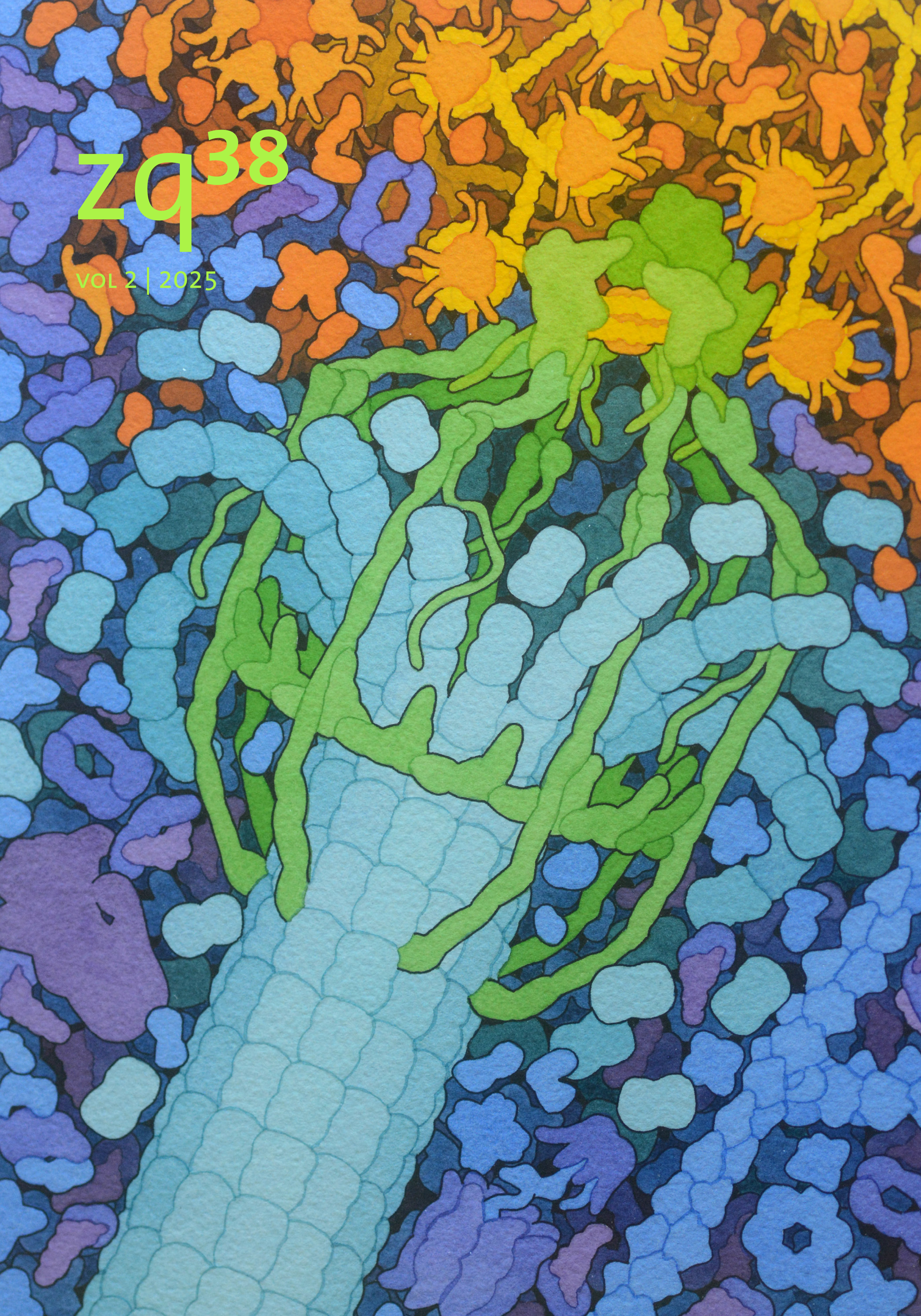

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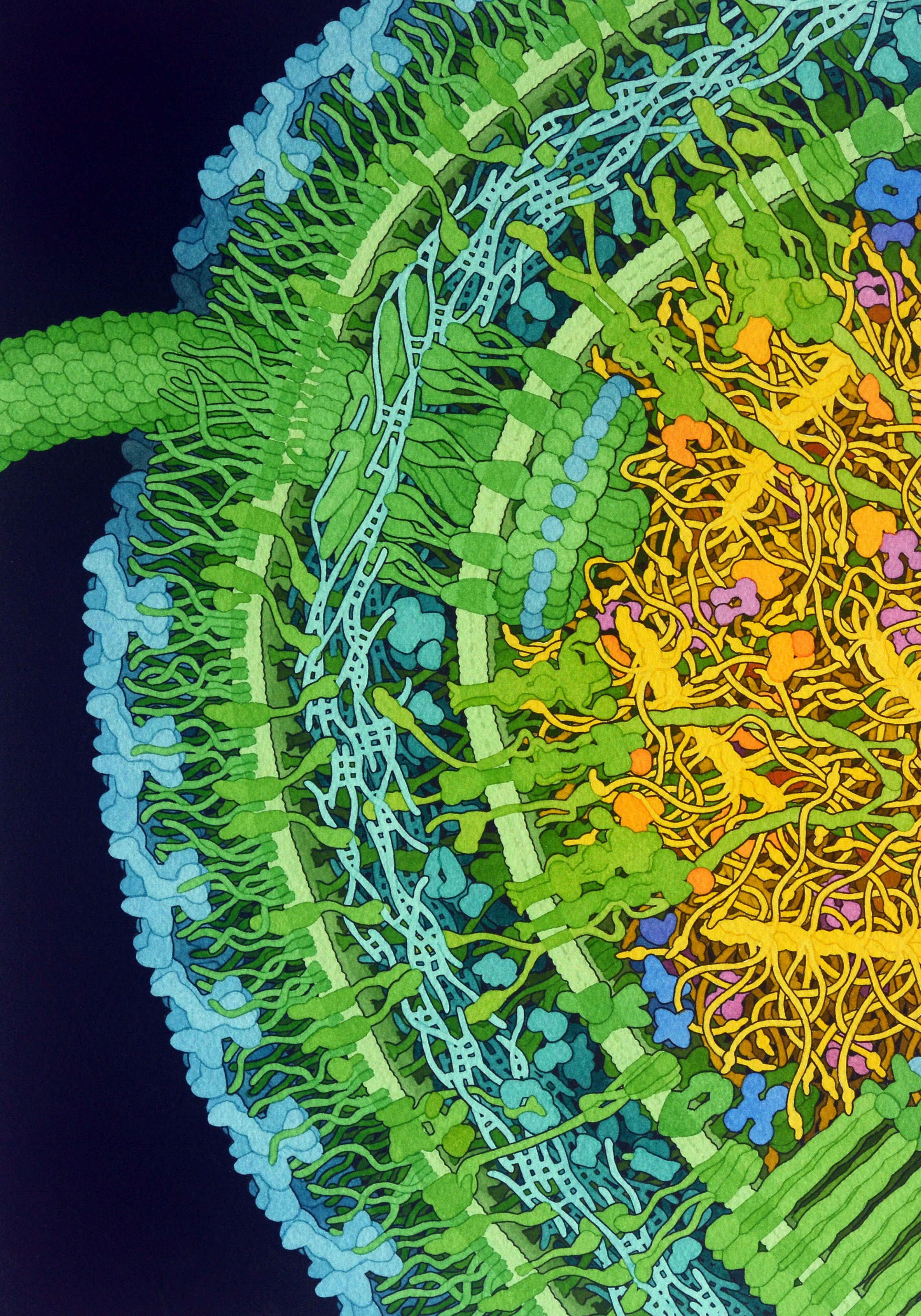
VOL 2 | 2025



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Silverfish (detail) | A silverfish composite image, made up of roughly 1000 photos, taken with a cellphone, through a microscope. Transverse light is switched off, and subject is illuminated with a torch.
Photo: Jessica and David Berliner, 2017

Editorial

Expansion/contraction is a powerful mechanical force in Nature, particularly when it is applied differentially, such as in the reaching and stretching of a twining vine. One can see some of these themes in this issue.

Annabelle Aish, and Tom Challands ask readers to consider reaching back in time for biologically inspired innovation. In *Unlocking innovation through fossils: how ancient life can inspire modern technology*, they point out that 99% of all the life forms that have been on earth are now gone - but need not be lost to our trove of design inspiration. They outline five ways ancient records can inspire and discuss applications and opportunities and constraints to expanding our sources for BID.

Manual Quirós and Oscar Aquado write about the mutualistic relationship between plants and insects that has evolved into the wondrous phantasmagoria of anatomical, structural and chemicals strategies we see today. Reaching across kingdoms to enlist aid in ensuring your progeny can be tricky business, and plants, for instance, are not above a few deceptive practices.

Irene Nooren would like to expand the sources for bio-inspiration in the designing of social organizations. She believes that a rich lode of models can be found at the sub-organism level of life. She cites three principles she has observed at the cellular scale: coherence with unified agency, intrinsic regulation and institutional memory and explains how these principles might be applied to how we organize ourselves. We pair her essay with the exquisite paintings of cellular processes by David Goodsell, whom we have featured in past issues.

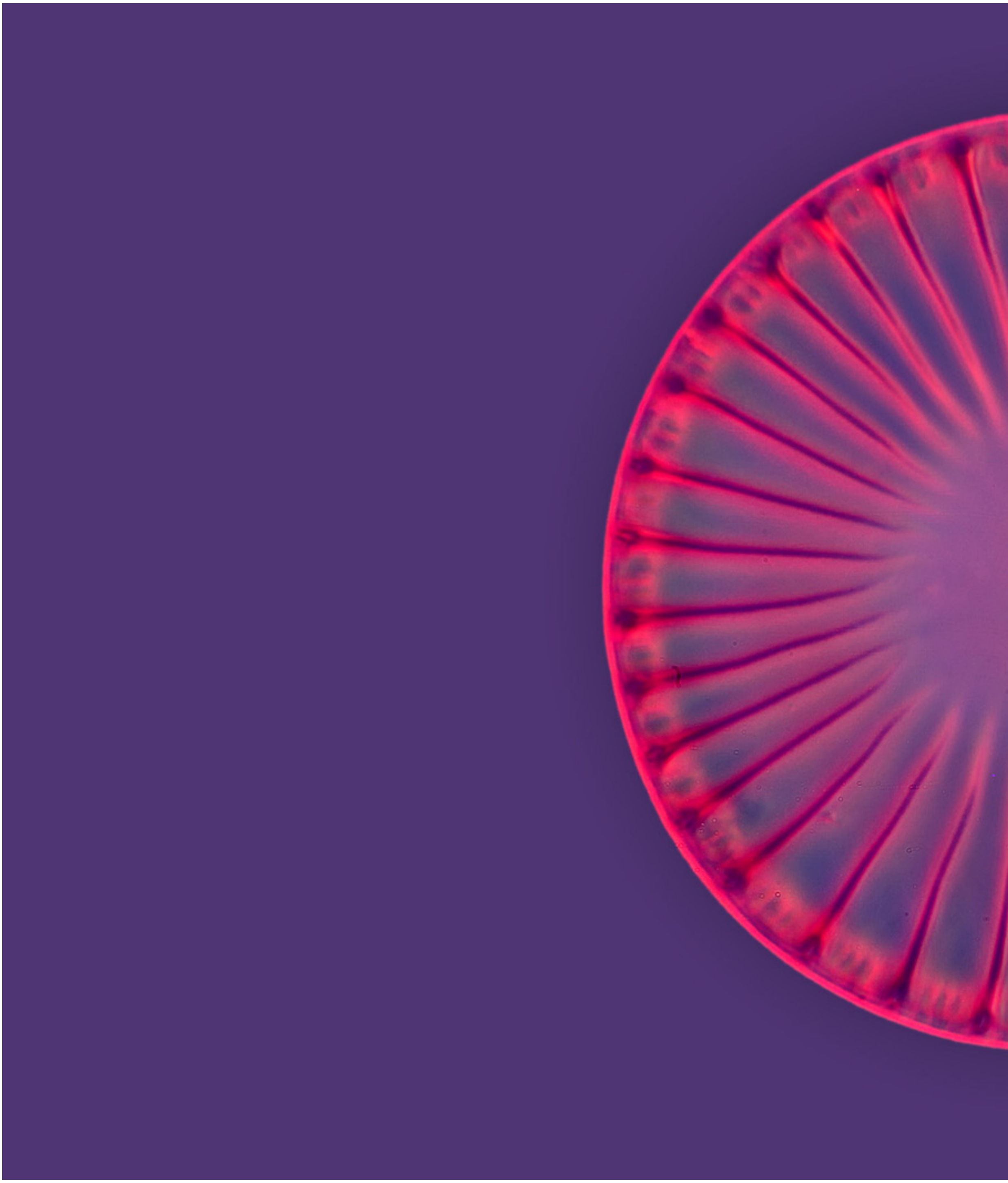
Jess Berliner writes fondly about the late Claire Janisch of South Africa and how she and the company that she founded have reached out to the public to spread the practice of biomimicry.

Finally, we tell the tale of the humble diatom, a one-celled organism that is critical to our survival. The diatom also has lessons to teach about how to make strong structures out of intrinsically weak materials by reaching across linear scales to design hierarchically. Researchers at Caltech, MIT and the University of Genoa have sought to expand our knowledge of mechanical engineering by emulating its makeup.

We hope this issue expands *your* world. Happy reading

Tom, Norbert, and Marjan

Contents



Diatom with Rheinberg Illumination
Photo: Frank Fox, 2011 | Wikimedia Commons

Article

Diatoms: Building Glass Houses

Tom McKeag

Diatoms: Building Glass Houses

Tom McKeag

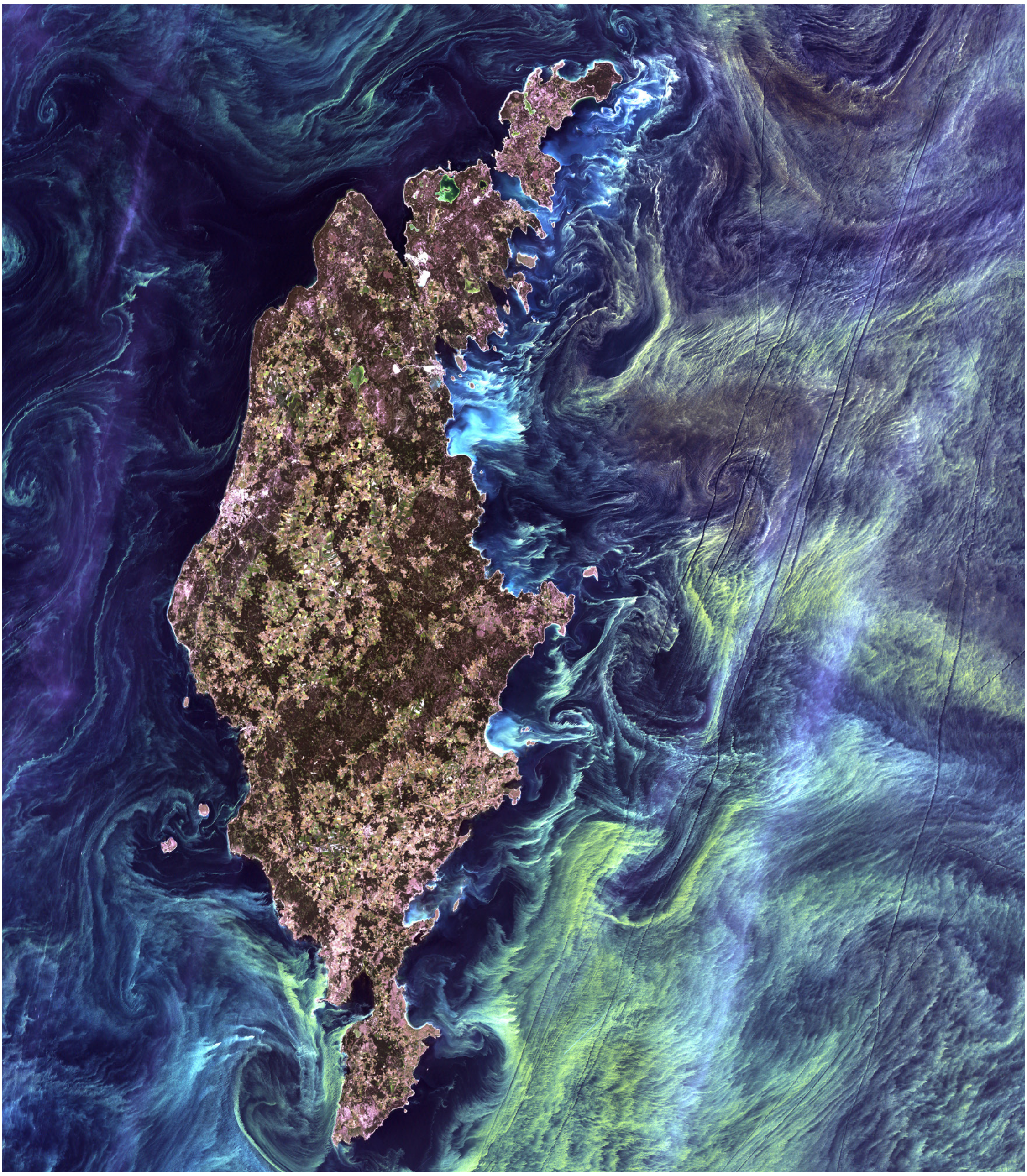
Let's say you wanted to build a transparent case for some valuable items. This case would have to be light enough to float, porous to water, streamlined and compact. Oh, and by the way, it would have to be strong enough to not break when run over by a truck. Would you build it out of *glass*?

Perhaps you might if you were inspired by one of the world's most abundant organisms, the diatom, a single-cell alga, a Eukaryotic phytoplankton that is invisible to the naked eye, yet visible from outer space when blooming with its fellows. It just might be instructive for us to learn from the diatom, for without it, the world as we know it would not exist.

Diatoms are found anywhere there is water, but their prime domain is the oceans, particularly the high latitude ones. They are prodigious primary producers, that is, they turn the inorganic into the organic so that the rest of us may eat; accounting, as a world-shaping byproduct, for 20-30% of the oxygen that we breathe while collecting and sequestering the carbon dioxide that we don't. This is equivalent to the output of all the rainforests of the world combined. Diatoms account for 45% of global primary production, while comprising only 1% of the world's photosynthetic biomass. While all this is done through photosynthesis, a diatom is not a plant, it is an alga, and comprises only a single cell. Its impressive photosynthetic production is achieved because the diatom is also a prodigious reproducer, being both sexually and asexually able, with quick frequency.

Diatoms are the most diverse species of phytoplankton on the planet. Twenty thousand species are known, but as many as two million may exist. Beyond being the basis for all marine life, the global food chain and an oxygenated atmosphere, they represent fundamental inputs to our economy, forming important, ancient geologic deposits and providing raw material used in filtration and non-toxic insect pest management. Much of this economic importance is due to the diatom's unique cell wall; it is made of silica. Upon the death of a diatom its silica exterior will sink to the seafloor and, over (a lot of) time and pressure, these deposits will form the reserves of limestone, chert, oil and gas that our economies depend on.

Diatomaceous deposits make up 26% of the earth's crust by weight. They are also the reason we have a Nobel Peace Prize. In 1867, Alfred Nobel discovered that diatomite, from diatoms, when combined with the unstable nitroglycerin, produced a safer and more stable form of explosive, dynamite. After amassing a huge fortune from the trade in destruction, he endowed the prize fund that bears his name.



Van Gogh from Space: A satellite image of phytoplankton swirling around the Swedish island of Gotland in the Baltic Sea.
Photo: NASA Goddard Space Flight Center, 2005 | Wikimedia Commons

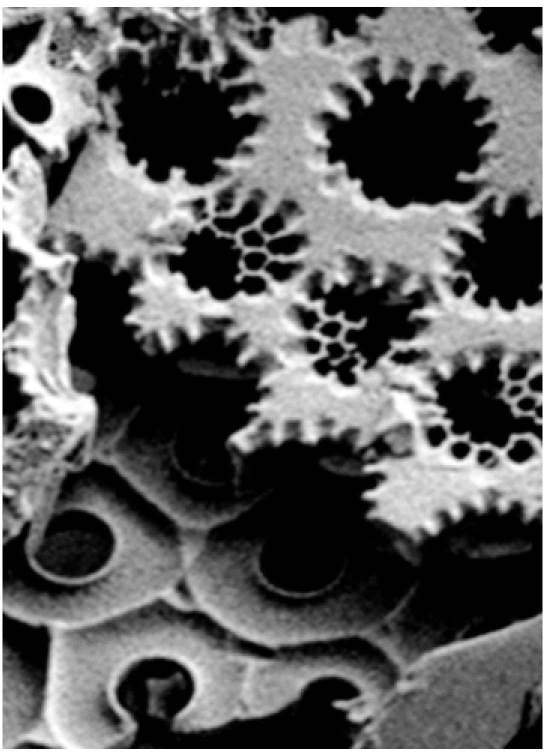
Diatoms: Building Glass Houses

Tom McKeag

Like plants, these diatoms have a cell wall, but this cell wall, uniquely, comprises mainly silicon dioxide, but also proteins, sugars (polysaccharides) and lipids. It is called the frustule and comes in two parts. On radially symmetrical diatoms this frustule resembles a petri dish with its round, overlapping lid and hemispherical girdle bands. Its general construction is that of a honeycomb sandwich, with a two-layer top called a cribellum and a cribrum, and a bottom, basal plate. Between these plates span the hexagonal supports called areolae. The basal plate is punctuated with pores called foramen, one within each of the 5 or 6-sided areolae columns. Diatoms come in two basic shapes, radially symmetrical (centric) and bilaterally symmetrical (pennate), with the latter often represented by peanut shaped forms.

Consider again the design brief for this evolutionary form: it must be porous to allow for nutrient uptake and waste disposal in a water environment; it must be light in order to float and sink within the upper photo zone of the water column; it must be strong and durable to resist crushing and damage from predators; and it must let in light for photosynthesis. A very tall order indeed, and does not completely list all of the biological functionality that this marvel achieves. What is most remarkable is that the material that the diatom uses for solving all of these challenges is so intrinsically brittle. As brittle, as, say glass.

The diatom evolved this type of cell wall about 200 million years ago, by taking advantage of the most prevalent inorganic material on the planet (besides water), silica, and using it for its own organic structure. This new cell wall allowed it to refine its oxygenic photosynthesis and capture more calcium carbonate and carbon dioxide for food production. This evolution changed

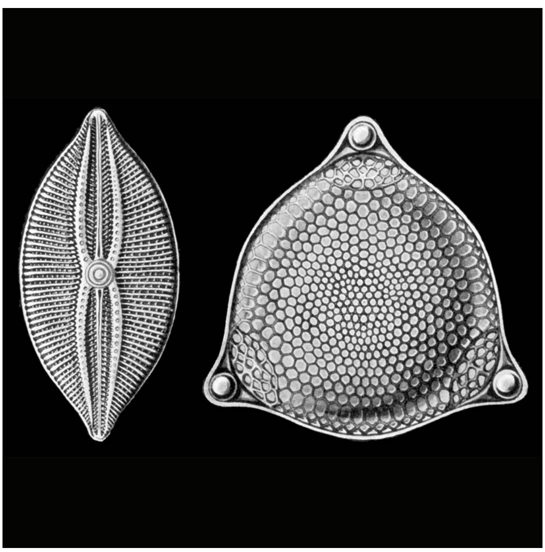


Diatom showing the layered structure (from outside to inside): cribrum, areolae, and foramen. Diatom SEM image adapted from https://doi.org/10.1039/D1NA00691F, under CC BY 3.0.
Image courtesy of Ludovico Musenich and Flavia Libonati, University of Genoa.

the very nature of our atmosphere, pumping more and more oxygen into it, banking carbon and piling up more food for organisms in the food web.

This alga takes up silicic acid ($Si(OH)_4$) in the water, transports it to a silica deposition vesicle (SDV) and there, using proteins and polyamines as control agents, strings the available monomers into compounds of silica, or silicon dioxide (SiO_2) which, in turn, are transported outside the cell to form the cell wall. The cell fuses the SDV membrane with the plasma membrane and then exports the silica outside the cell (exocytosis). It is within this complex process that the intricate and highly geometric shape and pore patterns of the cell wall are formed. This formation is an area of active research and several mechanisms for this have been proposed, including silicification on a preformed scaffold, and a template-independent self assembly. A third hypothesis has been advanced suggesting that physical contact point tethering between the two membranes is responsible for the ultimate shape. Scientists now have powerful new tools for observation with the development of cryo-electron microscopy, which allows the collection of high-resolution images within cells that are vitrified without the alteration caused by chemical fixation or staining.

The material savings of extracting silica from the water came with a cost for this



Selections from Ernst Haeckel's 1904 *Kunstformen der Natur* (Art Forms in Nature), showing pennate (left) and centric (right) frustules.
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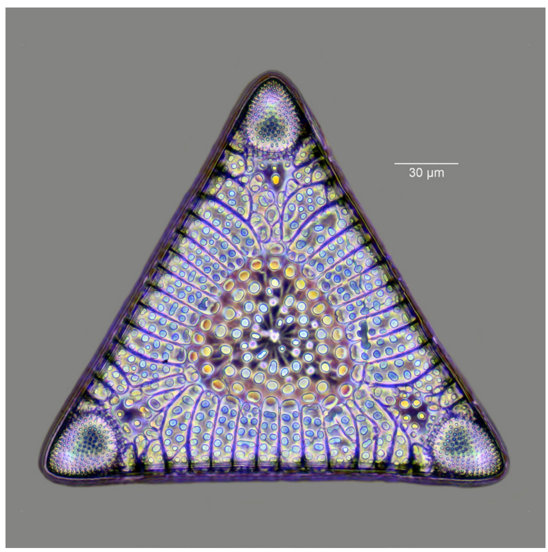
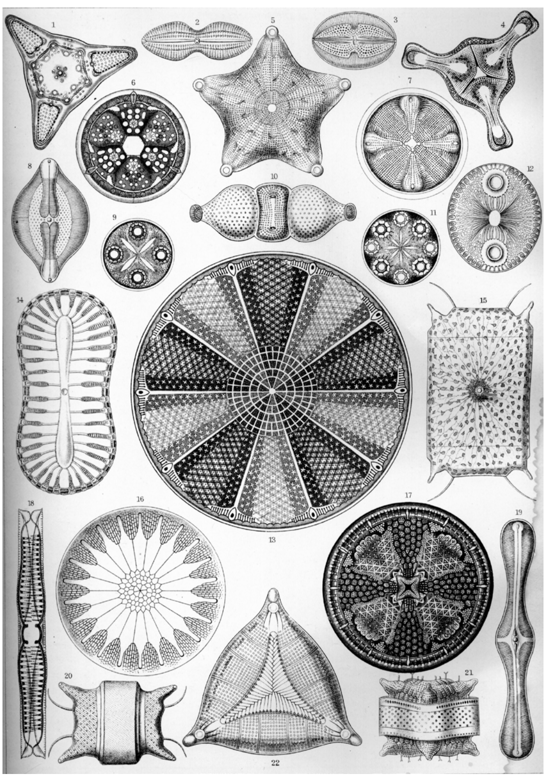


Intricate silicate (glass) shell, 32-40 million years old, of a diatom microfossil
Photo: Anatoly Mikhaltsov, 2014 | Wikimedia Commons

Diatoms: Building Glass Houses
Tom McKeag

single-cell organism, however. The rigidity of silica meant that asexual reproduction, the splitting of the cell into two, would be problematic. When a typical diatom splits into its two daughter cells, they must, necessarily, remain smaller than the parent, constrained as they are by the rigid cell wall. A sequence of splitting means smaller and smaller individuals in the succeeding generations. The diatom ultimately avoids this disappearing act by reverting to sexual reproduction when it reaches a base size.



Ernst Haeckel - *Kunstformen der Natur* (1904), plate 4: Diatomeae
Public Domain | Wikimedia Commons

These patterns and three-dimensional structures measure at the 2-500 micrometer scale (the largest being the width of a human hair), so are largely invisible to the naked eye. When found in abundance, however, their blooms can be seen from outer space. Fortunately, these beautiful shapes can be seen easily with a light microscope and they are ubiquitous, although the Southern Ocean, with its cold temperatures, high oxygen and nutrient-rich waters, is where they are most abundant. Consequently, they have been an object of study and delight since the beginning of the 18th century.

Ernst Haeckel, German biologist and contemporary supporter of Charles Darwin, is perhaps the most famous chronicler of diatoms, having spent 15 years documenting the hundreds of samples collected from the deep sea by the celebrated *HMS Challenger* expedition of 1872-1876. His illustrations are considered works of art, but his interest was strictly scientific, believing in his own taxonomic system and hoping to show visually the evolutionary principles he observed in physical form. While many of his theories have since been disproven (and his social ideology rejected), his was a groundbreaking cataloguing of deep sea life.

He also inspired those in the Art Nouveau movement and many other artists of the time, notably the artists Rene Binet (architect of the Grand Entrance of the Universal Exhibition of 1900, Paris), Emile Galle, and Hans Christiansen, and the photographer Karl Blossfeldt. This was through his *Kunstformen der Natur* (Art Forms in Nature) series of illustrated booklets between 1899 and 1904. One of the most interesting artists reputed to have been influenced by Haeckel was Naum Gabo, Russian American constructivist sculptor (1890-1977), whose work, with Haeckel's, seems part of a conceptual palindrome. While Haeckel used art to advance his principles of science, Gabo drew on science and technology to inform his art and investigation of space. More recently, the late Klaus Kemp was an artist who had revived the Victorian art of meticulously making photographic slides with arranged patterns of actual diatoms.

In addition to imparting great beauty to our world, diatoms can impart important lessons on how to build, filter, float and manipulate light. For example, the organism solves a fundamental structural contradiction by making a strong and tough structure from intrinsically brittle material, silica. Its strength-to-weight ratio, or specific strength, is one of the highest in the living world; higher than bone, antlers and teeth. Researchers have found that the diatom's secret to this great material strength is not in the material, but in how it is arranged: in a complex, hierarchical and porous architecture at the nano and micro scales that counterbalances potentially destructive forces.

The Greer Group at Caltech was the first to measure mechanical behavior of tiny beam samples of frustule using in situ three-point bending tests in 2016. They were astonished to learn the relative strength of this structure ("We determined the elastic

René Binet's Grand entrance, Exposition Universelle, Paris, France, 1900
Source: trialsanderrors, 2010 | Flickr cc

Diatoms: Building Glass Houses

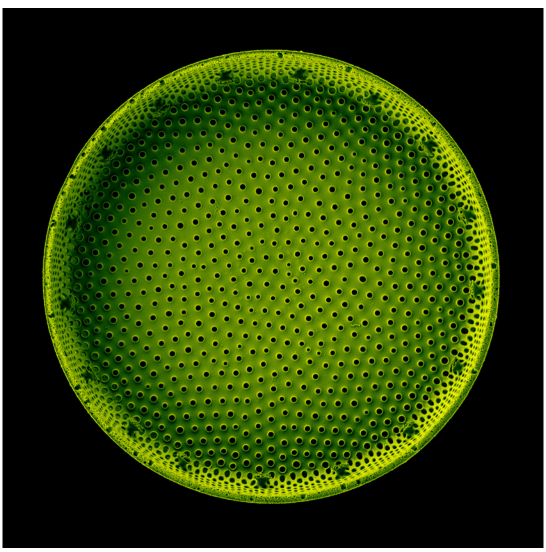
Tom McKeag

Arranged Diatoms on Microscope Slides in the California Academy of Sciences Diatom Collection | Scale bar = 100 µm
Photograph of diatoms arranged in October 1974 on a microscope slide by R.I. Firth, 2013 | Flickr cc

Arranged Diatoms on Microscope Slides in the California Academy of Sciences Diatom Collection | Scale bar = 100 µm
Photograph of 42 diatom species from Oamaru, New Zealand, arranged on a microscope slide in September 1974 by R.I. Firth, 2013 | Flickr cc

Diatoms: Building Glass Houses
Tom McKeag

modulus to be 36.4 ± 8.3 GPa and the failure strength to be 1.1 ± 0.3 GPa") An Ashby plot of strength vs. density showed the material to have specific strengths above all other reported cellular materials. They attributed this strength to the honeycomb architecture and the relative flawlessness of the deposited material. They also noted that the frustule is made almost entirely of amorphous solid biosilica, and that the layers appear to perform different structural functions, with the foramen deflecting crack propagation, the cribrum failing along its pores and most of the applied stress supported by the basal plate. They noted the crucial role that the porous structure of the frustule played in distributing stress



Coscinodiscus oculus-iridis (Ehrenberg)
Photo: Pavel Somov, 2021 | Wikimedia Commons

concentrations and preventing catastrophic failure.

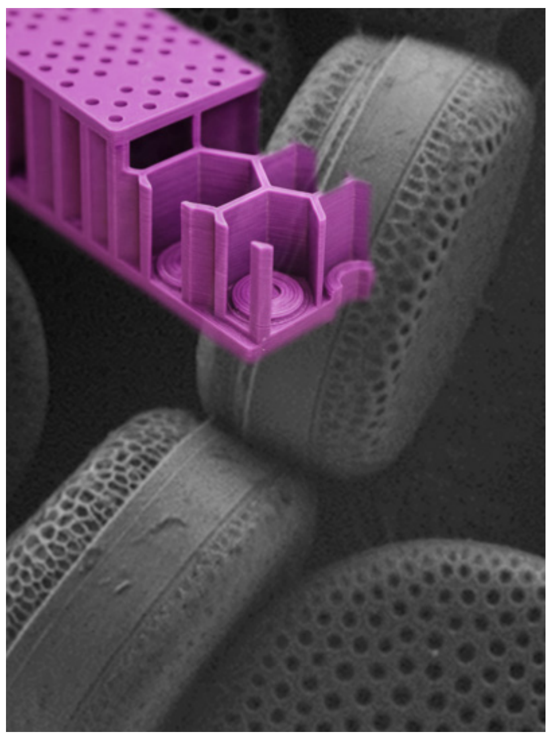
The Buehler Lab at MIT has investigated the creation of a synthetic material with a similar hierarchical structure at the nano scale, finding that meshes of crystalline silica can be tuned for greater toughness by manipulating individual foil thicknesses and density. When measuring mechanical stresses placed upon these meshes, they found that there was a homogenous distribution of surface stress throughout the entire structure, that the rectangular voids in the mesh conformed into hexagonal pores, and that certain actions of shear actually improved crack arrest, thanks to the hierarchy of subcomponents. Reducing the width of individual foils and closely packing them increased the strength and durability of the mesh.

A collaboration of the University of Genoa, Polytechnic Milan and the Massachusetts Institute of Technology has been investigating the diatom cell wall as a model for multifunctionality. The diatom manages to solve many challenges simultaneously with its frustule. It regulates nutrient flow, controls the sink rate of the organism, filters against harmful viruses, and manages light absorption for its photosynthesis.

In a recent paper in *Advanced Functional Materials* the group has proposed a standard model for the study of the bending, compressive and fluid dynamic behavior as well as the hierarchy effect found in the frustule. The researchers investigated mechanical properties like bending stiffness and buckling strength, alongside fluid dynamic efficiency and flow optimization, and used additive manufacturing to create prototypes, Writes Dr. Markus Buehler of MIT, “A unique feature of this work is the combination of in-situ experimental testing of 3D-printed diatom-inspired structures with advanced finite element analysis and computational fluid dynamics”.

In a controlled comparison with the Greer Group’s 2016 work they focused on the *Coscinodiscus* species and tested natural and synthetic sample mechanical behavior in three point bending and compression tests and compared with finite element analysis on a stress/strain graph. The team manufactured a synthetic structure, rescaled it to dimensions suitable for 3D printing and then tested it and its constituent layers of cribrum, areolae and basal plate. They found that flexible stiffness relative to density of the full architecture was two orders of magnitude higher than its parts and that the areolae layer was the most efficient component in resisting stress. They also noted that the reinforcement of the foramen pores, the enrichment of the amorphous silica with protein and the uniform distribution of cribrum pores all contributed to the strength of the frustule.

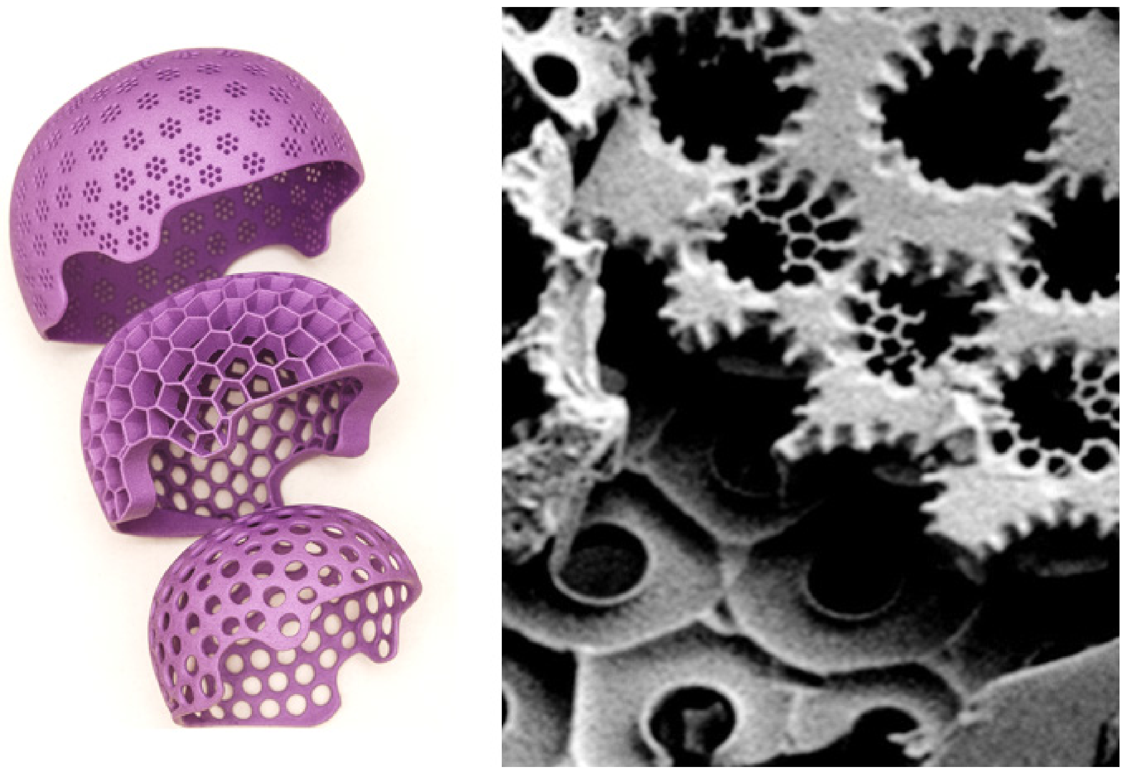
Dr. Flavia Libonati, lead researcher of the collaboration and associate professor, University of Genoa, writes, “We strongly believe that it is a combination of pore arrangement, functional gradient of materials, and other geometric strategies that prevents crack propagation”.



Biomimetic model of multifunctional material inspired by *Coscinodiscus* diatoms.
Image courtesy of Ludovico Musenich and Flavia Libonati, University of Genoa.

She explained that while honeycomb sandwich structures had been engineered before, these structures had been made with a constant wall thickness of the areolae. The diatom, by contrast, shows a variable thickness with a characteristic thickness gradient. When the team mimicked this approach they achieved a 150% increase in performance over conventional honeycombs. They have followed this research with a proof of concept model of a helmet that exhibits tunable and multifunctional architecture inspired by the porous diatom exoskeleton. The design incorporated the layering and hierarchical structure of the frustule while using the synthetic material thermoplastic polyurethane (TPU). This is a first step toward a multifunctional helmet that synergistically provides energy-absorbing qualities for both mechanical protection and breathability.

Dr. Libonati is quite mindful of her ultimate source of inspiration: “Nature has cleverly turned this apparent weakness



Helmet design compared with its natural diatom counterpart, highlighting the layered structure (from outside to inside): cribrum, areolae, and foramen. Diatom SEM image adapted from https://doi.org/10.1039/D1NA00691F, under CC BY 3.0. Image courtesy of Ludovico Musenich and Flavia Libonati, University of Genoa.

into a strength by locally optimizing the pore design and distribution and globally enhancing the material properties to create a lightweight yet damage-resistant structure that sustains the organism and ensures its survival and proliferation". She and her team will continue to explore the exciting possibilities that these structural insights from diatoms afford.

The diatom has inspired artists and engineers for centuries and yet the intricacies of its structure and its formation are still not fully known, let alone known to be replicable with our current technologies. The emergent properties of its structural strength, multifunctional capabilities and precision manufacturing will continue to inspire the many researchers who appreciate the superlative characteristics of this humble, one-cell organism, upon whom we all depend. ×

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Artistic reconstruction of *Suchomimus* pair in water.
Illustration: Fred Wierum, 2021 | Wikimedia Commons

Article

Unlocking innovation through fossils

Annabelle Aish and Tom Challands

Unlocking innovation through fossils
Annabelle Aish and Tom Challands

Unlocking innovation through fossils: How ancient life can inspire modern technology

When thinking about nature-inspired design, we usually imagine the living systems of today as our muses. But what if the key to expanding the scope of bioinspired innovation lies in the distant past, in fossil organisms that lived millions of years ago? This is the idea behind "palaeo-bioinspiration", a newly emerging field described earlier this year in *Nature Communications Biology* (Aish et al. 2025).

What is palaeo-bioinspiration?

Palaeo-bioinspiration is defined as "a creative approach based on the observation of palaeobiological systems". It is inherently interdisciplinary and taps into extinct life forms to inform innovative design. By studying fossil organisms and the ecosystems they inhabited, scientists can uncover novel solutions to human challenges based on paleontological adaptations that have been lost to time. This offers a far broader library of ideas to respond to modern challenges. For example, certain flying reptiles evolved wing designs unlike those seen in modern birds or bats; some dinosaurs developed sophisticated natural armour that offered both protection and agility; and ancient plants and trees grew complex, resilient structures distinct from those of today.

Stegosaurus stenops "Sophie".
Illustration: Fred Wierum, 2022 | Wikimedia Commons

Palaeo-bioinspiration has four key attributes:

1. The "biological library" of Deep Time: fossils provide access to an enormous diversity of biological forms and functions, many of which do not exist in today's biosphere: indeed 99.9% of all life forms that have existed on earth are now extinct.
2. The evolution of form and function: studying extinct organisms reveals how traits evolved and adapted over millions of years in response to environmental pressures.
3. Convergent evolution: many unrelated species adapted to comparable environmental constraints independently, indicating that their similar forms are particularly robust and effective as a basis for bioinspired design.
4. Environmental context: fossils often illustrate adaptations to ecosystems that have disappeared or dramatically changed, such as ice ages or CO_2-rich environments. These adaptations can inspire technologies resilient to global change at different scales.

How can fossils inspire innovation?

The process of palaeo-bioinspiration is multi-step, and just like "standard" bioinspiration can be approached from a biology-push or technology-pull direction using both cutting-edge techniques and interdisciplinary collaboration:

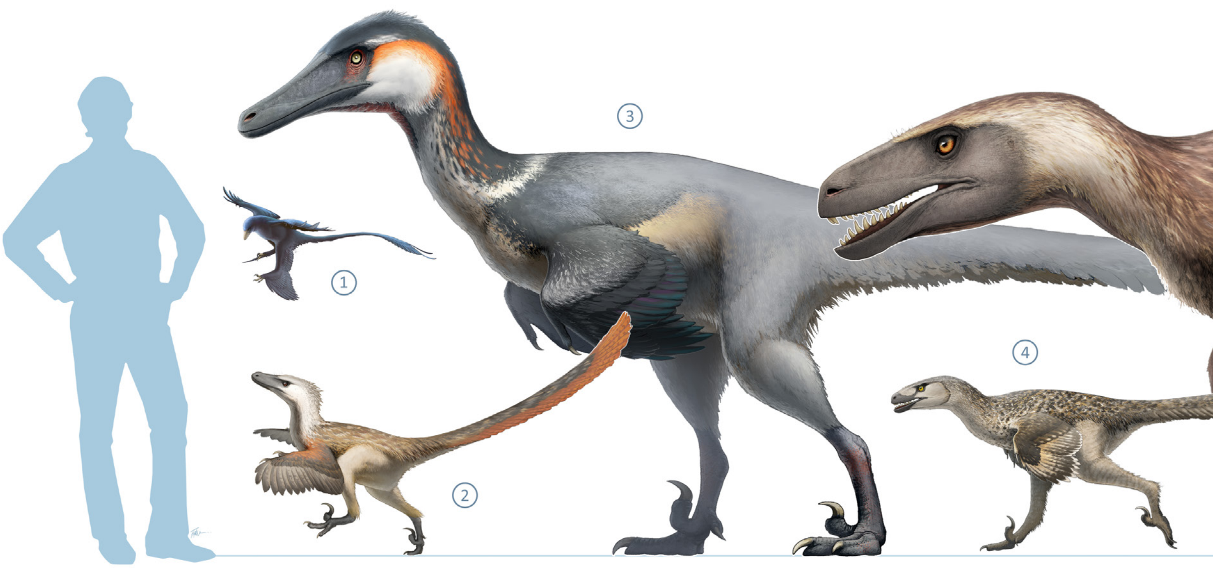
- Fossil analysis and imaging: Scientists use advanced imaging tools like micro-CT scanning, scanning electron microscopy (SEM), and microscopy to generate detailed models of fossils. This allows them to study the anatomy and morphology of extinct organisms with unprecedented precision—even parts that are hidden inside the fossil.
- Functional interpretation: Using these models, and prior paleontological knowledge, researchers try to understand how the organism functioned. For example, they might analyse how the domed skull of a certain dinosaur helped absorb impacts or how the wing bones of a pterosaur sustained flight. This biological interpretation is often supported by extant analogues (i.e. structurally similar modern species).
- Modelling and testing: In an engineering context, scientists may then use computer simulations like finite element analysis (FEA) to test the mechanical properties of biological structures under various forces, stresses, or fluid flows. This helps quantify how fossil shapes performed functionally and whether they can inspire engineering

solutions. Biomechanical testing can also be applied to physical models.

- Design abstraction: The next step is extracting the fundamental principles from these studies—such as energy absorption mechanisms, aerodynamic shapes, or material distribution patterns—and translating them into design concepts that can be adapted for different uses.
- Prototyping and evaluation: Finally, practitioners can build physical or digital prototypes—using technologies like 3D printing and synthetic composites—to test whether the fossil-inspired designs perform well in practical applications, from protective gear to vehicle parts.

Applications of palaeo-bioinspiration

The fossil record captures life's variety and complexity, providing a largely unexploited source of responses to the challenges of movement, protection, and energy efficiency not found in modern species. Hydrodynamics, aeromechanics, materials science, architecture, and climate resilience research could all benefit from insights from the fossil record.[1] For example, the streamlined bodies and flippers of marine



[1] See section "Palaeo-bioinspiration: stories of Potential and Success" in Aish et al. (2025) for further details.

reptiles like plesiosaurs have inspired the development of efficient underwater vehicles. Similarly, pterosaur wings, with their unique bone and membrane structures, have influenced novel mobile craft designs, including those intended for space exploration. The thick, bony armour of ankylosaurs, armoured dinosaurs, has led to the creation of new materials designed to absorb impacts and enhance protection in helmets and body armour. In robotics, fossilised plant structures, such as ancient stems, have been studied to develop soft, flexible pneumatic actuators. The internal architecture of fossil bones and woody plant tissues has also inspired the design of lightweight, strong building materials and structural designs. Finally, species that survived extinction events or dramatic environmental changes provide valuable models for developing technologies aimed at building resilience against ongoing climate change and biodiversity loss.

Size chart of different well known dromaeosaurs: *1. Microraptor gui, 2. Velociraptor mongoliensis, 3. Austroraptor cabazai, 4. Dromaeosaurus albertensis, 5. Utahraptor ostrommaysorum,* and *6. Deinonychus antirrhopus*.
Illustration: Fred Wierum, 2017 | Wikimedia Commons

Unlocking innovation through fossils

Annabelle Aish and Tom Challands

Case study - The architecture of giants[2]

Many animal bones contain a lightweight internal architecture offering trade-offs between strength and material efficiency. Dr Alexandra Houssaye (French Natural History Museum) undertakes research on the microstructure of fossil animal bones across a wide range of taxa (from mammoths to the colossal *Paraceratherium* (p. 30) and even sauropods) to uncover how these ancient animals successfully supported such immense body weights. These insights not only expand our understanding of biomechanics in large terrestrial animals but also offer practical applications. The impressive strength-to-weight ratio of these skeletal structures is inspiring the development of more efficient construction materials with potential across various domains, including architecture, prosthetic design, robotics, and aerospace engineering.

Scientific reconstruction of a pair of *Amargasaurus cazaui*
Illustration: Fred Wierum, 2022 | Wikimedia Commons

[2] https://www.mnhn.fr/en/palaeo-bioinspiration

Challenges and limitations

While a promising new sub-field, palaeo-bioinspiration faces several challenges. One major issue is ongoing misconceptions about extinction in the public consciousness, whereby fossil species are still sometimes seen as "failures," ignoring the fact that many extinct traits were successful adaptations in their own environmental context, often lasting millions of years. Furthermore, the fossil record is incomplete and fossils are often fragmentary, making it difficult to fully reconstruct some organisms with certainty. Reconstructions and interpretations of fossils are also subject to functional uncertainty: without living analogues, it is difficult to know precisely how certain fossil traits functioned, necessitating careful interpretation and validation. Finally, the process of translating this information into workable designs presents both logistical and conceptual challenges. Moving from fossil morphology to a manufactured product requires a high degree of abstraction, adaptation, and compromise on the part of

Preparator Otto Falkenbach with skull of *Paraceratherium transouralicum*.
Photo: Henry F. Osborn 1923 | Wikimedia Commons

Unlocking innovation through fossils
Annabelle Aish and Tom Challands

the interdisciplinary collaborators. Despite these hurdles, advances in imaging technology, computer simulations, and 3D printing, and the creation of spaces to collaborate on palaeo-bioinspiration projects, are helping researchers overcome challenges and prototype fossil-inspired designs more effectively.

The future of palaeo-bioinspiration

Several promising directions could be explored to unlock the potential of palaeo-bioinspiration. Curated fossil databases are being developed to create publicly accessible libraries of fossil forms and their digital counterparts, linked to inferred functions and mechanical data, helping designers and engineers in their work. AI and generative design are also being utilized, combining fossil-inspired design principles with computational creativity to generate innovative solutions more effectively. Success in this field also depends on interdisciplinary collaboration, with teams comprising palaeontologists, engineers, designers, materials scientists, and biologists working together to maximize the impact of bioinspired design. To engage the broader public, education and public outreach efforts are growing through museums, virtual reality, and digital media, raising awareness about how ancient life can inform future technologies. Finally, industrial partnerships are being

Life Reconstruction of *Microraptor gui*.
Illustration: Fred Wierum, 2017 | Wikimedia Commons

initiated to bring sustainable, innovative, fossil-inspired technologies to markets.

Conclusion

Palaeo-bioinspiration is more than just a scientific curiosity: it both expands the horizons of bioinspired innovation and deepens our appreciation of the fossil record as a source of practical knowledge. As human societies face urgent challenges like climate change, resource scarcity, and the need for sustainable materials, biological knowledge across Deep Time can provide invaluable guidance. Many past life forms adapted to environmental challenges that differ from those faced by modern species, offering fresh perspectives for design and innovation in the context of a rapidly changing world. We hope, through our article in *Communications Biology*, to generate a paradigm shift in biomimetic innovation by demonstrating that extinct organisms, shaped by millions of years of evolution, provide valuable (and sometimes unconventional) inspiration for new technologies meeting modern needs. Sometimes, the best way forward is to look back. ×

Pachycephalosaurus.
Illustration: Fred Wierum, 2017 | Wikimedia Commons

Unlocking innovation through fossils
Annabelle Aish and Tom Challands

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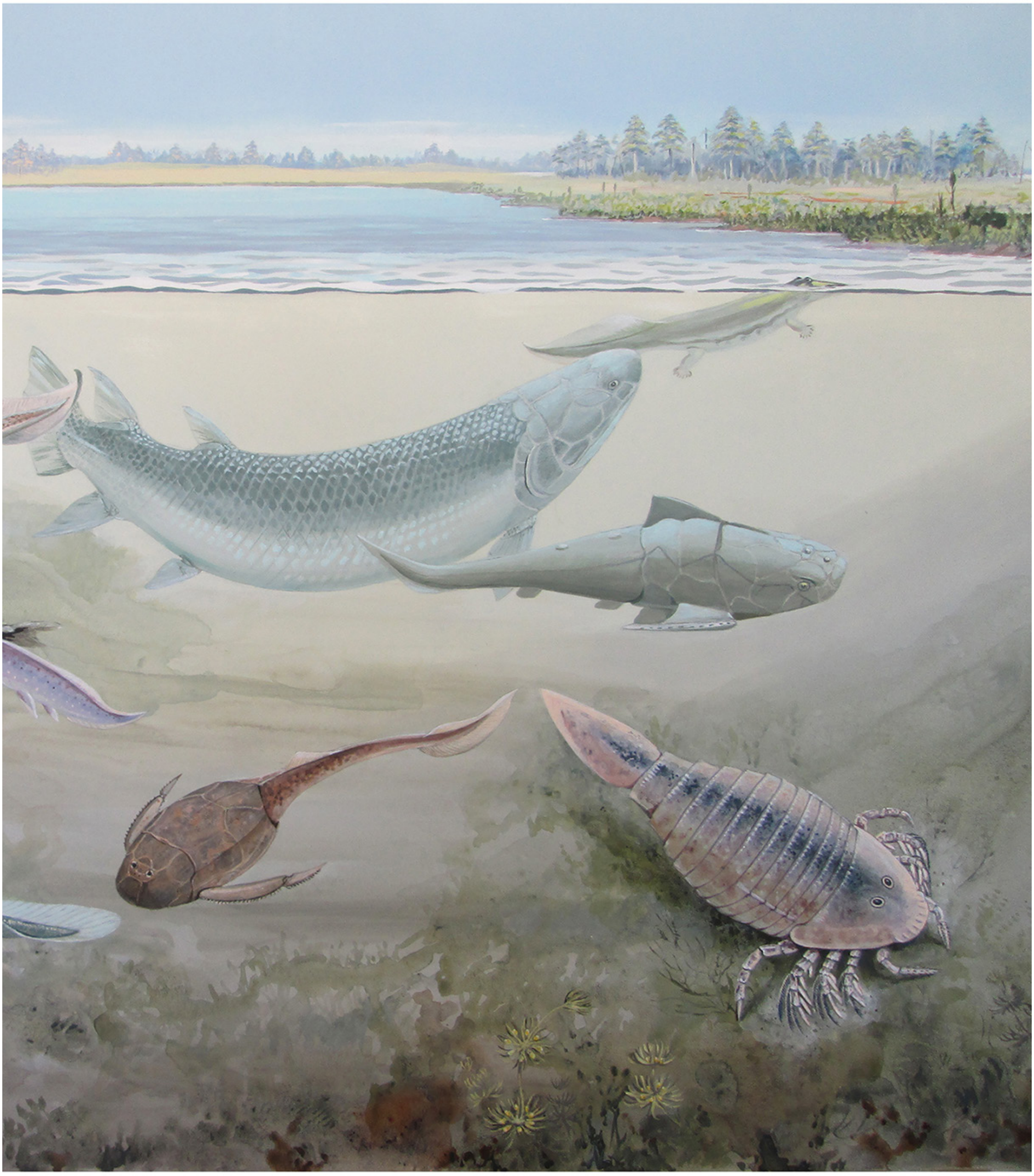
Annabelle Aish is Project Lead for Bioinspire-Museum (https://www.mnhn.fr/en/bioinspire-museum), an initiative launched in 2019 to foster, coordinate, and advance bioinspiration at the Muséum National d'Histoire Naturelle (MNHN), Paris. With a background in geography, Annabelle transitioned into tropical marine science, which sparked an interest for marine biodiversity conservation—a field in which she worked for over 15 years. Annabelle discovered bioinspiration in 2018 and her career began a new path. Her current goal is to integrate bioinspiration at all levels of the Museum's activities - from molecular to ecosystem-based approaches - and ensure these actions contribute to biodiversity conservation and sustainable development.

Dr. Tom Challands holds an honorary position in the School of Geosciences, University of Edinburgh. He has worked as a lecturer in the University of Edinburgh and conducts research on fossil fish and the evolution of sensory systems in vertebrates during the transition from water to land. He began exploring palaeo-bioinspiration when he recognised the potential for fossil fish sensory systems to be applied to modern remotely-operated underwater vehicles and continues to search for new and innovative ways to explore and use the fossil record.



A high latitude Gondwanan species of the Late Devonian tristichopterid *Hyneria* (Osteichthyes: Sarcopterygii), https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0281333.
Illustration: Maggie Newman, Robert W. Gess, Per E. Ahlberg, 2023 | Wikimedia Commons

Pollen of *Myosotis alpestris*
Photo courtesy of O. Aguado

Article

Who Controls Whom?

Manuel Quirós and Oscar Aguado

Who Controls Whom?

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Who Controls Whom? The Marvelous Evolutionary Alliance Between Flowers and Pollinating Insects: Part 1

Wild bees contribute significantly to the biodiversity of terrestrial ecosystems. Thanks to their range of body sizes, foraging behaviours, and preferences for specific flowering plant species, wild bees deliver a sophisticated and efficient pollination network. The wide foraging ranges of many wild bees facilitate gene flow between plant populations, promoting genetic diversity, supporting resilience, adaptability, and long-term survival of plant species in the face of environmental change. Wild bees also play a role in improving ecosystem resilience in agriculture crops.

But today, wild and agricultural pollinators are declining dramatically worldwide in what has become known as the "insect apocalypse." Pollinator decline can lead to a loss of pollination services, affecting conservation of wild plant diversity, the stability of terrestrial ecosystems, agricultural production, food security, and human well-being. By conserving wild bees, we conserve ourselves.

Humans love flowers. We grow them, display them, buy them, and they have inspired artists and also scientists in disciplines as varied as botany, floral structure, floral ecology, and more recently, applied molecular genetics. But they are not just fascinating to us. Behind their vibrant colors, enveloping aromas, and seductive shapes lies one of nature's most brilliant and complex evolutionary strategies: a mutualistic collaboration between plants and animals that has radically transformed the planet. But do plants manipulate animals to survive and diversify? Or have insects guided floral evolution and diversification with their preferences and habits?

The appearance of flowers was a revolution in the history of life. The first terrestrial plants, some 470 million years ago, did not have flowers. They were gymnosperms that include modern pines and yews, and their mode of reproduction depended on wind or water. It wasn't until about 125 million years ago, in the middle of the Early Cretaceous, that the first flowering plants, or angiosperms, emerged. But they didn't just emerge; in just 40 million years, they conquered the plant world, displacing gymnosperms and colonizing virtually all terrestrial ecosystems, surpassed only by arthropods in the number of species. This expansion was so rapid and inexplicable that Charles Darwin called it the "abominable mystery," and to this day, it remains one of the greatest examples of adaptive radiation in the history of terrestrial biology (Figure 1).

The recognition that animal pollination was essential for reproductive success in many plants was not acknowledged until after the 18th century through the work of two German botanists, Joseph Koelreuter, who fought his contemporaries' repudiation of plant sexuality, and later Christian Sprengel, who is recognized as the father of modern floral biology and pollination biology. Darwin subsequently studied how "orchids had changed various parts of their flowers to attract, entice, trick, and otherwise lure insects to move pollen from one flower to another."[1]

Gymnosperms have ovules protected by modified leaves, called bracts, that are freely exposed, allowing wind pollination. Angiosperms protect their ovules inside the ovary, which increases reproductive success but complicates fertilization - wind and water are no longer effective options - necessitating new agents and systems for pollen transport. (Figure 2).

The angiosperm flower allowed plants to shift from pollination dependent on chance to one primarily oriented toward attracting insects, significantly increasing the

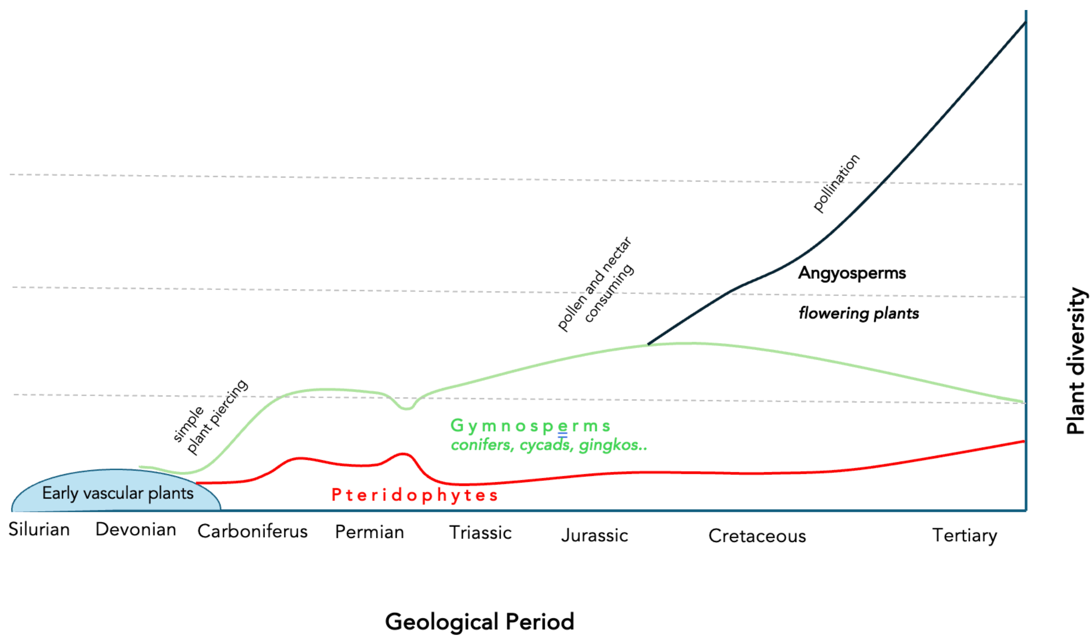

Figure 1: Plant diversity along the geological periods, from various sources. | Designed by the article´s authors.

[1]Allmon, Warren D. (2020, Feb. 12). Darwin, Pollination, and Evolutionary Contrivances. https://www.priweb.org/blog-post/darwin-pollination-and-evolution

probability of pollen transfer and ensuring cross-pollination for plants. A sophisticated evolutionary race began, leading to floral morphological diversity. Flowers developed novel features to seduce pollinators and stand out from the monotony of the green vegetation. Plants first coated their pollen grains with a sticky coating, increasing the size of the pollen, and making it a highly prized food. To further increase this attraction, the styles of the female flowers began to secrete sweet liquid substances and sugars in the form of nectar. Later, the anthers and pollen grains acquired a pleasant, irresistible scent, while the flower petals began to adopt colors and shapes that made them stand out from their surroundings, even from a distance. Shapes, colors, and scents, in short, are sophisticated anatomical, structural, and chemical strategies that represent a mutualistic process (Figure 3). We can interpret these innovations as truly collaborative, manipulative, win-win plant marketing – coevolution based on the exchange of multiple advertising appeals: nectar, oils, pollen, colors, shapes, symmetries, and grip, tailored to the consumer's taste.

Pollen, due to its abundance and chemical composition, constitutes a food source

Types of pollination

ABIOTIC

Anemophily: wind

Hydrophily: water

BIOTIC

Zoophily (90%): animals

- Artificial: honey bee and manual
- Mammals: Bats, foxes, lemurs,...
- Saurophily: Reptiles
- Ornithophily (5%): Birds
- Entomophily: Insects (82-90%)
  - Melittophily: Hymenoptera: Bees, bumblebees and Wasps + 70,000 spp
  - Psycophily: Lepidoptera: Butterflies and Moths + 140,000 spp
  - Myophily: Diptera: Flies + 5,000 spp
  - Canthrophily: Coleoptera: Beetles +77,000 spp

Figure 2: Types of pollination and their agents.
Source: several authors. Design by M.Quirós.

with high energy potential for pollinating insects. The nutritional value of pollen varies depending on its origin and its chemical composition varies depending on the plants from which it comes, although it typically contains proteins, sugars, amino acids, starch, lipids, carbohydrates, and minerals, in addition to being rich in vitamins B, C, E, and H. They owe their color to the presence of carotenoid and flavonoid pigments, and they also display a diverse appearance, with spherical, cylindrical, ellipsoidal, and polyhedral shapes. But the design does not end here, as the pollen of insect-pollinated flowers has spikes, thorns, and irregularities, elements that, together with sticky coatings of pollen cement or viscin threads, facilitate the adhesion of grains to the bodies of insects, similar to the popular VELCRO®. These aspects are truly exceptional considering the size of the pollen grains, ranging from 0.025 mm, like those of *Myosotis alpestris* (the flower of desperate love or the eternal lover), to 0.24 mm, like those of the zucchini or *Cucurbita pepo* (Images 1 and 2).

Cross-pollination (the transport of pollen from one individual to another, as opposed to self-pollination) increases the amount of recombination within the plant genome and therefore the speed of angiosperm

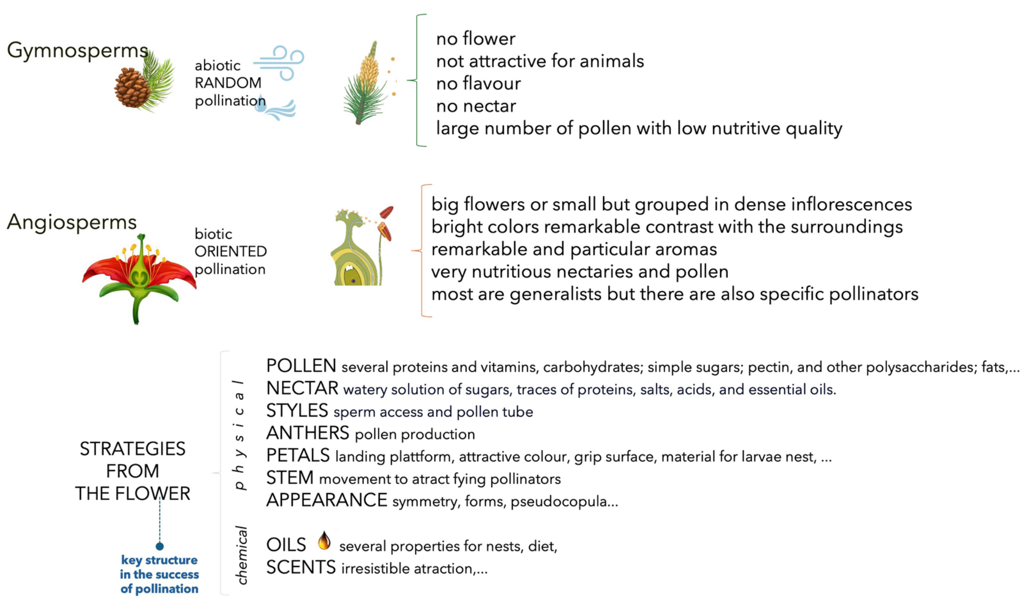

Figure 3: Various characteristics of plants and flower strategies to attract pollinators. Source: several authors. Design by M.Quirós.

Who Controls Whom?

Manuel Quirós and Oscar Aguado

Image 1: Pollen of *Myosotis alpestris.*
Photo courtesy of O. Aguado.

Image 2: Zucchini pollen on checkered beetle *Mylabris variabilis*.
Photo courtesy of O. Aguado.

Who Controls Whom?
Manuel Quirós and Oscar Aguado

evolution, as well as preventing long-term genetic drift (Glover, 2014). Compared to self-pollination or random pollination in gymnosperms, this represents a major evolutionary advance. The flower is adapted to maximize cross-pollination, allowing genes from different individuals to mix with other individuals within the species, increasing genetic variability and the species' evolutionary chances of survival (Figure 4).

Animals, and especially insects, also evolved in this process. They adapted anatomically, specializing in accessing floral rewards. In some cases, the relationship is so close that one plant species depends exclusively on one insect species (obligate mutualism), and vice versa, although generalist pollination prevails. In the next installment, we will share some strategies of pollinators, primarily wild and solitary bees, the group that represents the greatest success in animal pollination and on which numerous valuable ecosystem services depend. We will explore how sets of flower characteristics or “flower syndromes” help us identify potential pollinators, and how ultraviolet light, invisible to humans, reveals an unseen world. ×

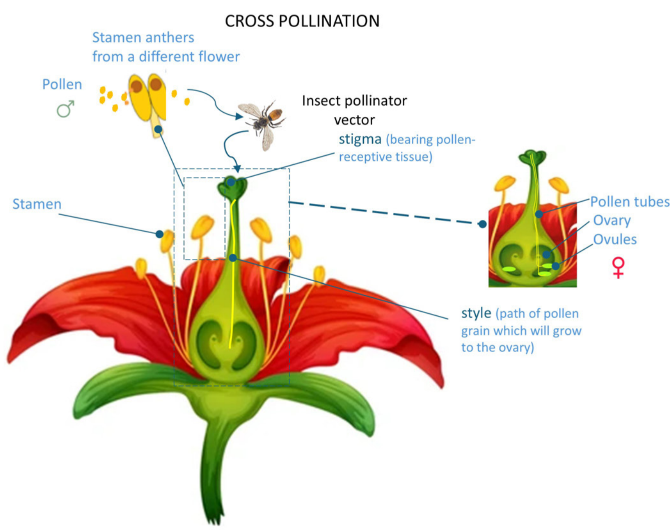

Figure 4: Cross pollination process until fertilization in angiosperms by a Hymenoptera (Genus *Andrena*).
Design by M. Quirós.

Manuel Quirós, BSc, MSc, PhD is a passionate nature conservationist. He guides, and as an independent teacher in several Spanish universities inspires students to adopt sustainability and biomimicry as a transformational behavior strategy towards regenerative culture. He is the owner of NIU (https://www.natureinspireus.com/), a biomimicry consultancy; cofounder of Red Internacional Biomimesis (RI3: https://redinternacionalbiomimesis.org/) and Biomimicry Iberia (https://zqjournal.org/editions/zq19.html). He participates as a speaker in many international symposia such as ONU-Habitat and COP 25. He has been a contributing editor and author (*ZQ29, ZQ30, ZQ34*) for *Zygote Quarterly* since 2013.

Oscar Aguado is an expert taxonomist and scholar of pollinating insects, as well as a consultant on entomological biodiversity for various government agencies and the private sector. Since childhood, he has built a collection of more than 150,000 specimens from around the world, with the goal of creating his own foundation in Spain. He has achieved national prominence through numerous articles, his presence in courses, conferences, and events, and authored the award-winning *Guides to Pollinators of Spain* and two volumes of *Butterflies of Castile and León*.

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Claire Janisch

In Memoriam
Claire Janisch

Jess Berliner

Claire Janisch
Jess Berliner

Claire Janisch (1975-2022): Her legacy in growing the practice of Biomimicry

Claire was a keynote speaker, futurist, regenerative design consultant, and innovation advisor. She found inspiration and innovative solutions to human challenges by emulating organisms and ecosystems that fit in on this beautiful planet in well-adapted, life-enhancing ways. She shared this new way of viewing and valuing nature through expeditions and workshops – teaching and training professionals, students, and scholars. She would also dive deeper into research for companies and organisations, translating nature's innovation and sustainability principles for the design of new products, processes, and systems.

After her Biomimicry Professional qualification and experience, Claire Janisch founded Biomimicry South Africa (or BiomimicrySA as it's more commonly known) around 2010 to grow the awareness, practice and education of biomimicry in South Africa. With her as Director, a transient team of specialists (myself included) applied our skills to implementing various biomimicry-based projects, from

Claire Janisch and Jess Berliner
Photo: Learn Biomimicry

Silverfish | A silverfish composite image, made up of roughly 1000 photos, taken with a cellphone, through a microscope. Transverse light is switched off, and subject is illuminated with a torch.
Photo: Jessica and David Berliner, 2017

Claire Janisch
Jess Berliner

water remediation to classroom education. Though much has changed over the years, the organisation still exists and its work continues under the care of Jane Lourens, Stefano Semprini and Milan Masters.

Claire was selected in the Mail & Guardian's "200 Young South Africans" awards in 2009, 2010, and 2011 and was a finalist in the Most Influential Women in Business & Government awards in 2012. She was also a co-creator of the Genius Lab, an experiential learning organisation inspiring innovation and future thinking for organisations and individuals, both children and adults. She was posthumously awarded the Eco-Light Bearer award by Eco-Logic in 2022[1]. Claire was also a mother - her legacy lives on in her beautiful and brilliant son, Jamie.

At Claire's memorial, a friend remarked; *it seems like everyone here has a turning-point-in-their-life story that starts with "... and then I met Claire."*

In 2012, I was stuck in the doldrums of my advertising job and happened to come across a local newspaper talking about something that immediately lit me up: biomimicry. It was this wild combination of biology (which, as a total nature nerd, I adore) and design (which I am qualified in).

Claire Janisch | Kruger Expeditions 2020 Learn Biomimicry Day 12 Canon Stills

[1] https://eco-logicawards.com/wp-content/uploads/2022/09/ECO-LOGIC-AWARDS-E-ZINE-2022-low-res.pdf#page=19

It turned out that a local network group called BiomimicrySA was having a meetup that week. I went, feeling nervous and wondering if there'd even be a place for me in all of this ... and then I met Claire.

Far from shunning me for a lack of biological qualifications, she celebrated the fact that I had strong communication design skills. "I need one of you!" she declared triumphantly, and that settled that. We were to be friends, mentors and partners. Over the years we worked together on various education projects, refining how we communicated biomimicry, building up experience and assets and finally culminating in what came to be the Foundational Biomimicry Short Courses.

But these were only products, and if you want to sell products, it helps to have a business. Learn Biomimicry was co-founded in 2020 with Alistair Daynes of ReWild Africa (https://www.rewildafrica.org/). From the beginning, Learn Biomimicry was run in a human-friendly, life-friendly, mutually beneficial way. We slashed restraint of trade clauses, we prioritised relationships before tasks, we built trust with transparency, we put family first, and we spoke our truths. We wanted to tackle the lack of biomimicry training that was publicly available - our mission became to make biomimicry accessible, affordable and applicable.

Learn Biomimicry currently has three products:

1. Three Foundational Biomimicry Short Courses that are delivered "on demand" to anyone, from students to professionals. Our goal for the set was "the depth of a degree, the ease of a TED talk". End-to-end, it gives a ton of insight into biomimicry and its various applications.
2. The Biomimicry Practitioner Programme helps working professionals apply the Challenge to Biology design methodology to a particular challenge from their own context.
3. The Biomimicry Educator Programme helps educators from high schools to universities as well as corporate trainers and coaches to integrate biomimicry into their teachings.

The latter two are six-month, mentored programmes, run in four cohorts a year. They are centred around project-based learning, and learners work on a challenge that is specific to them. By exploring the different methods and aspects of biomimicry through the lens of their personal context, we're helping our learners to build a skillset that gets them the work that they want to be doing.

We cannot promise to give them solutions, but we can help them with the hard

Claire Janisch
Jess Berliner

work necessary to truly understand what the challenge actually is, instead of starting with a solution in mind and retrofitting everything to that solution. How do we ask better questions? Are we working towards goals that are more life sustaining? The incentive has to come from within to check assumptions, understand the broader context, do insight and empathy interviews, and properly scope the project. This applies to educators as well. Who are your learners? What does learning look like to them? What is the transformation that you want to see? What impact do you want to make? It's about having the courage to emphasise curiosity over cleverness.

Mosquito Larva | A composite of ±60 shots, taken at 400x microscope magnification, with a cellphone camera. Compiled in Photoshop and then inverted. At this stage, they spend most of their time hanging upside-down from the surface, breathing through a siphon at the tail end.
Photo: Jessica Berliner, 2017

Really doing proper biomimicry is difficult, and we don't want to shy away from that. As Claire always said, "biomimicry is a practice; the more you do it, the better you'll get". With these mentored programmes, we're building a culture of being open to feedback, adopting a mindset around possibilities and continuous improvement, rather than scarcity, obstacles, and following rules. Learn Biomimicry emphasises "done, not perfect" and that progress is iterative. The goal is to plant a seed so that people will keep going and trying even if they are not initially successful. That being said, we've seen some amazing projects coming out of our programmes, and we are so excited to see some of them being taken forward, such as https://www.learnbiomimicry.com/blog/cycling-bib-shorts-biomimicry-in-product-design.

We recently sent out a survey to our 100+ mentored programme alumni, to hear if and how they've been applying what they learned in the programmes. So far the response has been overwhelmingly positive, with learners confirming that they're practicing their skills and still feel strongly connected to the community. We've found such joy in listening to our customers, and in hearing what they need and how we can continuously improve our products, services and support so we can get closer to making biomimicry more affordable, accessible, and applicable. Every cohort, we take our learners' and mentors' feedback into account, and adjust the programmes accordingly. Through this approach, we effectively have a three month iteration cycle.

Other initiatives that we've created on the community front are the "Communitree" (yes it's a pun, no we're not sorry) as a place where our cohort learners can gather on a monthly basis to continue their lifelong learning journey – during and after their course. We also run a bi-annual Confluence Conference, where we bring the international biomimicry community together online for two days and learn from experts who are really applying their biomimicry skills.

What continues to surprise me about nature is the sophistication of the natural world's mechanisms and strategies. For me, watching the awe increase with every kind

Kruger Expeditions.
Photo: Learn Biomimicry

Mosquito Larva in pupa stage | A composite of shots, taken at 400x microscope magnification, with a cellphone camera. 13 x groups of 6 focal depths, stacked and then compiled in Photoshop. Backlit via transverse light and top-lit with torch.
Photo: Jessica and David Berliner, 2017

Claire Janisch
Jess Berliner

of insight is just the most beautiful experience. There is still so much that we don't know, and still so much that we cannot replicate - we need to catch up. The good news is that as our technology advances, we are discovering more and are able to build better models.

Biomimicry encourages us to explore more life friendly developments by pushing the frontier of what we're actually capable of. At the same time, I am more appreciative of the human element, how much effort it takes to bring together the knowledge and perspectives from different fields that often work in silos. We are bringing together engineers, designers, business consultants, software developers, and teachers, united by this common vision. I've become more comfortable with the messy middle of what it actually takes to change things and recognise that nobody will ever change something that they're not interested in and don't feel motivated by. We believe that combining passion with skills is a powerful recipe for long-term success.

Looking forward, I am personally interested in the development of more life-friendly materials. The materials space touches so many facets of life from everything that we wear to what we hold, touch, and use every single day. I hope that education becomes more practical and less academic, enabling people to interact with the real world and solve real world challenges, rather than being wrapped up in theoretical problems and theoretical goals. Online technologies have expanded our ability to learn and communicate, but

Mosquito Larva in pupa stage (detail) | A composite of shots, taken at 400x microscope magnification, with a cellphone camera. 13 x groups of 6 focal depths, stacked and then compiled in Photoshop. Backlit via transverse light and top-lit with torch.
Photo: Jessica and David Berliner, 2017

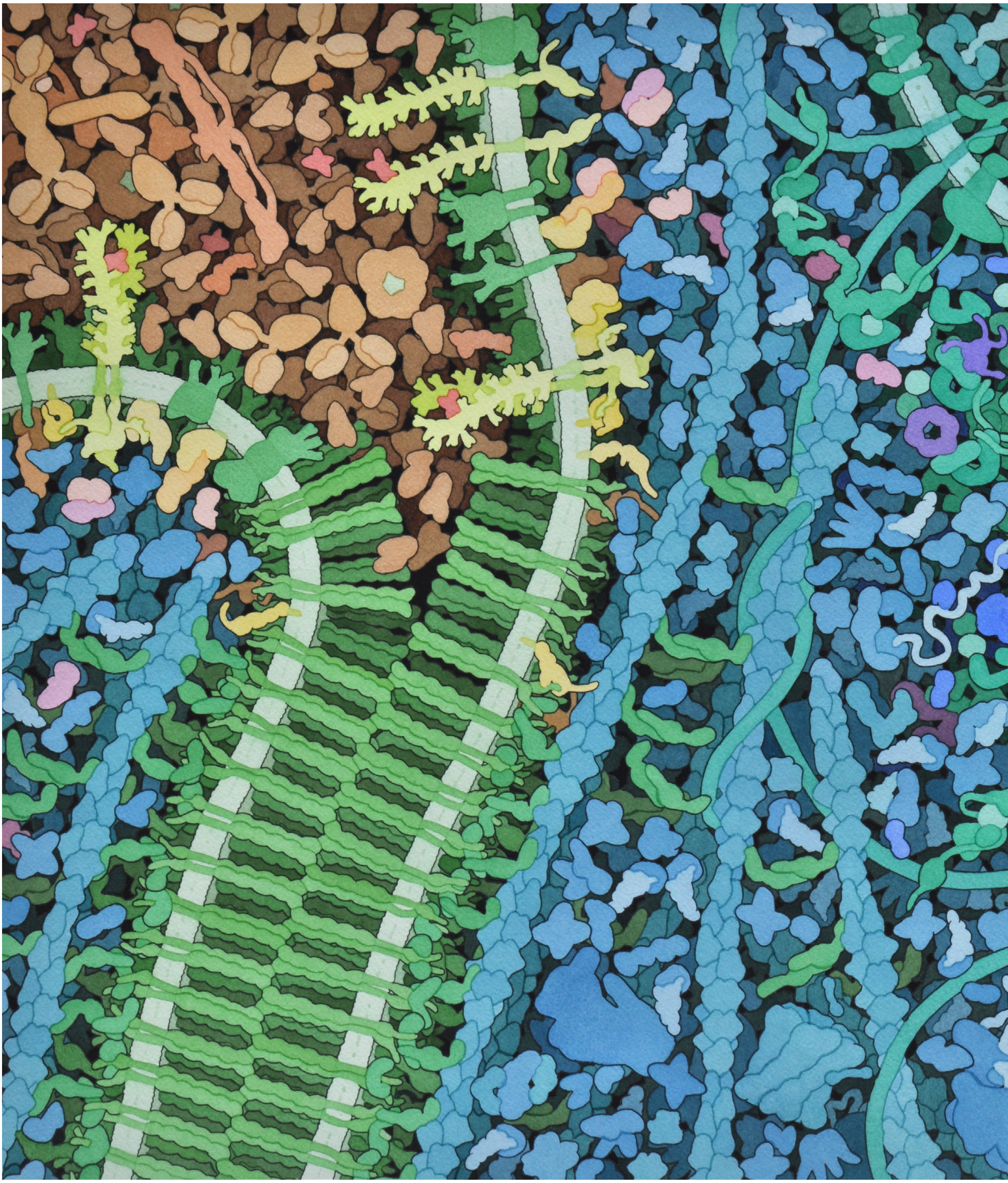
only by engaging with the real world can we build towards something more fulfilling.

Claire taught us to appreciate the magic of reality and of the living world. At talks on stage, on expeditions in the veld, on long haul flights, she always wore flip flops, so that at the first chance she could kick them off and ground herself. If I had ever asked Claire "how could I ever fill your shoes?" I'm pretty sure that she would have looked at me, and without missing a beat, say "Well, it's quite simple really. I don't wear shoes, so you're free to do your own thing".

Hasta la pasta, dear Claire. Until we meet again. ×

A special thanks to two people who have helped me through this incredibly difficult transition, by graciously letting me cry, mope, laugh and vent in their presence: Nirmala Nair, thank you for letting me sit with you, for telling me stories of the past, for holding space as I raged and cried and processed. Tess Rayner, thank you for always answering my calls and for sharing this journey with me, as we navigate the loss of our (adoptive) cousin. It was you who convinced me not to give up on this story. Thank you, Margo Farnsworth for suggesting that we write this, and thank you, Norbert Hoeller for your editing and support.

Claire Janisch | Kruger Expeditions 2020 Learn Biomimicry Day 12 Canon Stills



Vascular Endothelial Growth Factor (VegF) Signaling, 2011 | Blood serum is at upper left, with VegF in red. Cell membranes are in green at left, with VegF receptor in yellow green near the top and a disassembling adherens junction in darker green at bottom. Multiple kinases (in pink inside the cell) are activated and travel through the nuclear pore (green, at center) to phosphorylate transcription factors in the nucleus (at right).
Illustration by David S. Goodsell, RCSB Protein Data Bank. doi: 10.2210/rcsb_pdb/goodsell-gallery-041

Article

The value of the sub-organism perspective in organizational design

Irene Nooren

The value of the sub-organism perspective in organizational design

Irene Nooren

Modern organizations face profound challenges: accelerating change, information overload, inherent complexity, and the need for both precision and adaptability. Traditional hierarchical organizational models emphasize control and predictability, and yet struggle with rapid environmental shifts.

Within social biomimicry, strategies and principles from ecosystems and animal behavior are used to design social organizations and practices [1]. Whereas traditional biomimicry focuses on material and technical innovations, organizational-oriented biomimicry delves into the information processing and coordination mechanisms that govern living systems.

Yet, a deeper exploration of biological systems at the sub-organismal (organ, tissue, cellular, and molecular) scale can complement these insights by drawing inspiration on information processing and organization from innate mechanisms and structures. This article advocates for a 'reverse engineering' approach to understanding the underlying principles of how biological systems function and apply them to human systems. I argue that complex human organizations can draw inspiration from the foundational structures upon which all life evolved - cellular and molecular systems – to achieve internal coherence, precise though dynamic regulation of processes, and institutional memory. I show that these insights from the sub-organism scale are a valuable complement to the inspiration drawn from superorganisms and ecosystems

Processes within the organism are driven by the imperatives of survival and reproduction, creating unified selective pressures. Unlike ecosystems – which are open networks of interacting components without unified identity - or even superorganisms that coordinate individual actors, physiological systems offer organizationally closed, self-producing structures. Survival drives precision and efficiency in information processing through both local autonomy of components and global coordination. The 'memory' of how to act is intrinsically captured within DNA, a fundamental feature of the organism itself.

The evolving lens of organizational design

Historically, organizational design has shifted with paradigms and worldviews. In the mechanistic paradigm of the Industrial Revolution, organisms, particularly the human body, were viewed as machines. Complex systems theory was introduced in the mid-to-late 20th century by thinkers like Ludwig von Bertalanffy [2], shifting reductionist thinking to a holistic

Immunological Synapse, 2020 | This painting shows a key moment in the dialog between cells of the immune system, when an antigen presenting cell (top) is displaying a small piece of a virus (red dot at center) with MHC, and using it to stimulate the action of immune T-cells (bottom) through T-cell receptors.
Illustration: David S. Goodsell, RCSB Protein Data Bank. doi: 10.2210/rcsb_pdb/goodsell-gallery-022,

approach, focusing on the relationships and interactions within complex systems. Cybernetics, as formalized by Norbert Wiener, further emphasized the role of information, feedback, and control in both biological and artificial systems, laying groundwork for understanding organizations as information-processing entities [3]. From a cybernetic perspective, the goal in organization design is to establish and scale the information networks and mechanisms that facilitate a social system's dynamics. This requires structures for stability but also communication and decision-making mechanisms that allow for adaptability.

The autopoiesis theory of evolutionary biologists Humberto Maturana and Francisco Varela provided a rigorous and influential formalization of organisms as self-organizing, self-maintaining patterns, instead of relying on the organizational principle of control [4]. Ecosystem thinking has guided organizations towards developing characteristics of living systems themselves – inherently adaptive, regenerative, and resilient, and in harmony with nature [5]. Fast forward to today, systems biology has advanced our understanding of interactions and integrated processes in living systems [6]. Rethinking organizational design means exploring a different scale of biological inspiration, deeply integrating the self-organizing, information-driven, and intrinsically coherent mechanisms observed in sub-organism systems. This has led to a general set of organizational principles of biology including coordination, feedback, and bounded autonomy [7].

Organizations inspired by precision driven living systems

Traditional organizational models are structured top-down with hierarchical decision making and linear processes. The emphasis is on control and predictability. In contrast to the mechanistic view prevalent since the 19th century, living systems show remarkable adaptability and resilience with each specialized part contributing to the whole. Viewing organizations as information processing systems, akin to living systems, is particularly helpful in today's information-rich society.

Specialization is core to organizational design across all biological levels, with specific functions through interacting, inherently specialized actors that facilitate dynamic processes. It inspires a move towards decentralized decision making, where governance is fundamentally rooted in the specialized expertise of autonomous units, much like cells and organs function independently yet cohesively within the organism. Through evolution, the organization of physiological components at cellular levels has led to efficient biological process management at higher levels of organization. Each ascending level exhibits novel emergent properties derived from the interactions of its lower-level components at the subcellular level.

Cellular systems excel at information processing with context-appropriate reliability and speed - from rapid signal transduction to dynamic genetic regulation - providing the robust yet flexible responses essential for adaptability. They demonstrate precision, operating via tightly-coupled molecular signaling pathways with sophisticated error detection, feedback, and correction mechanisms. This reliability, combined with controlled variability, allows for rapid adaptive responses and robust coordination throughout cellular organization. This robust, adaptive design at the physiological level creates value for organizational design in three core principles: coherence with unified agency, intrinsic regulation, and institutional memory.

Coherence with unified agency

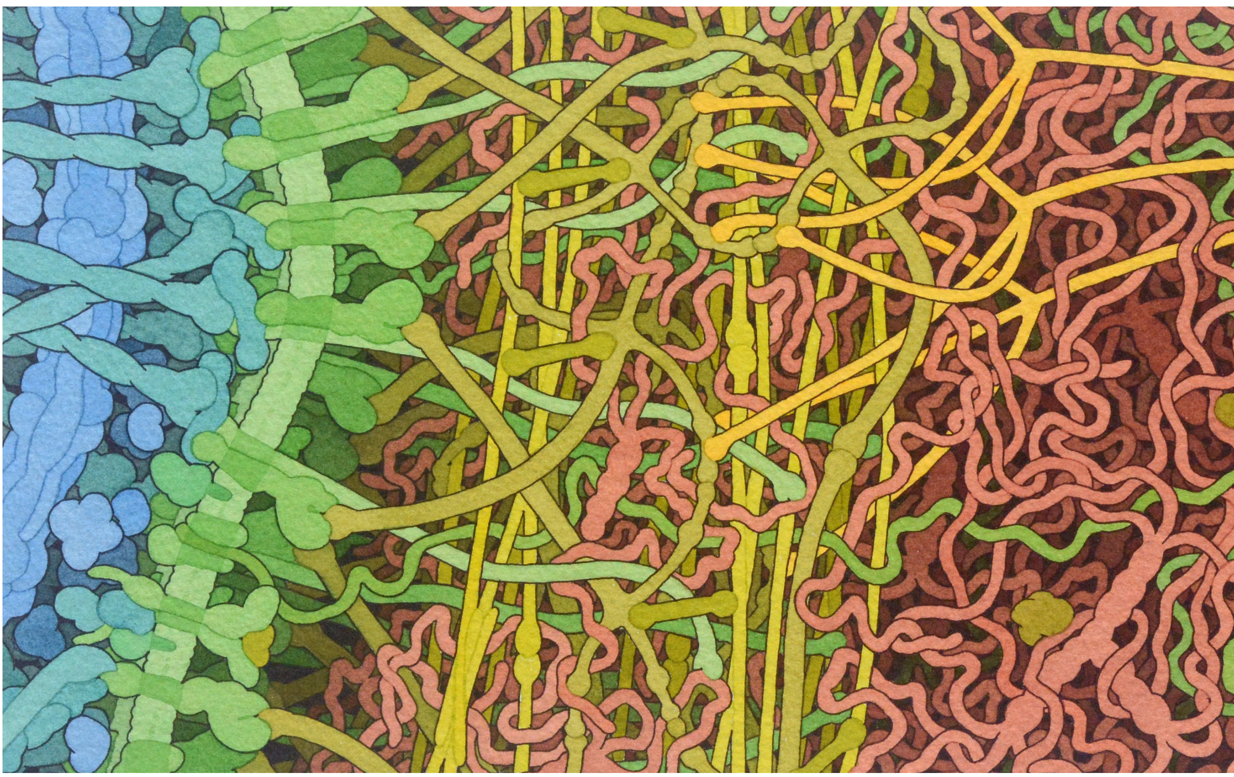
Biological systems demonstrate that true organizational power comes not from independent actors but from specialized units that are profoundly interdependent. In particular, each molecular and cellular component performs unique functions while relying heavily on others for inputs and contributing critical outputs to the whole. This creates unified agency for the organismal system: the many functionally autonomous parts like cells and organs act as one with coherent processes. It suggests designing organizational units like teams and departments to be highly specialized, yet deeply interconnected and integrated, working towards common goals.

Unlike mechanical systems that maintain coherence through rigid structure, biological coherence is dynamically maintained, and contextually responsive. The emphasis is on building seamless internal coordination with clear interfaces and roles, contributing coherently to a unified organizational purpose. Specialization isn't just about dividing tasks like the Taylor model [8], but about enabling profound interdependence and collective function through precise, active coordination. This organizational design shift moves from viewing an organization as a collection of somewhat independent actors (like in an ecosystem) to seeing it as a complex system with highly specialized yet deeply intertwined actors. At the cellular level proteins and cells are the actors that sense internal

The value of the sub-organism perspective in organizational design
Irene Nooren

and environmental conditions and fine-tune their interactions.

Living systems maintain coherence across vastly different scales—from quantum processes in photosynthesis and enzyme catalysis, through molecular and organ networks, to whole-organism behavior. Each level maintains its own coherence while contributing to higher-order coherence. Emerging structures are characterized by modularity and hierarchy to allow specialization of function while maintaining integrated system-wide coordination. Connections drive the evolution of both hierarchy and modularity, serving as key factors in enhancing network performance and adaptability [9]. This suggests that the most sophisticated forms of organization emerge from the coherent interaction of components that are themselves coherently organized. It inspires organizations to achieve multi-level, self-generating coherence rather than relying solely on hierarchical control in organizational design.

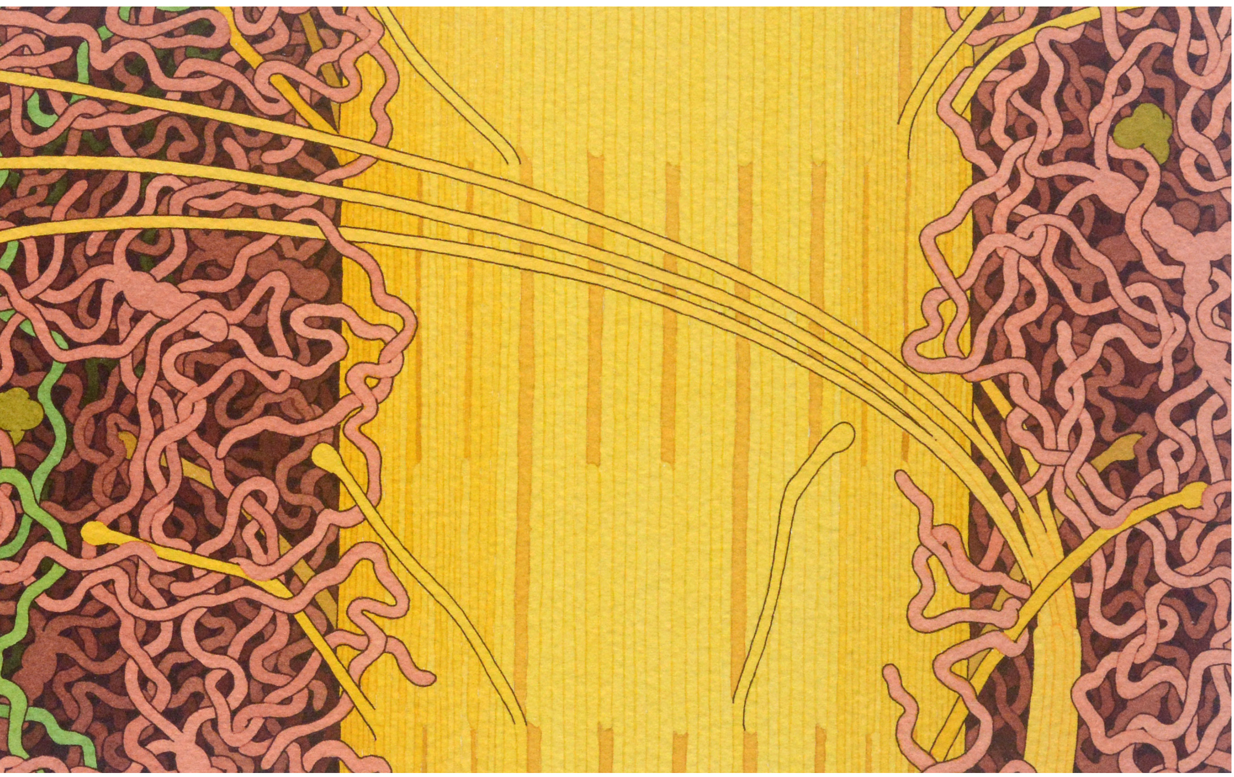


Collagen and Extracellular Matrix, 2021 | A network of fibrous proteins and polysaccharides form a structural matrix between cells in our bodies. In this cross section, a cell surface is at left. A dense basal lamina braces the outside of the cell, composed on long collagen fibers, cross-shaped laminin proteins, and snaky proteoglycan molecules. Other forms of collagen help to strengthen the extracellular matrix, including huge collagen structural fibrils (at

Intrinsic regulation

In living systems there is no central authority that enables unified agency. Order emerges from coordinated processes and interactions of autonomous components. This form of self-regulation is built upon common mechanisms that exist across scales, such as self-organization, feedback mechanisms and efficient information processing. Unique at the sub-organism level is the way these mechanisms ensure the integrity and reliability of information through self-regulation.

Sub-organism level regulatory mechanisms ensure both autonomy and integration simultaneously. Many organizations embrace decentralization, yet they often lack the sophisticated internal regulation and coordination seen at the sub-organismal level that underpins robust biological systems. Corporate decentralization frequently creates autonomous divisions without the sophisticated internal

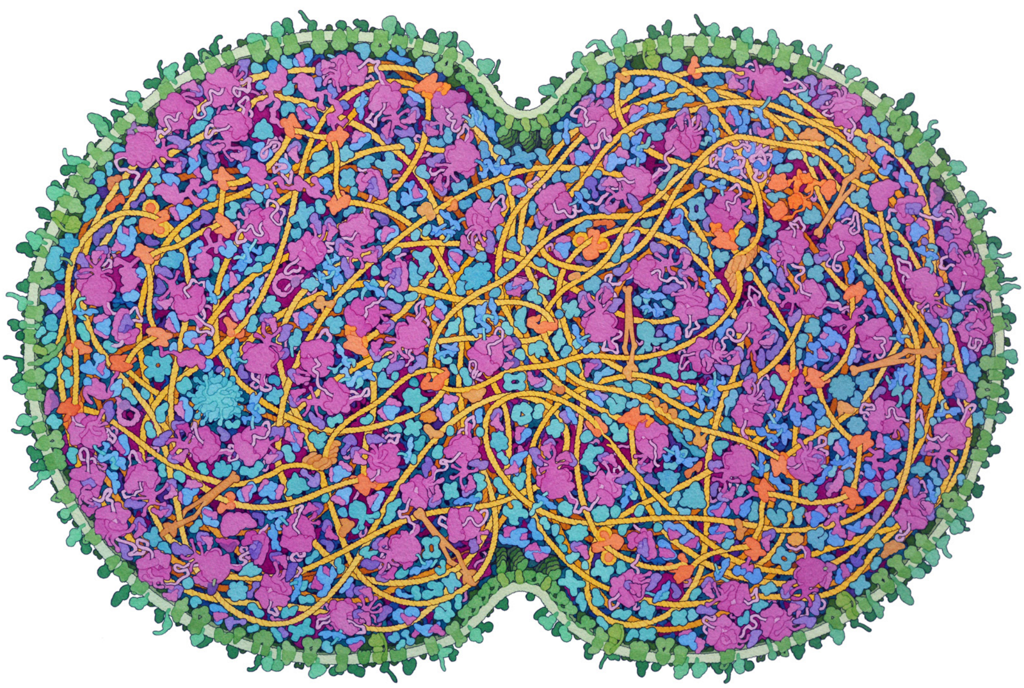


right in yellow) and anchoring fibrils (arching molecules in yellow). This painting was created as part of the celebration of the 50th anniversary of the Protein Data Bank, and is adapted from Figure 6.3 of "The Machinery of Life". Illustration by David S. Goodsell, RCSB Protein Data Bank. doi: 10.2210/rcsb_pdb/goodsell-gallery-033, CC-BY-4.0

The value of the sub-organism perspective in organizational design
Irene Nooren

coordination. This requires reliability in its internal information flows with high specificity, intrinsic feedback loops and effective information processing. Such regulation entails more than merely establishing technical information processing systems; it requires organizations to actively employ human competencies for the effective interpretation and contextualization of information. This, in turn, calls for deliberate reflection and active sense-making.

Cellular systems maintain internal equilibrium through homeostatic processes that respond to perturbations without external oversight. Consider metabolic pathways that self-regulate through feedback inhibition, maintaining balance without centralized control. They demonstrate how organizations can achieve precise coordination through embedded regulatory mechanisms rather than management oversight. Rather than relying on feedback from corporate metrics commonly used in current organizational processes, biology offers an alternative approach to governance. Standardization is not in protocols



JCVI-syn3A, 2022, is a minimal cell developed at the J. Craig Venter Institute, with a reduced genome of 493 genes. The cell is depicted just after beginning division. DNA is in bright yellow, DNA-associated proteins are in tan, and DNA-associated enzymes (polymerases and topoisomerases) are in orange.
Illustration by David S. Goodsell, RCSB Protein Data Bank. doi: 10.2210/rcsb_pdb/goodsell-gallery-042, CC-BY-4.0

or procedures to govern behavior as used in human organization but through the tightly-coupled tuning of relations.

While neuronal systems may appear to provide central control, they represent distributed information processing networks that coordinate responses across larger scales rather than hierarchical command structures. Hierarchical organization in cells and organs is not about hierarchical decision making but about scalable organizational design of information processing. Sub-organism systems achieve remarkable coordination through distributed intelligence and autonomous responsiveness - the opposite of bureaucratic control and organizational silos inhibiting information sharing. They demonstrate how organizations can be both precise and adaptive without top-down management structures.

Institutional memory

Perhaps most remarkably, cellular systems embed organizational wisdom directly into their operational structure through DNA - a distributed information system where every cell carries complete organizational knowledge. This physical memory enables collective intelligence development, incorporating interaction networks and governance frameworks. This enables autonomous decision-making while maintaining collective identity and purpose. Unlike conscious knowledge stored in leadership or documentation, this 'institutional memory' is encoded in the system's fundamental processes and reproduced across generations: its organizational wisdom, knowledge, and successful adaptations are directly embedded in the operational structure of a system.

Organizations can apply this principle by embedding critical knowledge and successful adaptations into their operational 'DNA'. This includes both explicit knowledge – like standard procedures, cultural practices, and decision-making frameworks that persist beyond individual employees – and implicit knowledge, acknowledging learning through shared experience and practice. This highlights the importance of direct interaction and collaborative environments.

The sub-organismal perspective challenges our understanding of knowledge itself. While we focus on conscious knowledge in the brain, biological systems demonstrate that fundamental organizational wisdom is encoded in cellular configurations and DNA - information that reproduces and evolves across generations. In our lives we do not tend to appreciate this as knowledge due to our emphasis on conscious knowledge in the brain. This raises profound questions about how we conceptualize learning and knowledge management in human organizations.

Integration of complementary principles

Every subsequent biological innovation - from multicellular organisms to superorganisms to ecosystems - builds upon foundational sub-organismal principles. At the organism system level, interconnections are more structured as compared to ecosystems. Physiological systems exhibit high integration, with coordinated interactions among organs, tissues, cells, and molecules. Biological processes such as biochemical pathways are typically tightly regulated and coordinated. Unlike ecosystems, organisms prioritize tightly coupled interactions for survival. Whereas stability is vital for an organism to survive and thrive in different conditions, a dynamic equilibrium of an ecosystem does not rely on it for its existence.

Homeostatic processes differ fundamentally from ecosystem-style networks where regulation occurs through competitive interactions, or superorganism coordination that relies on behavioral signals between distinct actors. Feedback loop thresholds in organisms have been evolutionary; established to trigger precise, targeted responses when specific conditions are met. Ecosystem regulation, conversely, relies on statistical distributions and dynamic population interplay. Stability emerges from the aggregate behavior of many organisms over time and space, where individual variations are absorbed by the system's overall resilience.

While ecosystems and superorganisms - exemplifying swarm intelligence - provide valuable metaphors for external relationships and broad adaptation, the sub-organism level offers deeper insights into how to design the internal workings of an organization for high performance, coordinated action, and efficient information processing. Ecosystem models excel at knowledge exchange and networks across organizational boundaries while sub-organism principles provide the internal coherence and coordination mechanisms needed for complex unified action, as an institutional foundation. Social insects like ants and bees offer a middle ground between organismal coordination and ecosystem dynamics. Unlike ecosystems, superorganisms maintain unified purpose and institutional memory through specialized roles and swarm intelligence mechanisms while preserving individual autonomy.

Towards a new organizational paradigm

The sub-organism level offers a unique opportunity to develop a biomimetic approach to organizational design, particularly when complemented and integrated with insights from other organizational levels. Rather than choosing between ecosystem thinking, swarm intelligence and traditional hierarchies, we can integrate insights from multiple biological levels to create organizations that are both precisely coordinated and highly adaptive.

Current bio-inspired organizational designs include holacracy and swarm intelligence models. Holacracy features tight integration, specialized functions and coordinated responses built on specialist autonomy without central authority [10]. Companies like Toyota and Patagonia exemplify this through distributed roles and structured governance. However, most applications lack the systematic precision of cellular information processing or the deep specialization that enables true functional integration. The challenge is to reduce structured governance, enhance intrinsic coherence, and improve integrative information processing and knowledge sharing without centralized control.

The integration challenge involves applying different biological levels appropriately: ecosystem approaches for inter-organizational collaboration and innovation networks, sub-organism principles for internal coordination and institutional development, and superorganism models (like social insects) for project teams requiring both individual autonomy and collective purpose.

Sub-organism principles suggest a fundamentally different approach to organizational design, both precisely coordinating and being highly adaptive. A systematic framework distinguishing between different organizational levels and their applications to human systems would facilitate this transition. Effective translation of sub-organism mechanisms into practical organizational design requires interdisciplinary collaboration among biologists, organizational theorists, and system architects. It demands the willingness to fundamentally rethink human system design through knowledge sharing and global networks. ×

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The value of the sub-organism perspective in organizational design
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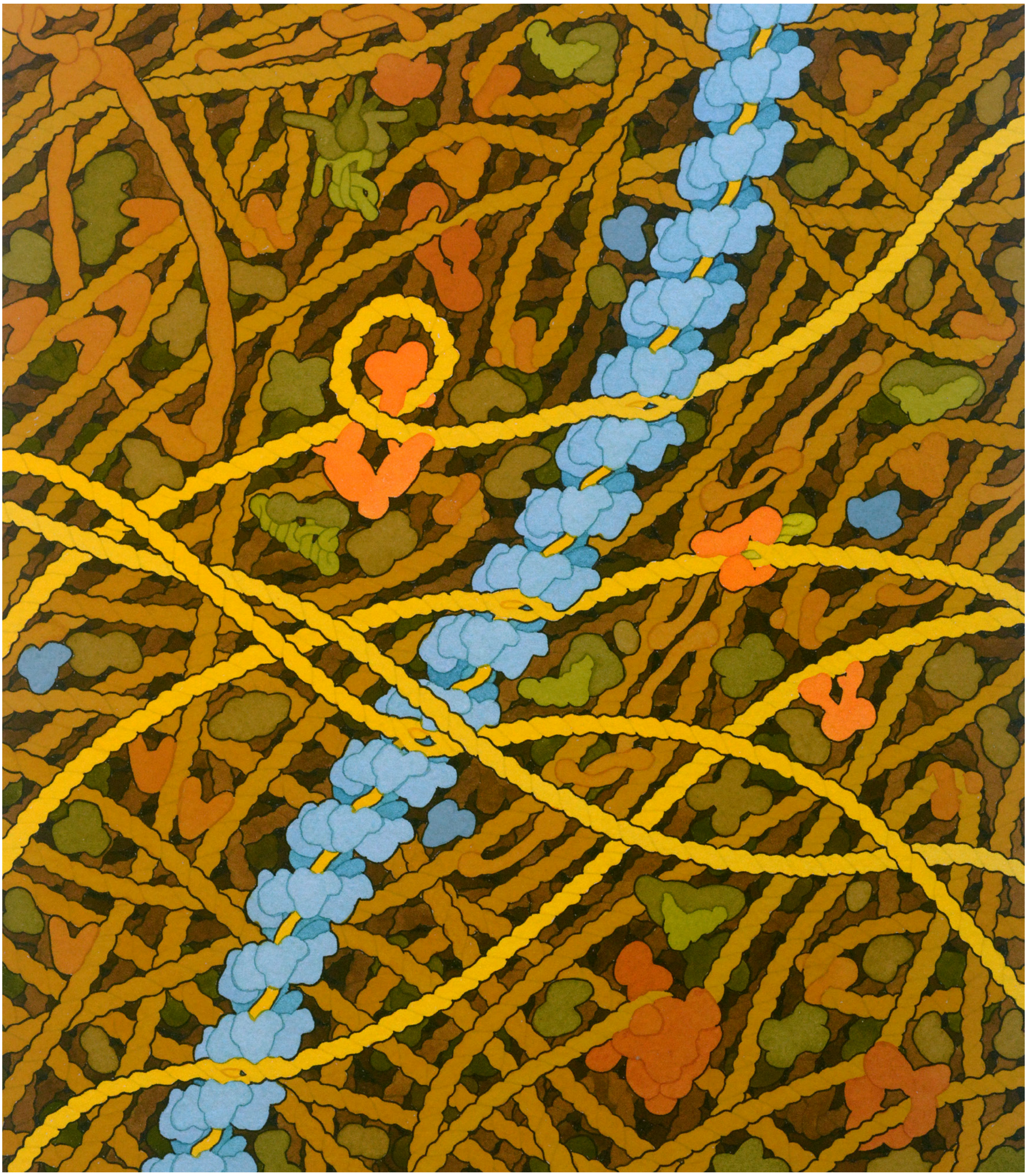
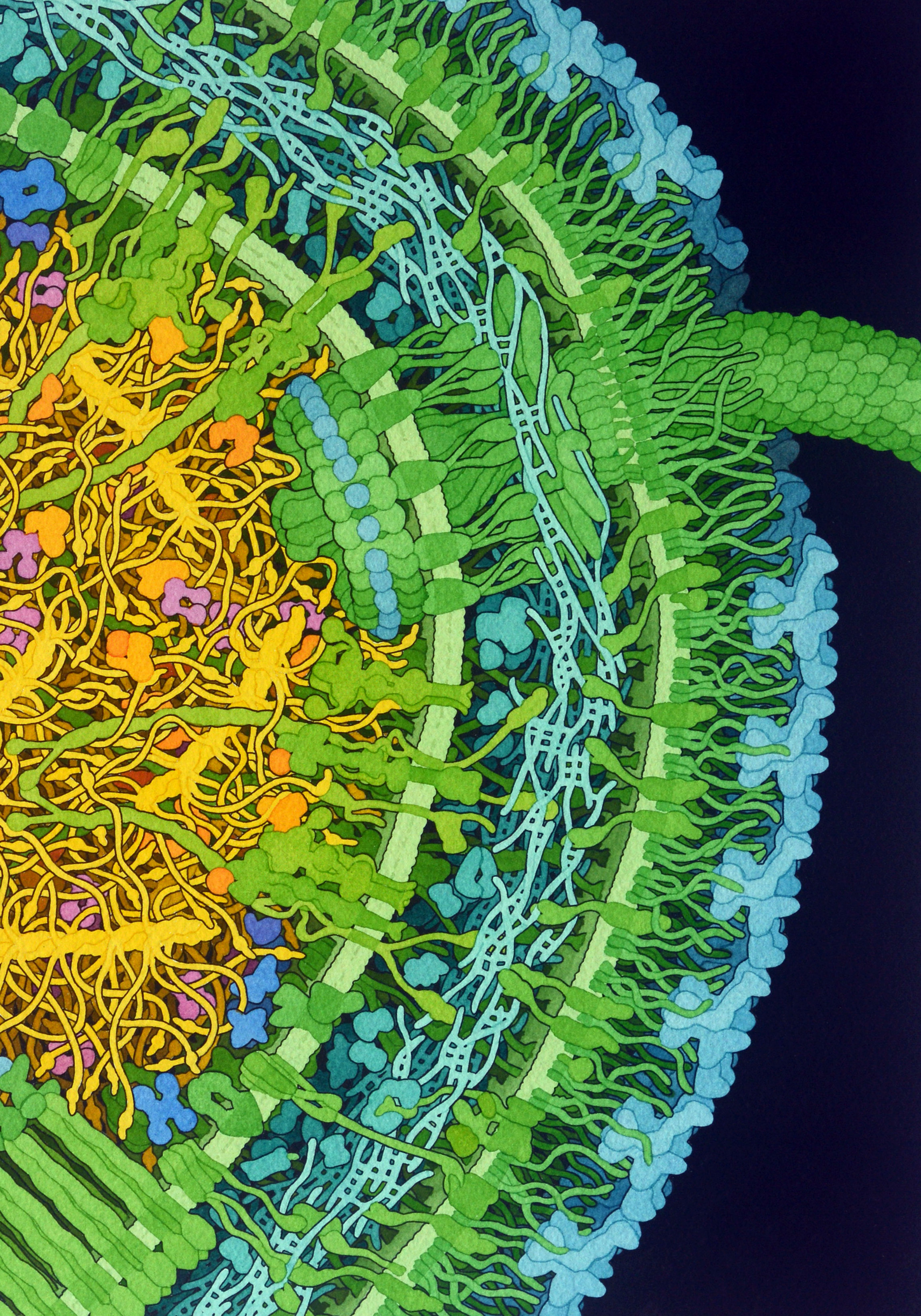


RecA and DNA, 2021 | RecA protein (in turquoise) associates with DNA and forms a long, thin filament that stretches through a cell, providing a scaffold to assist with the pairing of homologous strands during DNA repair. Here, several sites in the DNA are temporarily pairing with the RecA DNA filament as the filament searches for an exact pairing. Illustration by David S. Goodsell, RCSB Protein Data Bank. doi: 10.2210/rcsb_pdb/goodsell-gallery-038, CC-BY-4.0

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