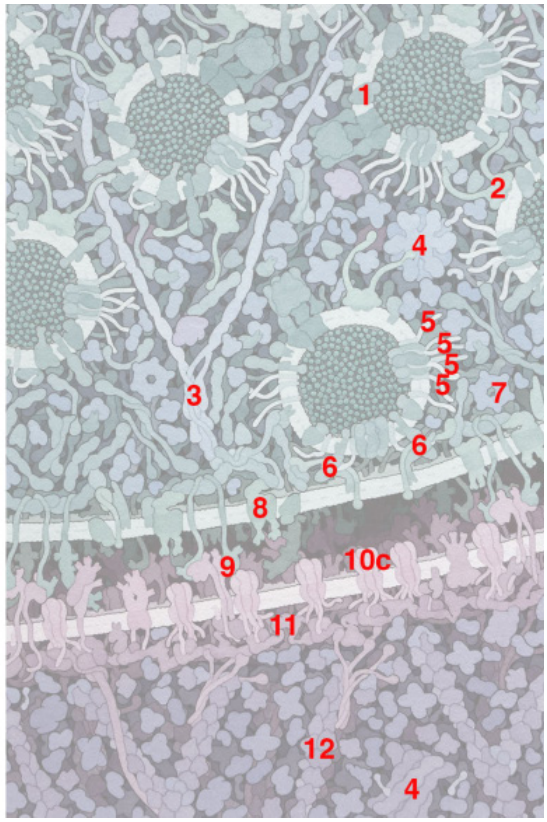
Excitatory and Inhibitory Synapses | David S. Goodsell (2018) and RCSB PDB, CC-BY-4.0



Portfolio

David Goodsell





Key for Excitatory and Inhibitory Synapses

1. Transporters pump glutamate or GABA into vesicles.

2. Synapsin holds vesicles in storage.

3. Scaffolding proteins guide vesicles to the surface.

4. CaMKII (Calmodulin-dependent protein kinase II) regulates the action of many proteins.

5. SNARE proteins will fuse vesicles with the membrane.

6. SNARE complexes have docked the vesicle in the inhibitory painting, and fused the vesicle with the membrane in the excitatory painting.

7. NSF protein separates the SNARE proteins after fusion.

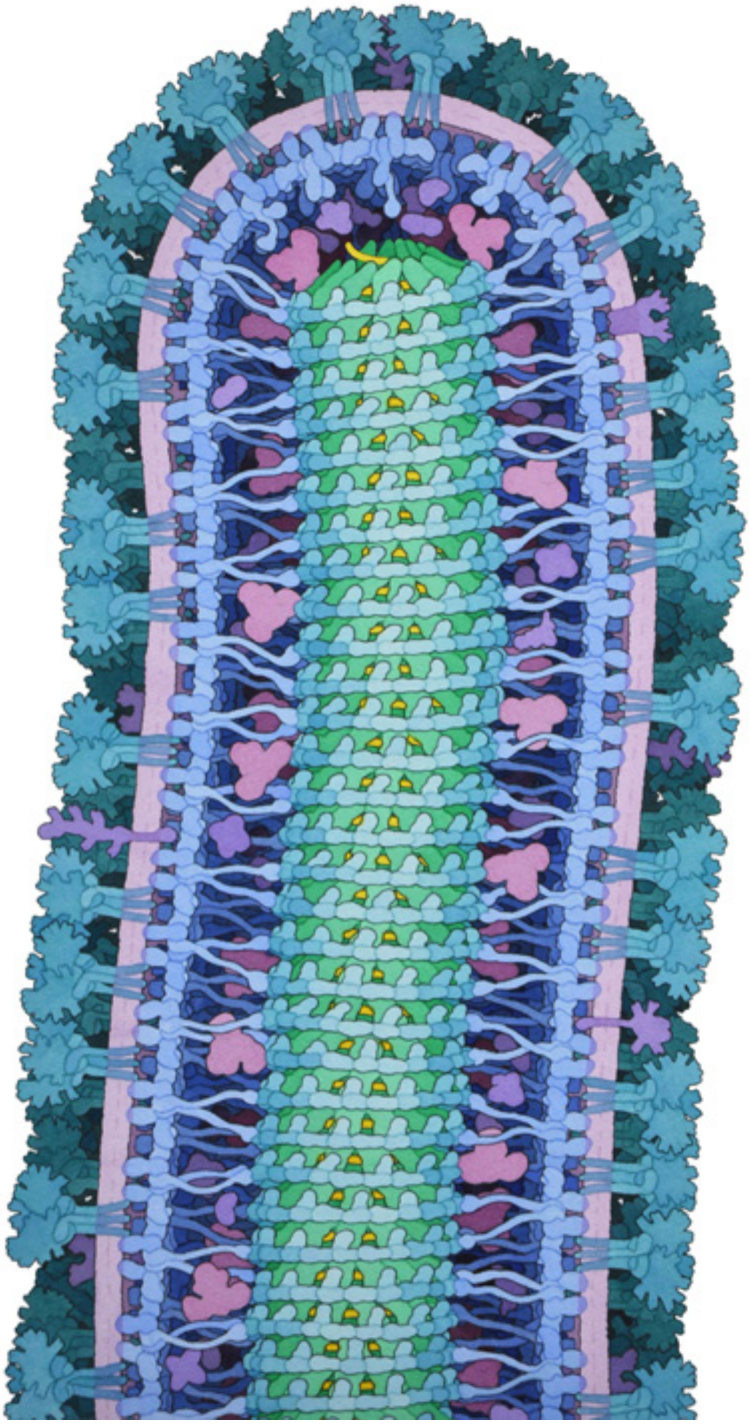
8. Voltage-dependent calcium channels trigger release of neurotransmitters.

9. Neurexin and Neuroligin connect the two cells across the synapse.

10a. AMPAR (glutamate receptor), b. NMDAR (glutamate receptor), and c. GABA receptors bind to neurotransmitters and allow ions to enter the receiving cell.

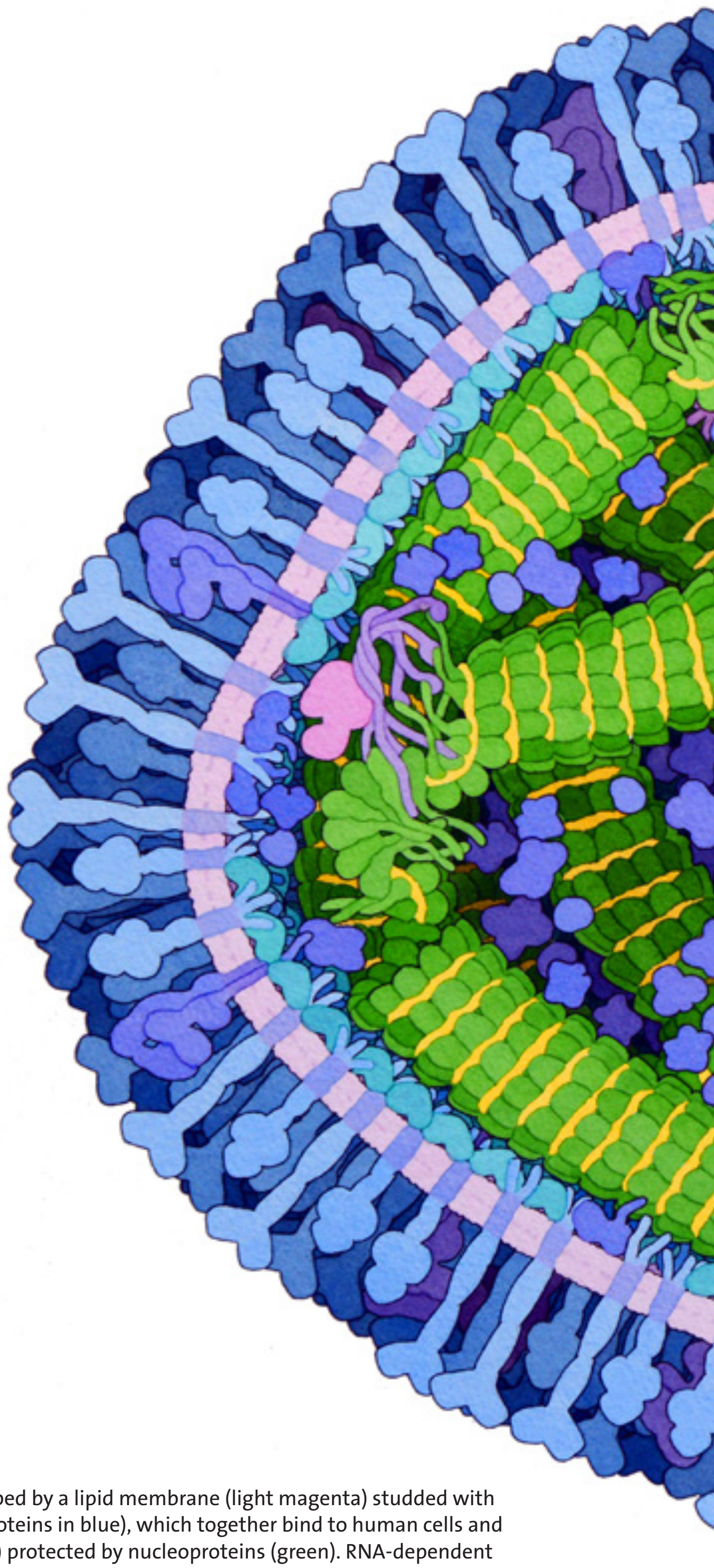
11. Postsynaptic density proteins form a scaffold to support the receiving cell.

12. Actin filaments are part of the cytoskeleton.

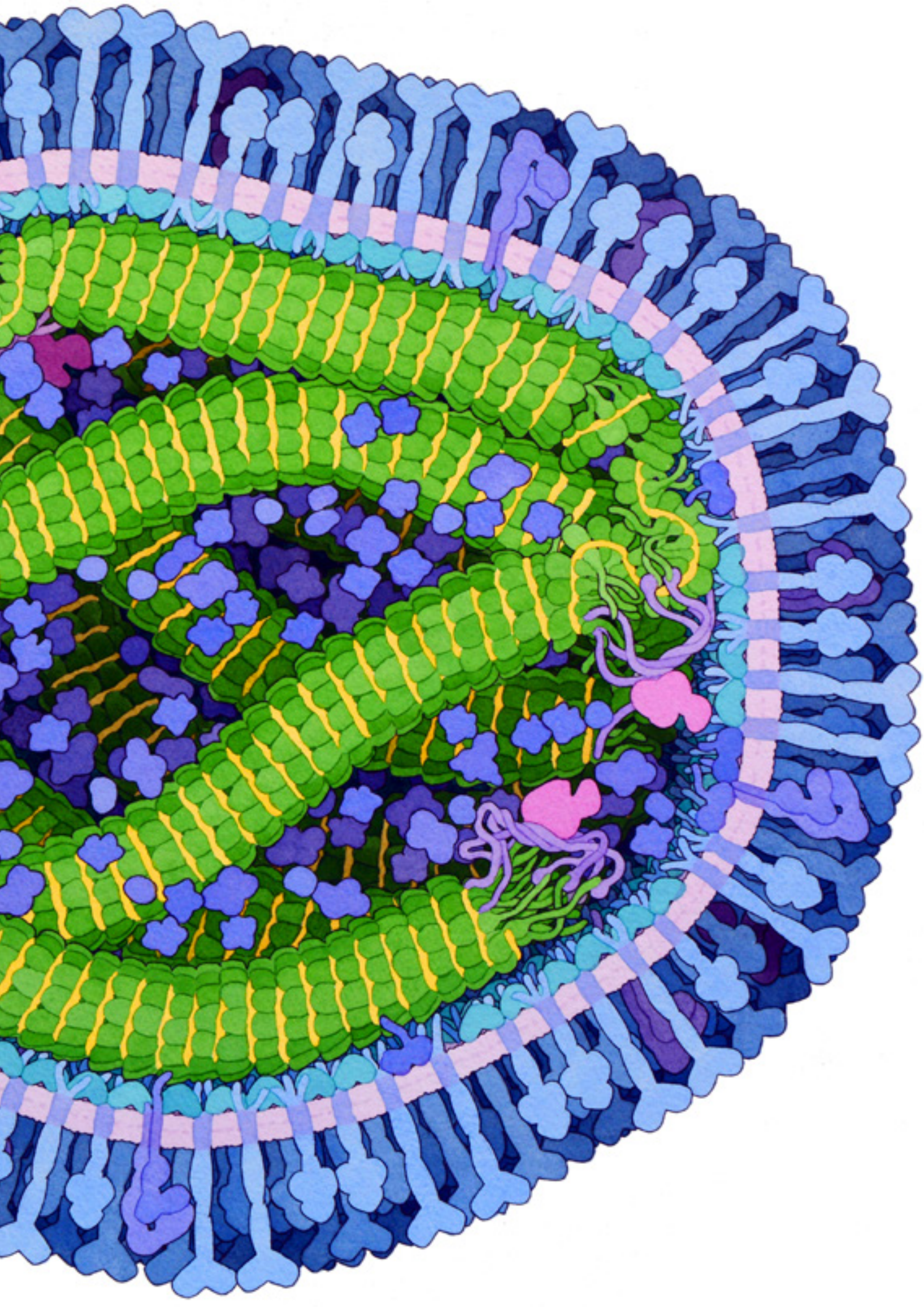


Cross section through ebola virus shows proteins in blue, green and magenta, the RNA genome in yellow, and the membrane in light purple.

Portfolio
David Goodsell



Cross section through measles virus. The virus is enveloped by a lipid membrane (light magenta) studded with many hemagglutinin and fusion proteins (outermost proteins in blue), which together bind to human cells and enter them. The viral genome is a strand of RNA (yellow) protected by nucleoproteins (green). RNA-dependent RNA polymerase (bright magenta) copies the RNA once the virus infects a cell, assisted by the largely-disordered phosphoprotein (purple strands connecting the polymerase to the nucleoprotein). Matrix protein (turquoise) helps the virus bud from infected cells. Several human proteins, such as actin and integrins, are also caught in the budding virus (shown in purple). | David S. Goodsell (2019) and RCSB PDB, CC-BY-4.0



Turquoise Longhorn (*Prosopocera lactator*)
Photo: Bernard Dupont, 2013 | Flickr cc

Interview
Annick Bay

Interview
Annick Bay

How did you get involved with fireflies?

Prof. Jean-Pol Vigneron of the Université de Namur was studying biophotonics, such as iridescent or structural color in beetles and butterflies. He often travelled to Panama to collect samples. He was relaxing one evening while the sun was setting, and fireflies were popping up making a beautiful light show. He realized that the fireflies must face the same challenges of light extraction as we do. When light is produced in a material that has a higher optical density than air, light gets trapped in the emitting material due to total internal reflection. He collected some fireflies and brought them to the lab.

I started studying physics because I was passionate about understanding how the world around me works. Although physics provided answers, it also raised questions. I wanted to study something that was more tangible, and where I could see the impact right away. I was in my last year of my Master's degree, looking for a thesis topic, and asked Prof. Vigneron whether I could work with him. Studying fireflies attracted me and I saw the potential for applying the research to improving the efficiency of LEDs.

Annick Bay

What did you discover about fireflies?

I had been working on structural color in beetles that involved specific structures at sizes of 400 to 700 nanometers, comparable to the wavelength of light. When I looked at fireflies under a scanning electron microscope, I found intriguing structures of the expected size. However, when I modelled the structures, they only slightly improved light extraction. I took a step back, had a closer look at the exoskeleton of the firefly abdomen, and found something that I did not expect: scale-like structures with a periodicity of ten micrometers that protruded about three micrometers. Although the structures were ten times larger than I had predicted, it turns out that they significantly increased light extraction (Bay, Cloetens, Suhonen, & Vigneron, 2013).

Polyteles coelestina (weevil) in the Bolivian jungle (close to Santa Cruz) | Photo: Annick Bay

Interview
Annick Bay

What did you bring to the research, and how did the research influence you?

As physicist, I looked at the firefly's bioluminescent organ from a completely different perspective than a biologist by bringing expertise and techniques for studying the structures influencing light propagation and extraction. Through the research and attempts to model the structure of the firefly's abdomen, I began to appreciate the firefly as a living organism that optimizes multiple parameters including rigidity combined with flexibility while being water repellent, instead of only focusing on light extraction. Constantly comparing the performance of the firefly to my models forced me to question my assumptions and take off my "physicist glasses".

How did you further develop your research?

I continued working on fireflies for my PhD. The refractive index of the firefly abdomen was about 1.56 – theory predicted that only 20% of the light would escape through a flat interface. The inherent variability and complexity of living organisms made validating the theory difficult – we could not establish a baseline to assess the benefits of the structures I had found because we had no examples of fireflies from the exact same species with smooth abdomens, nor could we remove the surface structure in a living firefly.

LEDs were a technical analogy of the firefly abdomen that enabled us to measure light extraction with a smooth surface and compare it to a surface with the firefly-inspired pattern. We partnered with a post-doctoral researcher, Nicolas André, at the University of Sherbrooke who worked in a manufacturing lab and was able to develop LED layers incorporating structures of different shapes and sizes to experimentally determine the effect on light extraction. Once we had adapted our model to the higher refractive index of materials used in LEDs, we demonstrated that our patterned surface increased light extraction by up to 55% (Bay et al., 2013).

What kinds of skills did you have on your team?

Prof. Vigneron was a physicist who started out researching electron diffraction and later switched to studying electro-magnetic (light) waves. He started his work in a solid-state physics lab that transitioned into a more experimental laboratory, giving our team access to specialized equipment. Nicolas André, working in the team of Prof. Laurent Francis at the University of Louvain and doing his postdoctoral research at the University of Sherbrooke, had a strong engineering background and manufactured the factory-roof structure on the LED. We also worked with biologists in museums in Washington, New York, and Brussels to better understand the morphology of fireflies. We found it difficult to find biologists currently working on the morphology of fireflies – they tended to specialize at the cellular level. Interdisciplinary work is highly prized but is hard to accomplish.

Did you try to commercialize your research?

My PhD advisor had experienced issues in the past where academic/industry partnerships restricted what could be published due to intellectual property concerns. The bread-and-butter of researchers is publishing and getting grants, so the decision was made to publish the firefly results first and explore industry relationships later.

There were many factors that inhibited the transition to a commercial product included the level of support from university technology transfer offices, shifts in funding, team members moving on, and changes in lab direction. We did not test the durability of the structures layer that was added to the LEDs. The research is publicly available and it is possible that LED manufacturers used the now commonly available knowledge to improve their LEDs.

What are you working on now?

I worked for two years as a post-doctoral researcher in a marine biology lab at the Scripps Institution of Oceanography (San Diego). I wanted to get out of academia and extend my understanding of how the world of business works. I did management consulting in Munich for a year and a half but missed the science side. Although one of the companies was involved in semiconductor manufacturing, we spent only a little time on the product and then moved on to sales and operations strategies. I moved to Boston and joined a startup accelerator in the life sciences that provides a better balance of my scientific curiosity and my desire to make a difference.

What is the last book you enjoyed?

I am reading *Lost in Math: How Beauty Leads Physics Astray* that suggests striving to create a beautiful story can blind us to the complexity of the real world. We all observe the world through filters. Based on my background in physics, I was first focusing on structures smaller than a micrometer. I was convinced that the answer to improved

Cicada in the Bolivian jungle (close to Santa Cruz) | Photo: Annick Bay light extraction in fireflies would be found in the sub-micrometer range. The challenge is to look beyond the simple solutions and be open to the complexity of the real world.

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

I watched the documentary *Free Solo* and went to a talk by Alex Honnold, the American rock climber renowned for his free solo ascents. It was fascinating to understand how long and hard he prepared for a single goal, his dream. I was impressed by his dedication and patience, even though probably most people told him not to do it...

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

I believe my dream job would be wildlife photographer. I love being outdoors and find it to be a very humbling experience to observe nature closely, trying to grasp all its complexity. ×

We would appreciate your feedback on this article:

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Turquoise Longhorn (*Prosopocera lactator*) | Photo: Bernard Dupont, 2013 | Flickr cc

Darwin's beak
Photo: Stefano Cieri, 2012 | Flickr cc

Article

Envisioning Biomimicry Through an Ontological Lens

Colleen K. Unsworth, Thibaut Houette, Sarah J. McInerney, Austin M. Garner, Peter H. Niewiarowski

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Introduction

Ontologies are tools used to curate, organize, and learn from data and information in novel ways. As described by Dr. Julian F.V. Vincent in a previous *Zygote Quarterly* article (ZQ05, https://issuu.com/eggermont/docs/zq_issue_05/102), ontologies differ from databases by serving as networks of interrelated knowledge linked by defined relationships and semantic reasoning. The ontology extends beyond the basic framework of the database by allowing the creator to define semantic relationships between inputted terms, then automatically inferring implicit relationships between those and the other information within the collection. Ontologies typically involve formal naming schemes and definition of categories, properties, and relations between concepts in one or more domains. Although sometimes appearing complex, ontologies seek to limit complexity of information by organizing it into predefined and inferred relationships, effectually turning information into knowledge. As 20th Century philosopher Ludwig Wittgenstein said, “The problems are solved, not by giving new information, but by arranging what we have always known” (Malcolm, 1958).

Biologically-based ontologies, such as the Gene Ontology (Gene Ontology Consortium, 2000), demonstrate the potential utility of ontologies for constructing, organizing, and extracting information and knowledge from a dynamic source of heterogeneous and widely distributed data. In the past decade, the ontological framework has shown intriguing potential to further serve as a foundation for biomimicry tools. Biomimicry, the emulation of patterns and strategies underlying nature’s designs and processes for human-made engineering and design, will hereby refer to the broader field including bio-inspired design and biomimetics. Multiple ontologies for biomimicry exist at various stages of development including the BioMimetic Ontology (BMO) (Vincent, 2016), the Biomimetics Ontology (Kozaki & Mizoguchi, 2014), and the Ontology for Bio-inspired Design (Yim et al., 2008). Biomimicry has a fundamental complexity to it, as it seeks to abstract and translate basic functional principles from natural organisms and processes, which are in turn affected by ecological and biological trade-offs, random biological effects, and behavior metrics. The ontological framework is designed to accommodate the complexity of such domains through the curation and organization of information that is related or modeled in such a way that it is useful to people.

Darwin's finch | Photo: Anna, 2011 | Flickr cc

Envisioning Biomimicry Through an Ontological Lens

Colleen K. Unsworth, Thibaut Houette, Sarah J. McInerney, Austin M. Garner, Peter H. Niewiarowski

The word ontology has philosophical and computer science roots (Lambrix, 2004). In this commentary we restrict our discussion of ontologies mainly to the computer science context, especially as it relates to modern knowledge-based systems that are developed for and by humans and machines to take advantage of the enormous data availability on the semantic web (d'Aquin et al., 2007). Although a formal framework for building ontologies can be traced back to at least 1995 (Uschold and King, 1995), specific methods and tools for creating various stages in the life cycle of an ontology are very much emergent (Ashraf et al., 2015). Our commentary on the potential of ontologies to advance knowledge construction, capture, and retrieval considers some of the challenges and opportunities associated with a multi-domain context (biomimicry brings together at least biology, engineering, and design).

Perspectives on usefulness as biomimicry tools

We are an academically diverse group of Ph.D. students at the University of Akron with a common interest in biomimicry who decided to explore ontologies in a biomimicry special topics course in the spring of 2018. Our class consisted of seven Ph.D. students with an array of backgrounds including biology, engineering, physics, architecture, and computer science. Throughout the course of our work, we collaborated with Dr. Vincent and Dr. Jacquelyn Nagel, a systems engineer and biomimicry specialist, to explore the usefulness of ontologies for biomimicry. We realized early on that for ontologies to be useful as tools for practitioners, we needed to gauge how developers and users would like to use them. Through dialogue with biomimicry practitioners and potential users from industry and academia, we gathered the following perspectives.

According to Dr. Vincent, "from the biomimetic point of view, the ontology has to be a machine for solving problems." His BMO uses trade-offs to define problems in context, and through established relationships, the ontology can be "directed towards a biological resolution of the trade-off and make a recommendation for its resolution." Dr. Vincent acknowledges the complexity present in the system, but also reminds us of the "richness of information embedded within." Although currently in an experimental state, Dr. Vincent hopes to streamline the addition of more information into the BMO, as well as develop a front-end for engineers to access it.

As we aimed to gather a wide perspective on the usefulness of ontologies within both academia and industry, we interviewed Dr. Nagel who has experience working in both settings. We hoped to gain insight from her on how a biomimicry tool could be useful in both contexts. She shared that “facilitating the interaction between the engineer and the biological information so that it may be easier for the designer to make the necessary connections or analogies leading to bio-inspired designs” is paramount for successful biomimicry tools. To this end, Dr. Nagel developed the Engineering-to-Biology (E2B) Thesaurus that enables “an engineering designer that has limited knowledge of biology to search for and discover biological inspiration using engineering terms,” and vice versa. This aligned with our view that involving multiple disciplines in the biomimicry process and tool development would greatly benefit practice in many cases.

Another unique perspective we gained was from the PeTaL (Periodic Table of Life) team at NASA Glenn Research Center. The PeTaL team is working to develop an automated design tool to streamline the nature-inspired design process and promote deeper understandings of natural systems. PeTaL will ultimately be structured around an ontology based on natural structures, functions, behaviors, and environments. Principal Investigator Dr. Vikram Shyam, expressed his view that “humans aren’t good at making connections,” and that ontologies help us represent real world entities through hierarchies and relationships. He further explained that ontologies aid in tracing and identifying how seemingly small factors impact the larger system. He suggested that ontologies can be used as tools to ultimately aid humans in decision making.

A final perspective we find important to note is the biologist's perspective. Many projects referenced as biomimicry are being developed with limited input from biologists and sometimes use nature's inspiration as a marketing strategy for industry. By removing biologists from the equation, the project scope is limited to a small subset of biological strategies. This is probably one of the reasons why numerous biomimicry projects mostly exploit a few known and recurrent biological strategies. On the other hand, biologists can help unlock knowledge beyond what is easily accessible and can be defined as common knowledge, specifically during the identification of biological models and the abstraction of biological principles (see McInerney et al., 2018 for more information about the importance of biologists in the biomimicry process). The University of Akron Biomimicry Research and Innovation Center is actively bringing


Darwin Finch | Photo: tim ellis, 2008 | Flickr cc

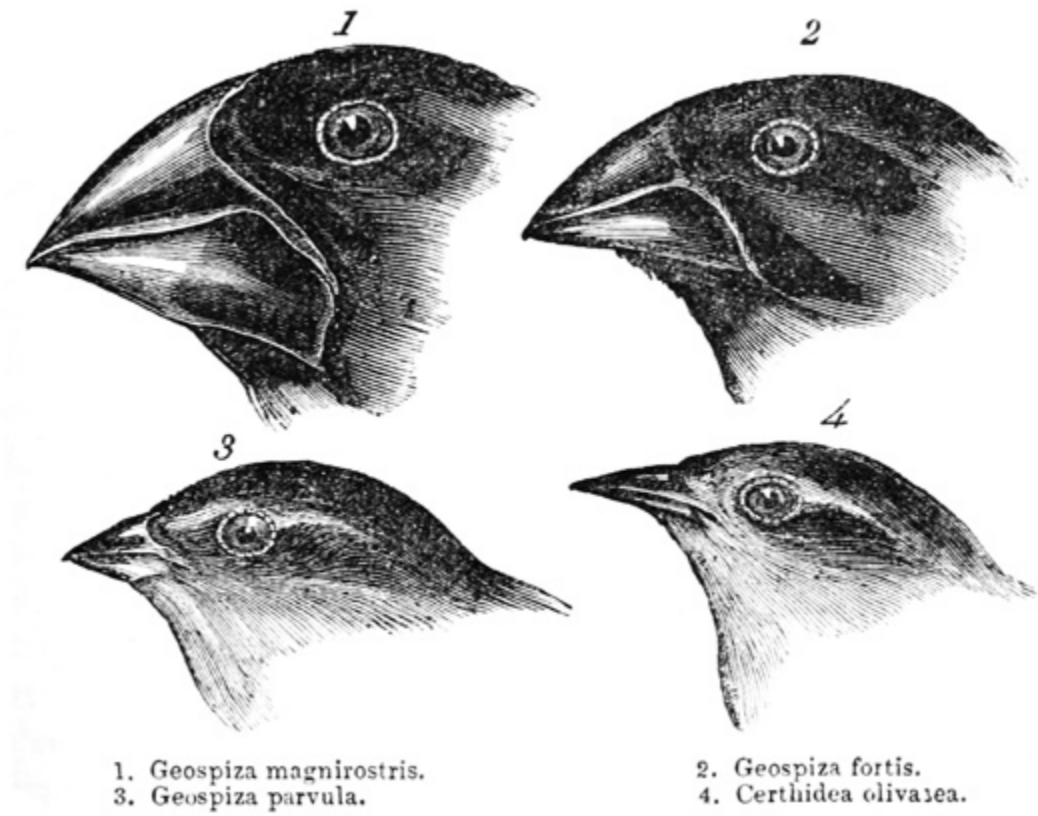
biologists into the biomimicry process, especially in industries through a Fellowship Program. Thus, by having a network of information turned knowledge, e.g. an ontology that captures or can capture some of the complexities associated within biological systems at their disposal, biologists can better assist multidisciplinary groups engaged in the biomimicry process, and this may eventually uncover novel connections and collaborations.

The insight we gained from these dialogues and among our collaborators suggests that ontologies can be useful to biomimicry, but currently only to a small group of users. Since biomimicry is inherently transdisciplinary, a developer of a biomimicry ontology must integrate information from multiple disciplines, as compared to those that create an ontology for a single discipline domain. In order to target a larger audience, more interdisciplinary translation and simplified user interaction must be integrated. Moreover, Dr. Vincent's BMO and the PeTaL project show that ontologies for biomimicry have the potential to be used as either standalone tools or as tools integrated into larger systems, which further expands their utility.

Current hurdles to the widespread use of ontologies for biomimicry

Despite the success of ontologies in many fields, there are notable hurdles to the widespread use of ontologies for biomimicry including content retrieval, information translation, content delivery, creator bias, and relevance to diverse disciplines. Some hurdles are inherent to the use of ontologies in general and can be addressed by following specific structural guidelines, such as provided by the Basic Formal Ontology (BFO) framework. Others require adapting or otherwise straying from an established framework, depending upon the goals of the ontology or the discipline at hand. For biomimicry, many of these hurdles are magnified by the transdisciplinary nature of field as it merges at least two disciplines into a single domain (i.e. biology and engineering). As compared to a single discipline domain, a multidisciplinary domain would require greater integration of diverse content and perspectives if a developer seeks to accommodate and represent all disciplines with the ontology.

When it comes to retrieving and developing content, a developer must consider the sources from which to draw initial data, and how to do so in a standardized way. With today's advances in biology and electronic communication, information is often in excess, and filtering through available data to identify what is most relevant and useful to a biomimicry practitioner poses an interesting challenge. Even once a developer decides what information he or she wants to include in the ontology, he or she then has to figure out how to standardize, input, organize, and maintain the information. Moreover, no ontology can reasonably be comprehensive as access to knowledge is finite, so the developer must deduce what information will be most useful with these factors in mind. Again, this can pose an extra challenge to biomimicry ontology developers as they must consider the needs of not only one, but multiple disciplines if they intend to reach a multidisciplinary audience or user base.



Darwin's finches or Galapagos finches. Darwin, 1845.
John Gould, before 1882 | Wikimedia Commons

Once a developer decides how and what content to include in the ontology, he or she must figure out how to translate the information from data into functional knowledge. The first step in the process involves manually establishing some core relations between related terms, for instance, defining initial hierarchical semantic relationships between classes and concepts. An example of such tagging is the schema Dr. Vincent uses in his BioMimetic Ontology, which involves reading biological literature and linking key biological functions through trade-offs. Once these core relationships are established, the ontology can analyze new and existing information automatically and generate new connections and associations. It's important to keep in mind that the content and relationships defined in any given ontology are largely dependent on the developer's viewpoint, and that there are many, if not endless, ways of relating information.

Due to the dependence of ontology development on individual perspective, many ontologies lack relevance to a wide range of users. While content flexibility can serve as a catalyst for the development of creative and novel knowledgebases, ontologies are often developed to be useful to only a specific discipline. Again, this adds potential issues for fields like biomimicry that have a multidisciplinary domain and brings up some new considerations. Is it appropriate or reasonable to consider making the content useful to more than one discipline? If so, how? For biomimicry, it would be beneficial and maybe even necessary to identify how to develop and deliver content from an ontology in ways that are relevant to biologists, engineers, and designers. Unfortunately, due to the nature of manually defining semantic relationships within an ontology, many of the complex interrelationships are often discipline-specific if they are inputted by a single individual or a small group. This leaves room for jargon and discipline-specific interpretations, issues that could potentially be mitigated by involving more than one discipline in the development process.

Another limitation to the widespread use of the ontologies for biomimicry that exist is their general lack of simplified user interfaces. Currently, the primary access points for most biomimicry ontologies are their development and editing platforms, such as Protégé. Although tremendously useful and effective for developers, these platforms were not designed for general users. Moreover, the content and structure of ontologies is multifaceted and can be explored and interpreted from various angles. Although this can be a benefit to users in some cases, this may also be overwhelming for non-experts, thus discouraging potential users from interacting with them. For ontologies to be useful to a broader range of users, developers need to consider retrieving and delivering their contents in multiple relevant ways through simplified user interfaces.

Potential to extend utility of ontologies through simplified user interfaces

Ontologies' complexity can be daunting for non-expert ontology developers. If the purpose of an ontology is to share the knowledge within it to the widest audience possible, users should have reasonably straightforward access to it. Most users will want a simplified interface which pulls information from the ontology. In this case, the ontology can appear as a black box where its internal structure is hidden and not necessarily understood by the user. On the other hand, adding the potential for users to explore the entire ontology as an extra feature could benefit users that are familiar with them, or those that would like to learn more. In this process, knowledge that was not displayed in the user interface for a variety of reasons can be discovered.

User interfaces typically present a subset of the actual information included in an ontology. The nature and complexity of ontologies raise questions. What does one do with so much information? How can users benefit from this complex knowledge network? What parts of the ontology should be accessible to the audience? User interfaces are a way of selecting relevant information for users, which will differ based on the ontology's purpose and the targeted users.

A user interface could present a common ground where information can be understood by practitioners from diverse fields and facilitate interdisciplinary collaboration. For example, the BioMimetic Ontology follows the trade-off language with is familiar to many biomimicry practitioners, but not necessarily to all potential users. Our team developed a user interface for the BMO called the “E2BMO” to show one way of how users could interact with it. Although not at a fully developed stage, our interface serves as an example of one way to interact with a biomimicry ontology that did not previously have a direct access point beyond its development platform. Numerous interfaces could be generated to access the BMO's knowledge depending on the user’s respective purpose. To facilitate interdisciplinarity and the broader use of biomimicry ontologies, our interface showcases multiple entry points. Details on this work can be found in an article published

Untitled | Photo: Neil Gibson, 2015 | Flickr cc

in the *Designs* special issue "Advances in Biologically-Inspired Design" (McInerney et al., 2018).

In addition to anticipating the users' interaction with an ontology, its fundamental structure needs to be understood by interface developers if the goal is to display the most relevant information to the widest audience. As interface developers are not necessarily involved during development of the ontology, they do not always grasp the creators' vision, thus potentially missing crucial information. To combat this disconnect and streamline the process of making knowledge from an ontology more accessible to more people, ontology developers should not only be concerned with development of their ontology but should also consider how potential users may interact with it in the future. This would involve incorporating various perspectives or collaborating with interface designers in the development process.

Conclusions

Ontologies with user-friendly interfaces have exciting potential to contribute to the future of the bio-inspired design process, as well as to future biomimicry research and innovation efforts. The use of the ontological framework to convert information into knowledge has the potential to be valuable in biomimicry as an ontology can be used to translate abstracted principles between biology, engineering, and design. Ontologies for biomimicry could be used to not only suggest potential solutions to biomimicry questions but could be further utilized as exploratory tools. Exploring ontologies from multiple angles and access points would make use of the diverse knowledge housed within and increase their accessibility to practitioners from a variety of disciplines. Moreover, beyond their potential for usefulness as standalone tools, ontologies could be integrated into larger existing biomimicry tools and projects.

Our work to interface the BMO is only one of many examples of ways to interface an ontology. Every ontology can be uniquely structured with different content based on different core relationships, and each can have multiple entry points and interpretations. We hope that our E2BMO user interface will soon be joined by the development of other ontology front-end interfaces, and that biomimicry practitioners will be inspired to create new ways to interact with ontologies and other biomimicry tools in the future. ×

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