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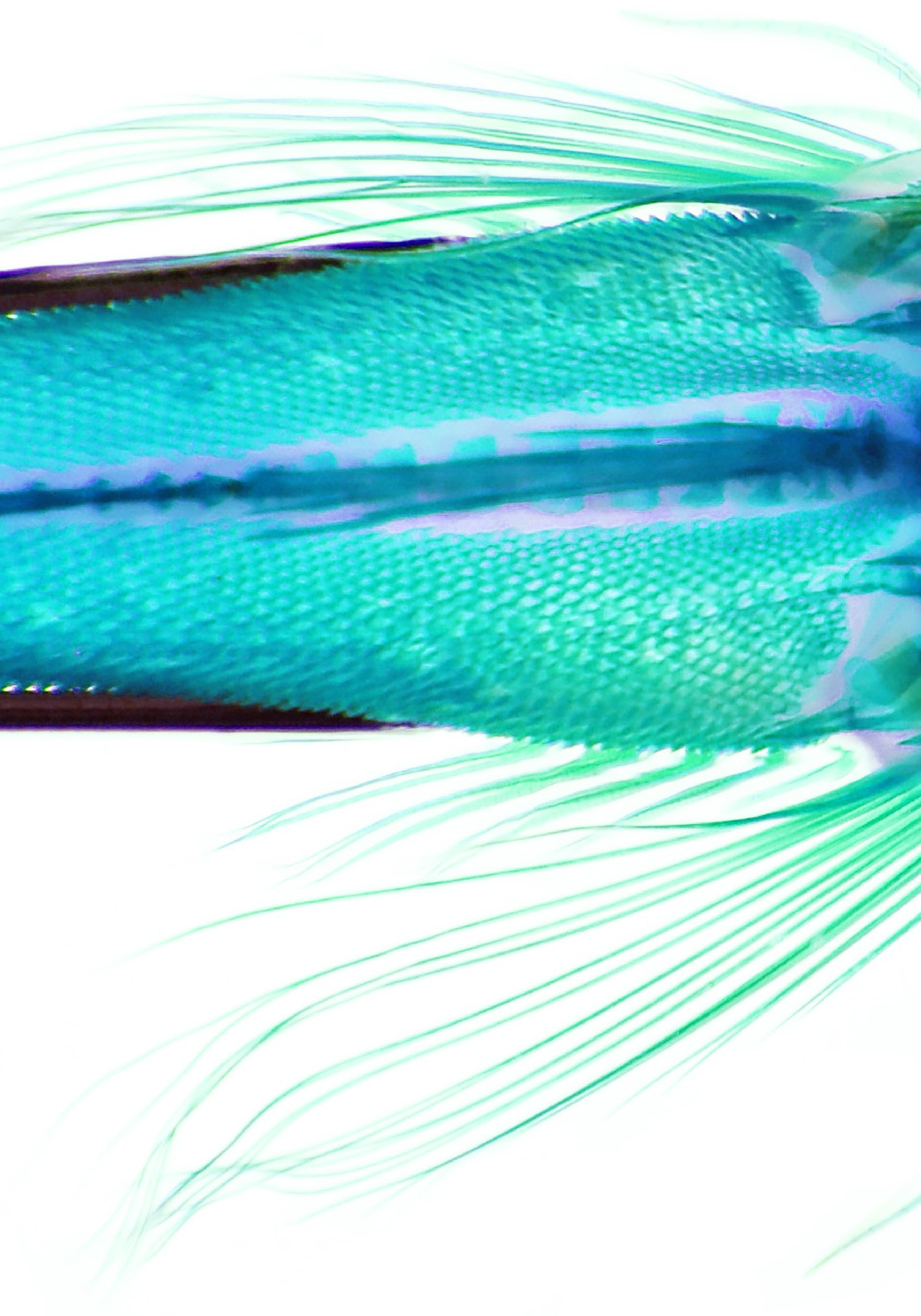

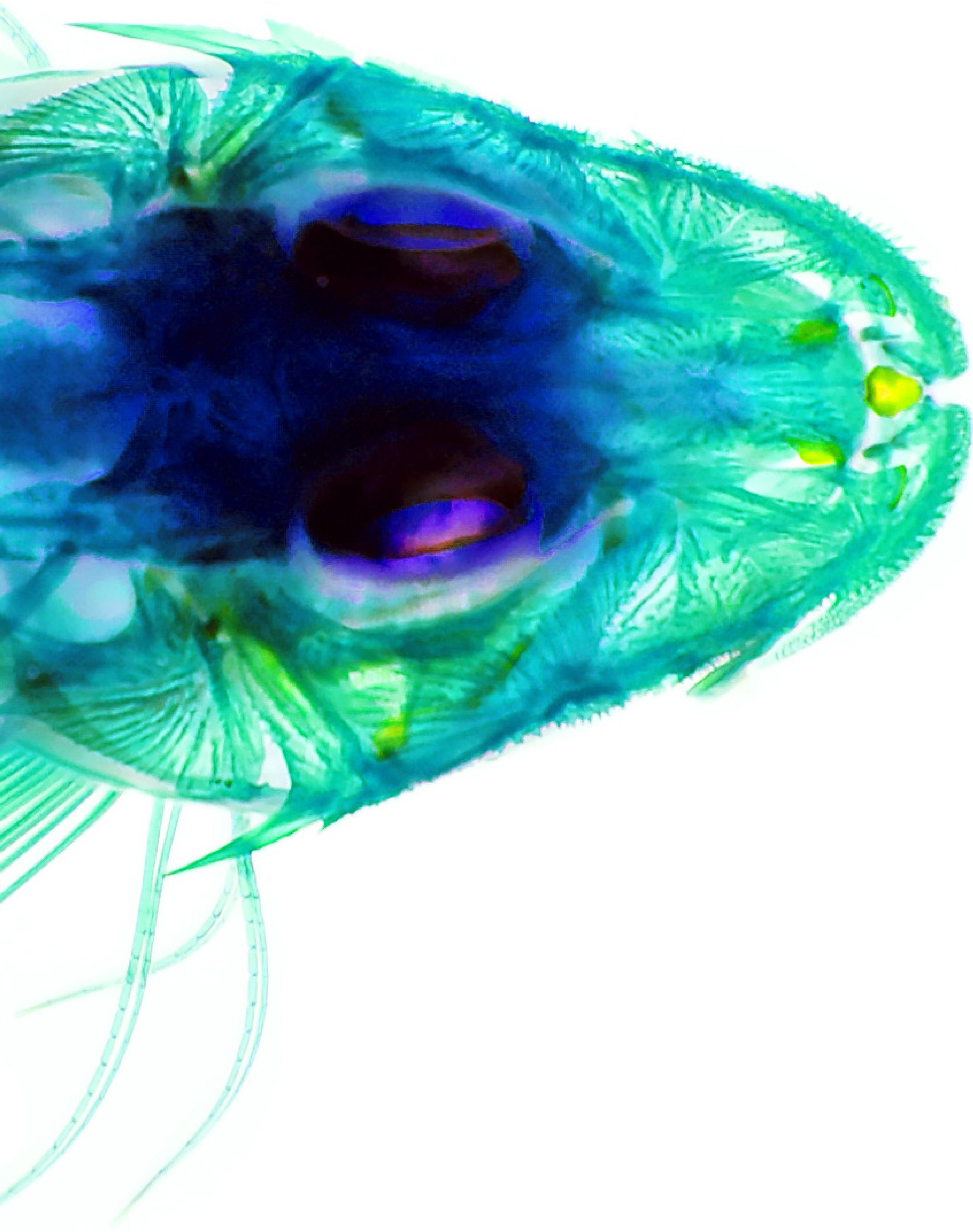

About Zygote Quarterly

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Copepod | Photo: Julie Laurin

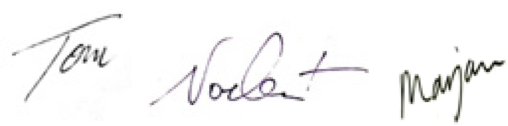
Editorial

Mosquitoes and mites and copepods, Oh My! All good bio-designers know that Arthropods rule (the largest phylum on the planet at over 1 million counted species), and this issue is largely about the very small. We have three of the four classes of Arthropoda represented: insects (mosquito), arachnids (mites), and crustaceans (copepods). Had we actually planned our topics, we might have thrown myriapods (centipedes and millipedes) in for good measure.

Julie Laurin, one of our portfolio artists, is enthralled with the microscopic creatures one can find in everyday surroundings, including copepods, and wants you to be, too. Both she and fellow artist and scientist Noah Bressman, bring a passion and curiosity and an urge to share their joy of nature to their two pieces. Julie describes her "A Tiny World" citizen curiosity project, and Noah explains his terrible case of "icthyofilia" and how he creates his stunning images of fish. Editor Tom McKeag pleads the case for the much-maligned mosquito in his article about some innovations inspired by this master vector. Heidi Fischer takes us to the bizarre world of the mite, and how intrepid researchers are expanding our knowledge of this invertebrate; sometimes telling us more than we might care to know!

In this issue we also interview biomimicry consultant Jamie Miller of Biomimicry Frontiers of Guelph, Ontario, Canada, and learn his views on the state of the practice, entrepreneurship, and the need for a societal change in attitude. Ben Morgan offers his metrics for greater success in the practice, using case study examples. Finally, Ryan Church discusses how the green chemistry of nature could inspire sustainability efforts across energy generation, storage, and distribution. Ryan details examples from nature's chemistry toolbox, photosynthesis, ATP (adenosine triphosphate), and bioenzymes like quinones. All for the good.

Happy reading! ×



Tom McKeag, Norbert Hoeller and Marjan Eggermont

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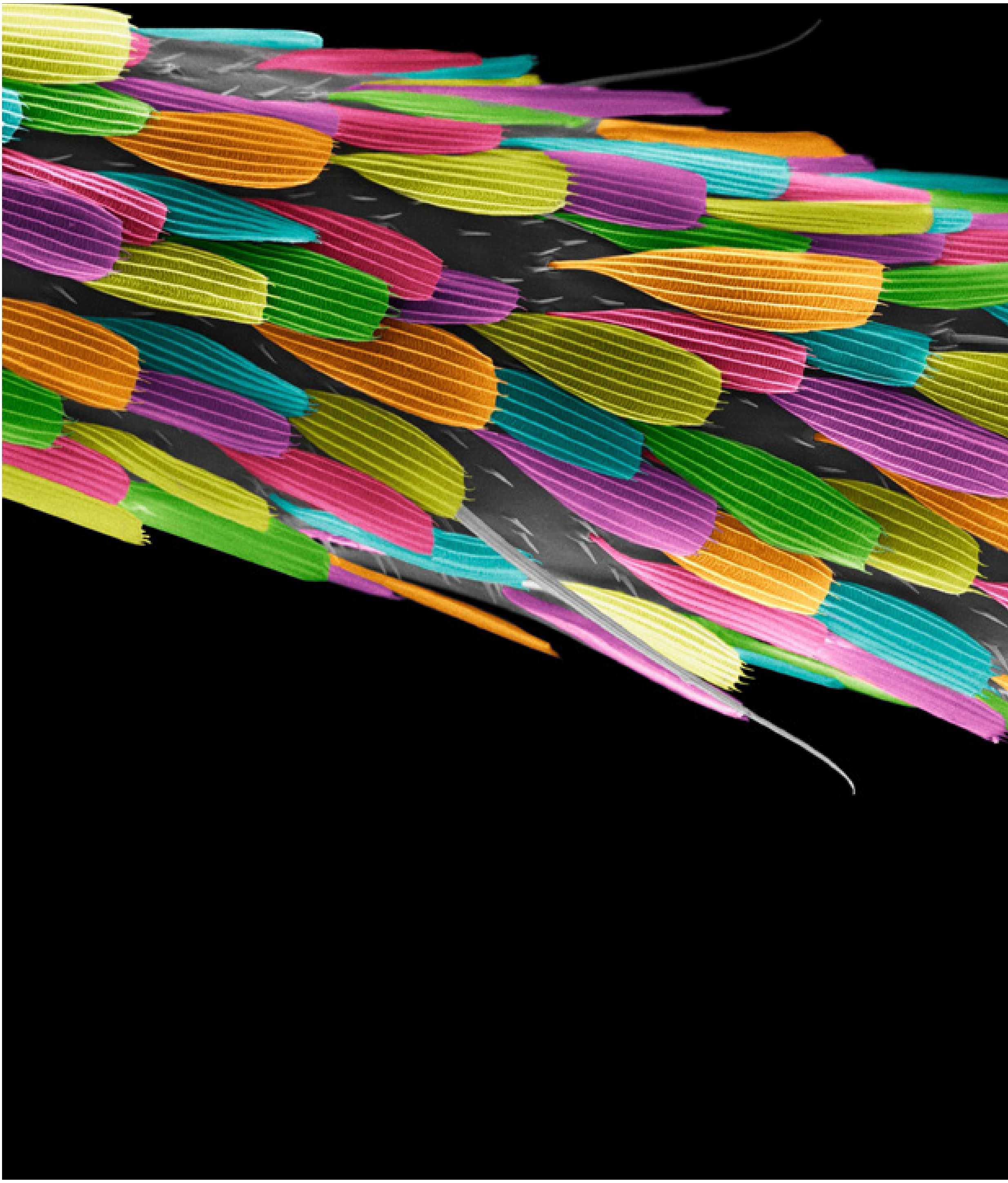


Scales on a mosquito leg (*Anopheles stephensi*).
Photo: Lauren Holden. | Wellcome Collection. Attribution 4.0 International (CC BY 4.0)

Article

The Latest Buzz

Tom McKeag

The Latest Buzz
Tom McKeag

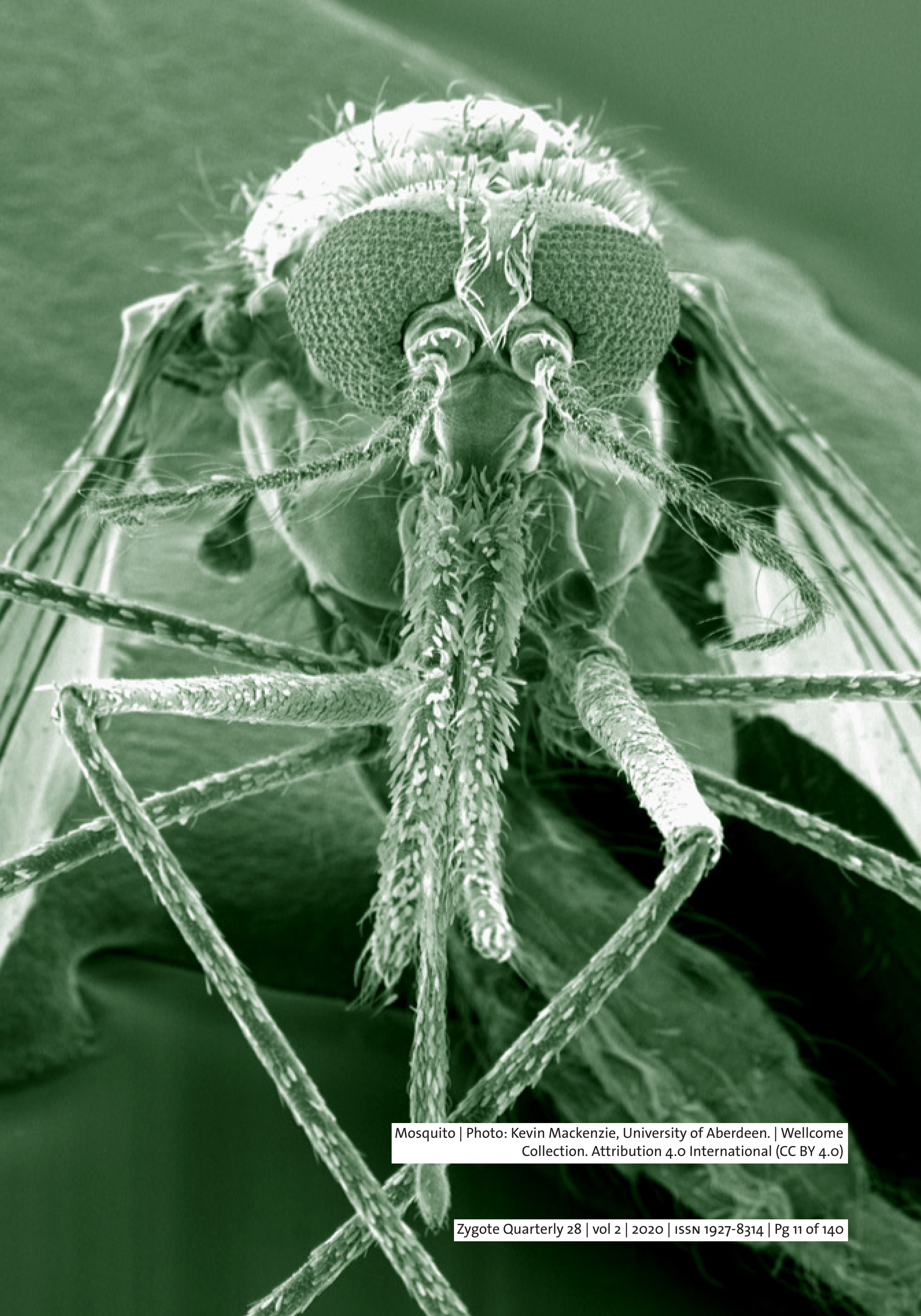
The Latest Buzz: Could the Mosquito Cause More Good than Harm?

It's summer, and it's hot, and you have just sat down in your backyard to have a nice cool drink and watch the sunset, until, of course, if you live in certain places with sufficient moisture, you hear that dreaded bugle call of an all-too-familiar insect, the mosquito. You know the party's over, don't you? For she will either find and impale you, or you will spend the next twenty minutes of your existence in frenzied watch and fitful conniptions. It is a "she", you know, and she needs your blood for protein to lay her eggs.

She will find you. The mosquito has an intriguing array of mechanisms to find her target, starting with detecting the CO_2 plumes from your exhalation within 10 meters, to recognizing the 340 different chemicals given off by your body within 1 meter, to a simple optical system to spot you in that chair, to heat sensors in her antennae that guide her to the warmth of the subdermal capillaries of your exposed skin within 20 centimeters. Imagine being co-pilot as she turns these sensor systems on sequentially and concurrently as you fly ever and ever closer to landing. We humans don't have a chance!

Or do we? Plants are masters at manipulating insects for all sorts of reasons and all sorts of ways. They especially do not want to be eaten by insects so have evolved all sorts of secondary metabolites, like the oils from the Lemon Eucalyptus tree, *E. citriodora*, otherwise known as PMD (p-methane 3,8-diol), that masks odors, or pyrethrins, from *Chrysanthemum* that repels or kills insects, or the oil from lemongrass, *Cymbopogon citratus*, that blocks CO_2 and impairs the mosquito's initial homing methods.

Pyrethroids, ultimately modeled on the natural compound pyrethrin, are a broad category of divergently structured compounds grouped according to their effectiveness as biocides. They work by locking open the voltage-gated sodium channels in the axonal membranes of nerve cells. With these channels frozen in the open position, no switching in polarity can occur and therefore no sodium ions pass through the membrane to initiate action: the animal is paralyzed. Many of the strongly scented plants, like mint, eucalyptus and pine also contain monoterpenes or isoprenoid compounds within their essential oil that repel animals. Like everything else in nature,



Mosquito | Photo: Kevin Mackenzie, University of Aberdeen. | Wellcome Collection.

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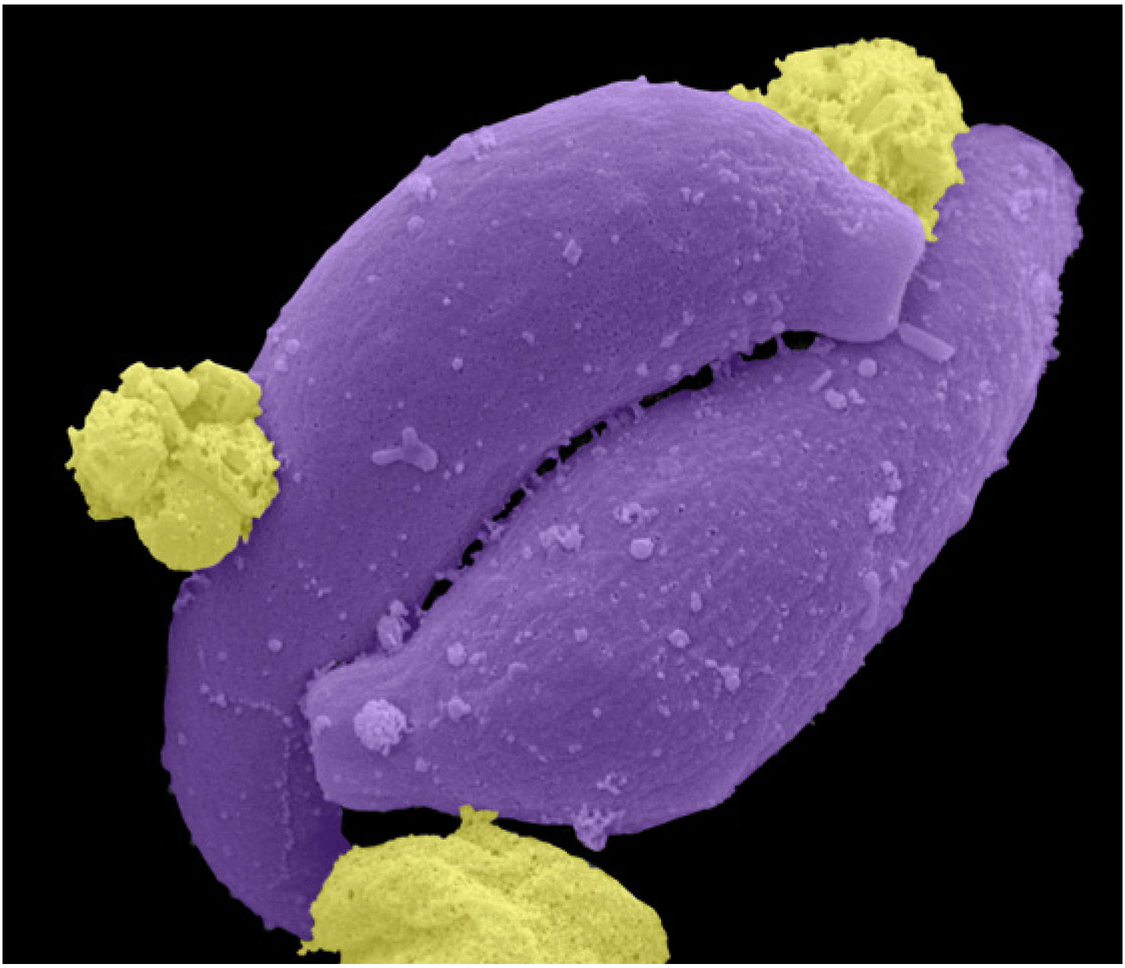
there seems to be a continually escalating (albeit evolutionarily slow) arms race on the insect front and quite a few organisms have achieved an uneasy parity with their flying antagonists.

Mosquitoes belong to the Order Diptera, the True Flies, and the family *Culicidae*. Their name means "little fly" in Spanish. There are over 3,500 known species and they have been on earth for at least 100 million years. Like many other insects, mosquitoes begin their life as aquatic larvae, going through four molting stages or instars as larvae, emerging from single or multi-cell "rafts" of eggs laid on the surface of water. During these larval stages they feed on algae, plankton, fungi and bacteria and other microorganisms. They do not have gills during this phase, so must rise to the surface frequently for oxygen. At this small scale, the surface tension of water is a major challenge, so mosquitoes have evolved a siphon to pierce through the clinging water molecules - a micro snorkel! Some species have even adapted to piercing the walls of aquatic plants to take advantage of the oxygen found in them. After as much as a fortnight of larval feeding and growth, the mosquito enters the pupa stage within a floating case where the final transformation to adult occurs. Male mosquitoes will live an average of about a week, and females average about six weeks, although lifespans vary widely across species and environments. Both sexes will feed on nectar, aphid honeydew and plant juices, with the females searching out both cold and warm blooded animals, even other invertebrates, for a protein supply. Different mosquitoes have different patterns of activity; the Asian Tiger, for instance, is known for aggressive daytime feeding, while many others come out only at dusk.

I suppose we humans would not care so much about studying this creature if it wasn't for the dangerous microbial hitchhikers inside of her. Three types are of especially serious concern. The *Anopheles* mosquito carries the *Plasmodium* (*falciparum* or *vivax*) protozoan parasite that causes malaria. Two types of *Aedes* mosquito, the Asian Tiger (*albopictus*) and the Egyptian (*aegypti*) carry the three viruses of Zika, Dengue Fever, and Chikungunya. In addition, various other genus of mosquito carry several encephalitis viruses of grave concern to humans and livestock.

A vector is an agent that carries and transmits a pathogen from one organism to another. The mosquito is the world's master vector, as it "mainlines" a parasite or virus, perhaps picked up from passerine birds, directly into a mammalian host's bloodstream.

We often say that the mosquito “bites”, but that analogy would only be accurate if we chose to bite with a sharp nose that stabs and suctions up liquid. Appropriately, this mechanism on the mosquito is called a proboscis; it comprises an outer sheath called a labium that surrounds a bundle of feeding stylets termed a fascicle. The chitin-based polymeric fascicle is made up of the labrum tube, thin tubes called mandibles, saw-toothed maxilla, and a flat central saliva duct called the hypopharynx. Each of these parts has a unique, complementary function that allows the mosquito to make



Plasmodium ookinetes, malaria parasite life cycle, SEM.
Photo: Leandro Lemgruber, University of Glasgow. | Wellcome Collection.

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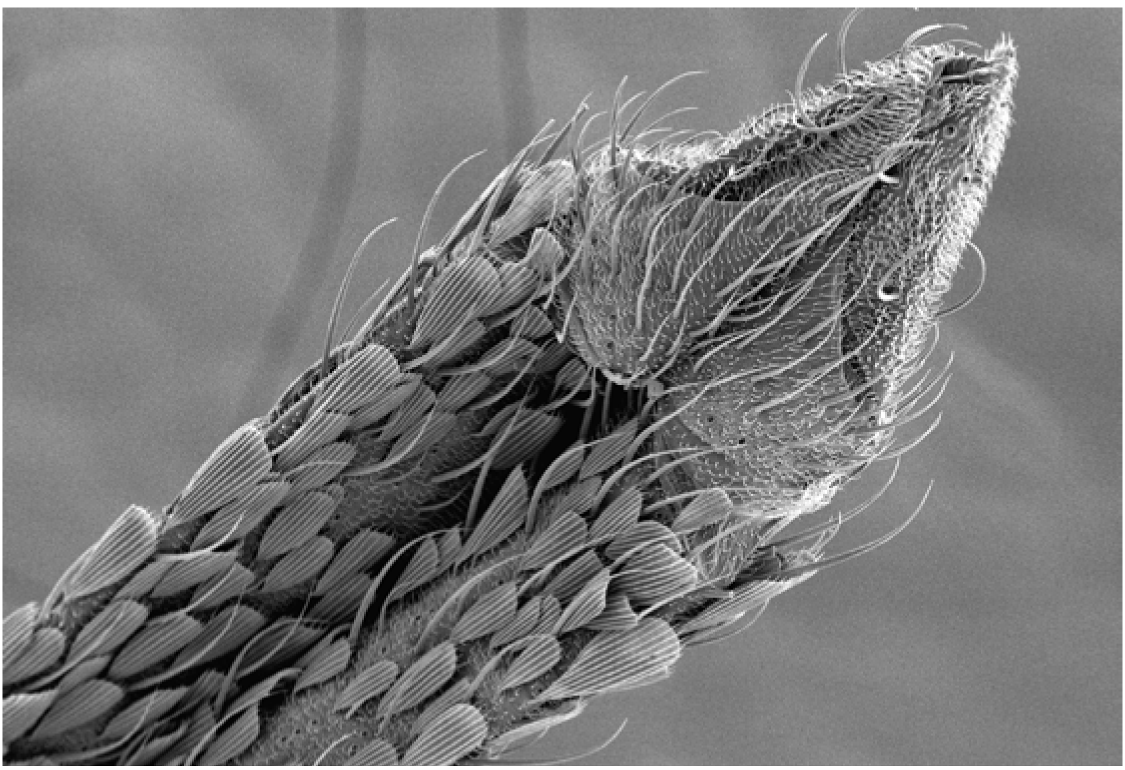
midnight withdrawals from your blood bank with a minimum of disturbance and detection.

The end of the fascicle is a marvel of engineering and a supreme example of using structure, rather than material, for strength. The tip of the fascicle is extremely sharp, and, much like a human-made hypodermic needle, is a creased sheet structure that gradually folds over itself into a tube. The fascicle is an order of magnitude smaller than a typical hypodermic needle and its inner diameter is only about 20 microns. Its sheet-structure tip is about 50 microns long and tapers sharply in a 10 to 1 ratio along that length. For added stiffness the two sides of this v-shaped tip have small reinforcing ridges. Unlike a traditional hypodermic needle, the fascicle is flexible, and relies on the labium for lateral support and the behavior of the mosquito to test the best placement to avoid buckling.

Once she has penetrated the outer layer of skin, the mosquito will bend her legs

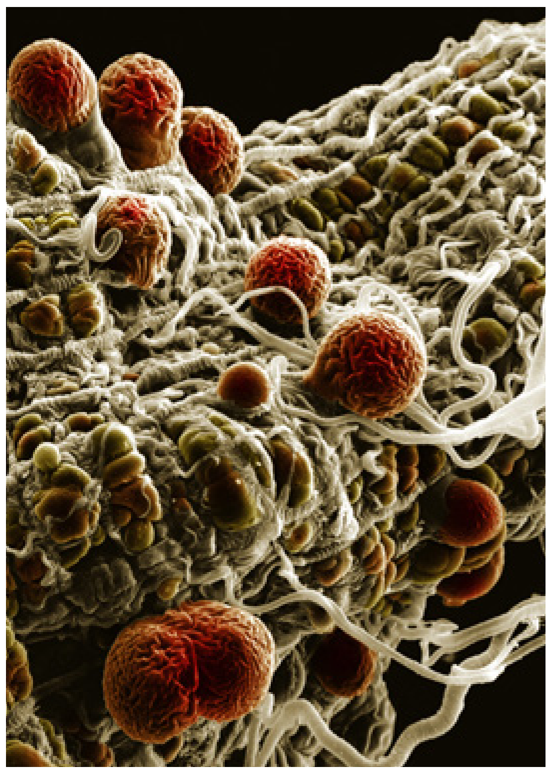


Scanning electron microscopy image of mosquito proboscis.
Photo: Judyta Dulnik, 2015 | Wikimedia Commons

and wag her head as she gradually works the vibrating fascicle in and out of the skin, the labium retracting and piling up against her "face" while completely supporting the fascicle end at your skin. The deeper the puncture gets, the more stable, and hemorrhaging of disrupted capillaries soon forms a blood pool from which to make the withdrawal. The saw-edged maxilla have already cut the skin cleanly so that no reactive force of puncture will be felt, and the hypopharynx is feeding saliva into your blood. The saliva contains numbing agents and anticoagulants to prevent clotting and to make the blood run smoothly to her. Contained also within the saliva could be some of the worse scourges of humanity.

There were an estimated 228 million cases of malaria worldwide in 2018, according the World Health Organization (WHO), causing 416,000 estimated deaths. These deaths were disproportionately distributed (85%) in 20 African countries and India. Moreover, children (67%) are the most likely to die of the disease. The greatest impact is on maternal, infant and child health, especially in vulnerable African populations. While death rates are being lowered and more countries join the malaria-free club each year, the worldwide reduction rate has leveled off, caused by a number of factors. One of those factors is the gradual evolution of the mosquito vector and the parasite she carries.

Resistance of mosquito populations to pyrethroid-based insecticides used typically to treat mosquito nets is widespread and increasing. The basic population dynamic is straightforward: the introduced toxicant or preventative effectively eliminates large segments of a population initially. Over time, however, members of the population that do survive because of some genetic advantage to resist are able to reproduce. Across



Malaria parasites.
Photo: Hilary Hurd | Wellcome Collection.

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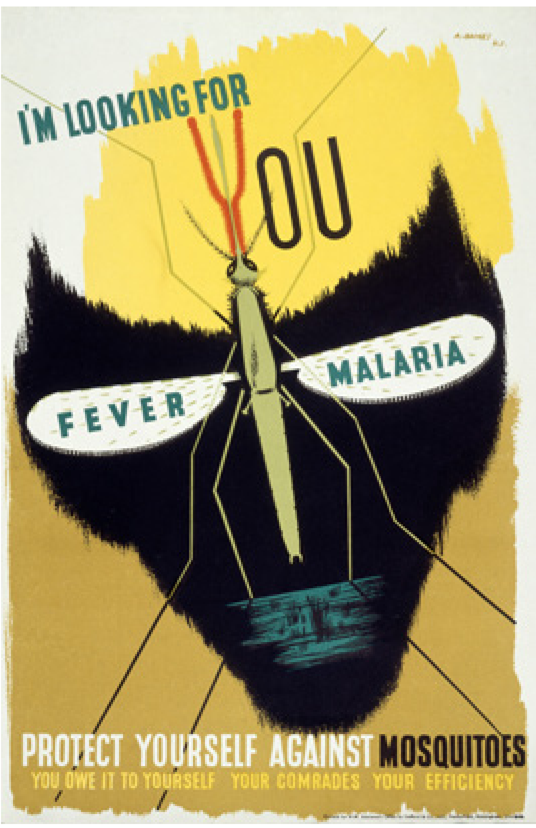
generations of interbreeding by increasingly resistant individuals, the toxicant becomes less effective, sometimes to the point of having no effect at all.

The protozoan parasite is also evolving, and this is affecting both detection of the disease and its treatment. Several gene markers used to identify malaria have been increasingly dropping out of the genome of the protozoan carrying the disease, causing false negatives and forcing the search for new diagnostics. *Plasmodium* is becoming increasingly resistant to the treatments. *P. falciparum* has developed resistance to nearly all of the currently available antimalarial drugs, such as chloroquine, sulfadoxine/pyrimethamine, mefloquine, halofantrine, and quinine.

Although $2.7 billion US was spent globally on control and elimination of malaria in 2018, the evolving genetic makeup of the animal and microbes suggests that this will continue to be a major burden on populations and prosperity for a long time to come. Moreover, while there are a variety of drugs one can take to offer partial protection from and treatment of malaria, there are currently neither vaccines nor treatments for the three virus-based diseases of Zika, Dengue Fever and Chikungunya. The Center for Disease Control of the U.S. (CDC) recommends avoidance of being bitten as the only effective means of combatting these diseases.

The mosquito has been called the most dangerous insect in the world because of its role as a vector of dangerous diseases that, by World Health Organization 2020 estimates, cause one million deaths per year. Surely, it has redeeming qualities that balance the ledger, however. Can it be a force for good as well as ill?



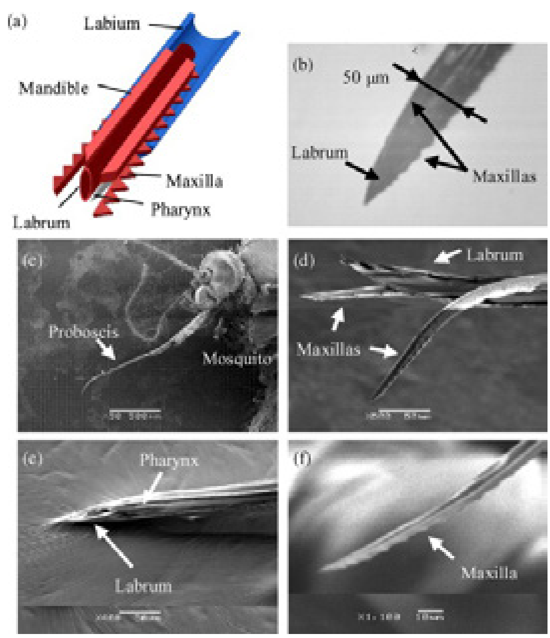
Colour lithograph after A. Games, 1941.

First, the mosquito exists within complex ecosystems and serves many roles. This insect is food for a huge variety of animals: birds, bats, fish, reptiles and other insects. Mosquito larvae are important processors of detritus and other organic aquatic matter as well as being fed upon by other organisms. Mosquitoes are also pollinators of thousands of plants since they feed mainly on nectar. In some places, like the Arctic tundra, they are so numerous, appearing in asphyxiating clouds, that they affect large ecological events like the migration paths of caribou. Beyond these ecological benefits, many of which are not completely understood, the mosquito has inspired several imitations that could have lasting benefit to the human species.

In a strictly anthropocentric vein, these bloodsuckers have inspired several inventions in the fields of sensing, medical devices and pharmacology, as well as prompted furious scientific investigations of how to combat both vector and disease.

The structure of the mosquito proboscis has inspired the development of microneedles that can deliver medication painlessly. Modeled after the bundling of the saw-edged maxillae and the pointed labrum tube on the animal, these needles cut a path for the puncture at a scale that reduces a painful jab to a tickling prick. Arraying many of these needles in a patch ensures a delivery of sufficient medication.

Japanese researchers at Kansai University in Osaka were some of the first in 2005 to examine the elegant form of the mosquito proboscis and translate it into a synthetic tool. They described a micro lancet of safe polylactic acid (PLA) that was made by wet chemical anisotropic etching of silicon negative groove, and micromolding the PLA.



Mosquito's proboscis comprising a center straight labrum and outer jagged maxillas: (a) schematic mosquito's proboscis, (b) optical image of mosquito's proboscis by high-speed camera (optical magnification; 115), and (c)–(f) SEM images of mosquito's proboscis..

Izumi, Hayato, et al. “Realistic Imitation of Mosquito's Proboscis: Electrochemically Etched Sharp and Jagged Needles and Their Cooperative Inserting Motion.” *Sensors and Actuators. A. Physical*., vol. 165, no. 1, 2011, pp. 115–123.

Mosquito proboscis (*Culiseta inornata*) | Photo: Macroscopic Solutions, 2019 | Flickr cc

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Engineers at Ohio State University have subsequently identified four key parameters to painless penetration: a numbing agent, the use of vibration, the serrated maxillae and, in a new insight, a functional grading of the labrum for hardness: softer near the tip and edges and harder the further in and up the labrum one went. The stiffness grading is correlated to the vibratory behavior of the insect.

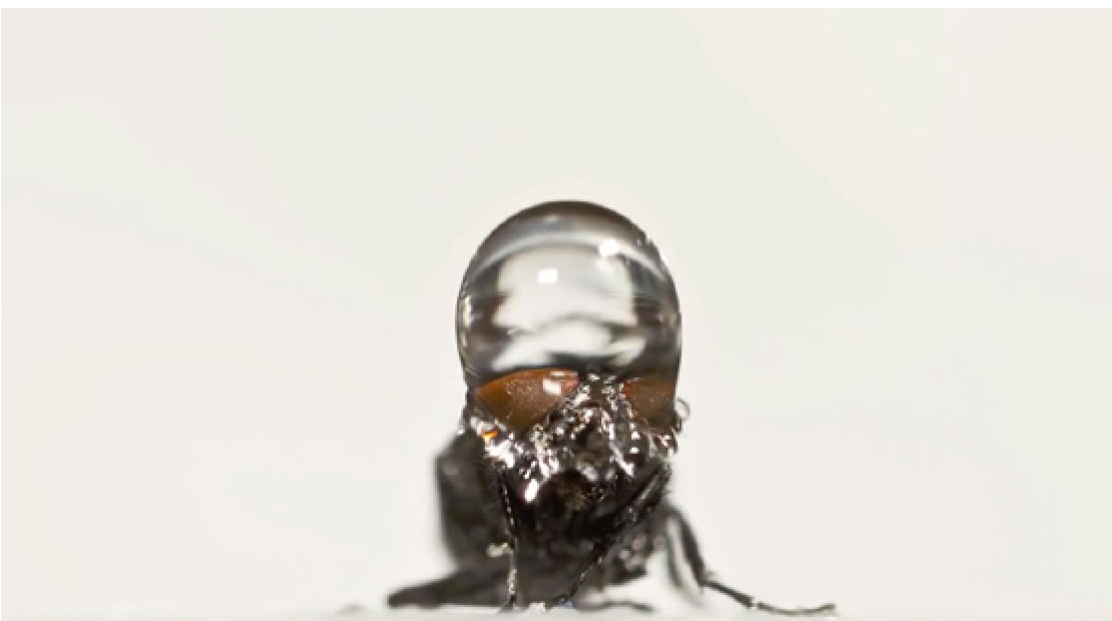
The chemical components in the mosquito's saliva are a trove of potential biomedical tools, performing many complex functions like anesthetizing, increasing blood flow and cell signal blocking. Anopheline mosquitoes produce the anosphensin family of proteins, which is responsible for numbing by inhibiting the growth of a pain-inducing peptide known as bradykinin. The anti-coagulants in her saliva that guarantee a smooth flow of blood and good digestion, as another example, are of great interest to researchers hoping to develop therapeutic drugs.

Scientists at the University of Porto in Portugal have unlocked the mechanism by which a protein in the saliva, anophelin, binds to an enzyme or proteinase, thrombin, in human blood, and inhibits it from initiating blood coagulation. Enzymes operate typically by lock and key binding sites that other proteins attach to, and the imposter anophelin occupies this site in (alpha)-thrombin and sabotages the chemical cascade of fibrinogen clotting and platelet activation that our bodies marshal against wounds. The structural and functional data obtained by the researchers will help open new perspectives to the rational design of improved anticoagulants.

Immunologists are also interested in the mechanisms with which some of the more than 100 proteins in mosquito saliva provoke an immune response (immunogenicity). Fascinatingly, the saliva also suppresses the human immune system itself. They have found that mosquito saliva "enhances the infectivity of pathogens and the progression of disease". It is not clear why, or exactly how, but a team at Baylor University has found that several immune cell types are put out of action, across multiple tissue types, and across a wider time interval after penetration than previously thought.

It had been known for a long time that the injection of the saliva circumvents vaso-constriction, platelet aggregation, coagulation and inflammation or hemostasis, but this was new. The mosquito was making it easier for any saliva-borne pathogens, especially viruses like Dengue and West Nile, to travel from the skin to other tissue like bone marrow, for up to a week after being introduced into the blood stream. The researchers have hypothesized that the saliva either kills the cells that produce cytokine, an essential signaling protein in immune cells, or inhibit its production by those cells. Understanding this mechanism better will aid in the development of an infection preventing vaccine for these types of viruses where none now exist. The pathogens that have evolved to piggyback unto the mosquito's saliva and use its formidable methods of attack might be finally thwarted by a study of the family martial art secrets of *Culicidae*.

Once the mosquito has gotten her full draft of blood she must make her getaway. This ultralight but durable flying machine, however, travels in a scale world very unlike what we humans experience. In this world of the very small, drag and surface tension are physical forces that humans, concerned more with the effects of gravity and inertia on our large masses, do not appreciate. She will fly at an ultrafast wingbeat frequency of 700 Hz in a flat amplitude of only 40 degrees. Interestingly, she will not get her lift, like most other flying organisms, by leading edge vortex, but by the trailing edge. She will be able to fly in the rain, with



Mosquitoes survive raindrop collisions | Andrew K. Dickerson, Peter G. Shankles, Nihar M. Madhavan, David L. Hu | Proceedings of the National Academy of Sciences Jun 2012, DOI: 10.1073/pnas.1205446109. | https://www.youtube.com/watch?v=XWy0y44oV3Q

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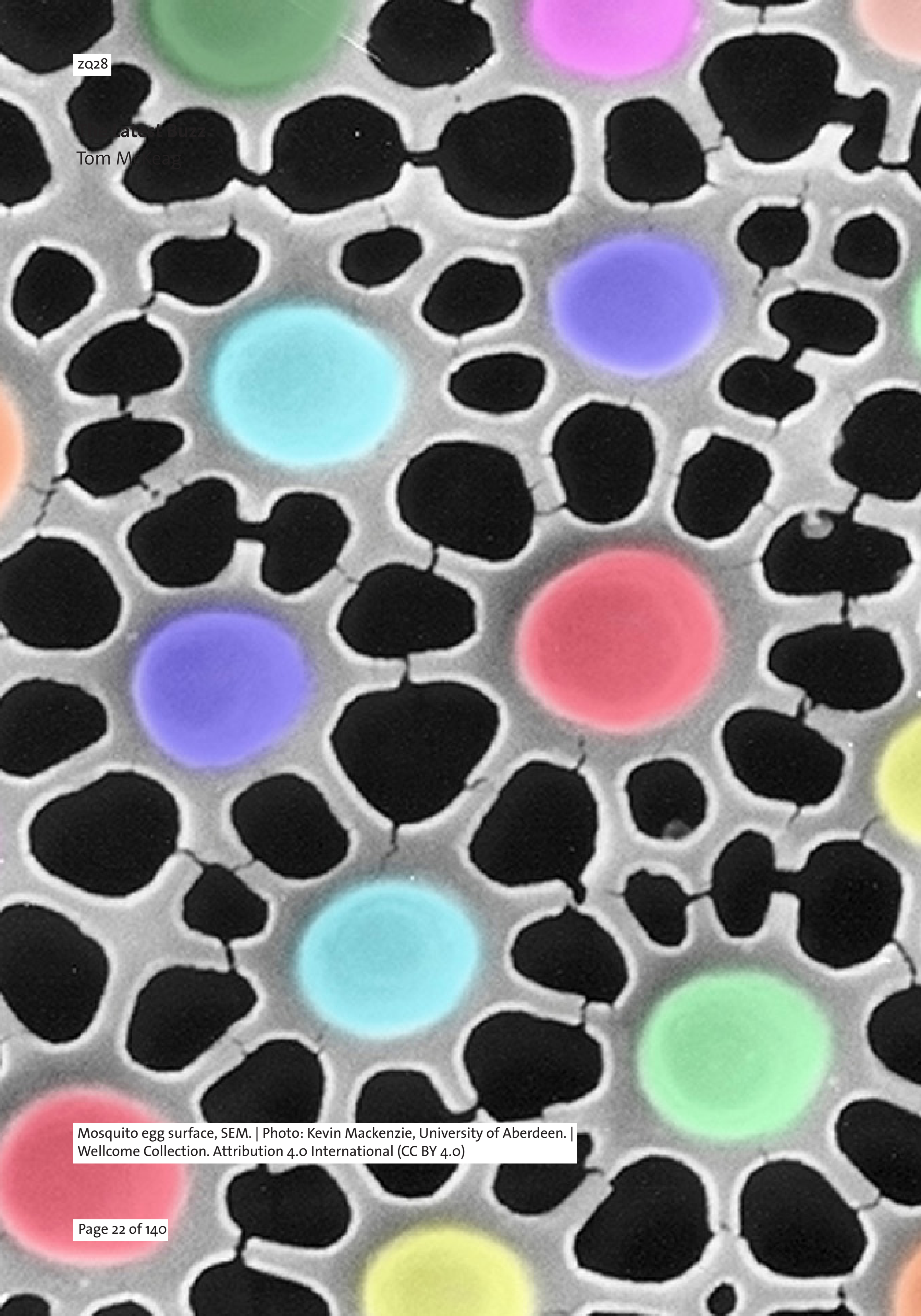

Mosquito egg surface, SEM. | Photo: Kevin Mackenzie, University of Aberdeen. | Wellcome Collection. Attribution 4.0 International (CC BY 4.0) hydrophobic wings, and land on virtually any surface, wet or dry, at any angle. Hooks and setae on her feet can employ mechanical gripping or Van der Waals forces for the dry, and the insect can walk on water, due to her light weight, angle of contact and the flexible tarsi of her legs. Avoiding crashes, she will use her antennae to sense differences in pressure and velocity of the air around her and gauge when solid surfaces are near. Researchers in the UK and Japan have devised a system for surface detection by autonomous rotor vehicles based on this method that is cheaper than traditional sensing like radar.

While we may revile the effects of the mosquito's behavior, we must begrudgingly admit that this little insect is a champion at what she does, with a stunning array of compounding (and confounding) tools to get the job done. Understanding how she does these things so very well may not only stop her delivery of deadly disease to so many, but may improve our lives in a myriad of other ways.

We would appreciate your feedback on this article:

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Mosquito saliva- anti-coagulant

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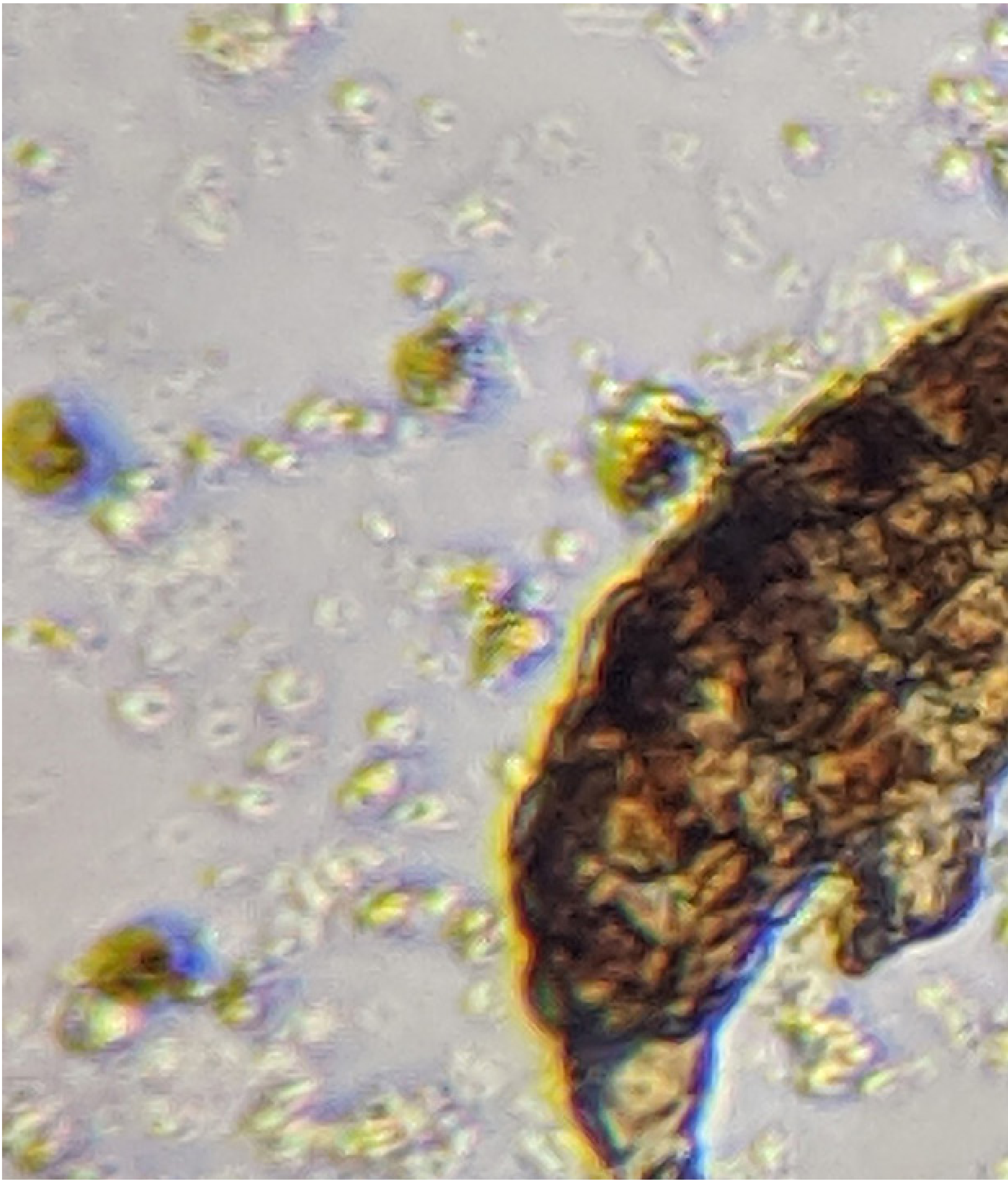
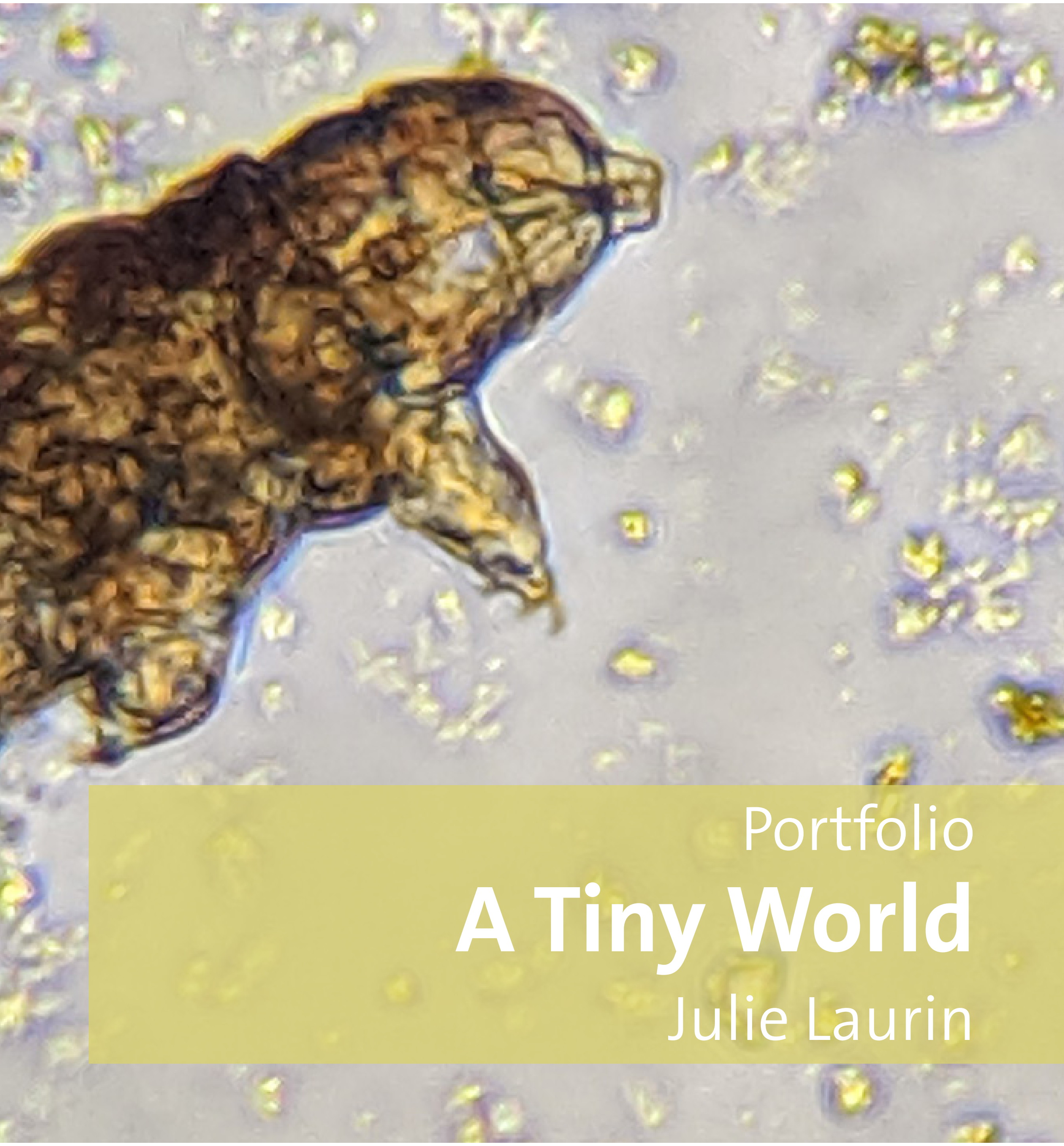


Tardigrade (*Ramazzottius*)
Photo: Julie Laurin



Portfolio

A Tiny World

Julie Laurin

A Tiny World

Julie Laurin

"A Tiny World" is a passion project, created by Canadian artist and software specialist, Julie Laurin. It's an ongoing project to introduce the general population to the microscopic world, and to share Julie's exploration and curiosities along the way. The project is largely self-funded, with additional funding from Twitch subscribers.

"A Tiny World" currently explores freshwater samples from ponds, creeks and swamps, as well as urban microscopic life that lives on balconies and sidewalks all around us. However, it was never intended to be exclusively focused on science. The goal of this project is to see what other possibilities we can explore from the point of view of everyone's curiosity, whether they be artists, scientists, or hobbyists.

Lastly, "A Tiny World" aims to encourage people to explore without always knowing anything about that which is being explored. The drive to be curious, and the impulse to try something new is the main reason why this project exists.

Julie Laurin works in software, has taught science and communications adult education, and is a fine arts photographer.

Julie Laurin

Could you tell us more about how you got started with a tiny world?

I purchased a microscope after reading Rob Dunn's book *Never Home Alone*. I researched good entry-level scopes and settled on a binocular OMAX microscope that I ordered on Amazon. Microscopes aren't really that hard to figure out. The hardest part was figuring out what I was looking at! I was taking pond samples, looking at leaves, and moss, and lichen. But, I wanted to learn more about what I was seeing. This led me to spending so much time filtering through website after website, paywall after paywall, and realizing that there's not much information out there for non-academic "microworld" enthusiasts! So, I decided to start an online project. Initially, I

Stentor (https://www.youtube.com/watch?v=EfFB1yQ-sI8)

A Tiny World
Julie Laurin

just wanted it to be a Twitter account, and an online portal. Slowly, I added a beginner guide, a creature page, a Facebook page, and I even converted my personal Instagram account to A Tiny World. Lastly, I discovered Twitch and I noticed that there wasn't anyone live-streaming from a microscope. (I later learned that there were a couple of people doing so, but they weren't easy to find!) That's when things really took off.

What kind of techniques/approaches/platforms do you use for a tiny world?

I don't know if "simplicity" could be considered a technique, or an approach, but that's really the entire motivation behind it. I wanted to create a project that could be understood by almost anyone, regardless of education. The simpler, the easier, the more accessible, the better. That's why I keep my language simple, and that's why I use nicknames for a lot of the creatures that we observe. For example, there's a running joke that midge fly larvae are called "Pete". All of them. So, when we see one during a stream, everyone yells, "Pete!". It's a way for people to relate to what they're seeing.

The other thing is, I want this project to remain neutral and apolitical inasmuch as possible. Tensions are high right now, especially with a pandemic and ongoing tensions in the United States. There's a lot of anger, a lot of pain, a lot of sadness. A Tiny World really endeavours to pique people's curiosities about the natural world, but it also gives them a break from everything that hurts. There is a place for escapism, entertainment, and education. Rather than making political statements online, I prefer to use my project to raise the voices of women and minorities, to make education accessible, and to help people find affordable ways to observe the microscopic world. The only way we can combat 'woo' and pseudoscience is to make science accessible to anyone and everyone, regardless of religious, or political beliefs.

In terms of technology platforms, I am using the usual social media platforms, like Twitter, Instagram, and Facebook. It was my first post on Imgur (a video of a Tardigrade), however, that made everything go viral. It got about 200K views almost overnight, and I got over 1,000 followers on Twitch from that single post. I'm still not adept at using Imgur, but I do recognize that it has a lot of potential for science education since it's an image-based community!

Twitch is my favourite platform, so far. I find it almost embarrassing for the science communications community that there are literally only a handful of scientists that are engaging in regular livestreams on Twitch. (There are many computer scientists, but

Multiple tardigrades (https://www.youtube.com/watch?v=ByJRu9e9Hiw)

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very few biologists, chemists, geologists, etc). The livestreaming world, whether it's Twitch or YouTube, offers huge opportunities for scientists to connect with average people. While Twitch is primarily frequented by the gaming community, I have found that my audience is older, more mature, and generally curious about science. Even younger gamers have taken an interest! Twitch also has a great community aspect to it, including monetization options that allow your fans and audience to support you and your project. I'd love to see more scientists using this platform to connect with the wider public.

Nematode (https://www.youtube.com/watch?v=fsrosctBqLA)

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

Everything. Everything is interesting to me. Sidewalks, leaves, watches, planets, pens, feet, how motors work, how birds fly, how people sweat. I can spend hours examining a rock, wondering "why", and "how come". It's interesting because when I was a fine art photographer, all of my inspiration came from pain and love. Now that I'm inspired by nature (including the things we've created from nature), I find inspiration outside of myself. As in, my feelings about anything are irrelevant. The only thing I pay attention to now is my curiosity, and the curiosity of others. What's great about livestreaming is that there are moments when I'm not excited about a topic, but if my audience is excited, that feeling becomes contagious. And nothing thrills me more than to fulfill their curiosities. And that's what feeds me the most: a shared sense of exploration and open-mindedness with others. Because, in this day and age, it is rebellious to be happy. And this kind of work fulfills me so much.

You mentioned art photography - can you tell us a bit more about that?

I picked up a camera about ten years ago. I didn't know much about how it worked, but I knew I wanted to make art with it. I wanted to tell stories, I wanted to create whimsical worlds, I wanted to create my own style of imagery. In the photography world, it's very common for photographers to manipulate images with Photoshop. I decided against it because I wanted my work to be raw. So, I made it a general rule as a photographer: I created images using illusions and distortion with common objects like plexiglass, vaseline, theatre makeup and paint. It became my signature, in a way. It's funny because we often think that artists thrive when there's a lack of constraints, but it's been my experience that constraints actually fuel creativity. All I really needed were the people to make it happen. I needed to find my creatives, my muses, my circus clowns and acrobats.

So, I moved to Montreal in 2013, and that's when my art photography really took off. I was able to work with some of the most creative people I'd ever met in my life. Since my work was rooted in emotion and expression, I sought out people who were dancers, actors, singers, and circus artists. They became my muses and models. We understood each other, and they brought my work to life. My work revolved around finding the beauty in the grotesque, finding love in pain, finding stillness in storms.

The bulk of my work was divided between fine art work with models and creative self-portraiture. I used my self-portraits to express my own voice, but also to test concepts for art series. This allowed me to completely relate to my models, as they could rest assured that whatever new

Tardigrade life (https://www.youtube.com/watch?v=Yv8Se5KoMHQ)

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concept I'd try on them, had already been tried on myself.

My artistic work in Montreal was quite prolific. I was published in magazines, I was interviewed by the media, I did radio shows. I travelled through Europe and worked with amazing talent in Paris and Lisbon. I even got to direct a music video for a Berlin-based DJ, starring Quebec actress Pascale Bussieres. It was the artistic life I'd always dreamed of. But, by early 2017, it was clear to me that I'd said everything I wanted to say. Things were changing, I was changing. It was, in some ways, a rockstar life for someone who no longer felt like a rockstar. I wanted peace and quiet. I wanted to explore something new. So, I moved to Ottawa, hung up my camera, and replaced it with a microscope.

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

A Tiny World is pretty much what I spend all of my free time on these days! However, I am launching a new podcast called "Planet B612" (it's an ode to The Little Prince - his "planet" is actually Asteroid B612). It's a podcast that will involve long-form discussions with artists, scientists, historians and anyone who has a curious specialty. I want to ask them the kinds of questions that everyone has. I want to talk to people that the media don't talk to, like cinematographers, and linguists, and limnologists. I want to learn about their profession, but I also want to dig into their personalities and discover what kind of people study mushrooms, or the rings of Saturn, and why they do it. I want to know why grass is green, and not any other colour, and I want to find a specialist to talk about just that. It's essentially going to be a different kind of playground for me, and I look forward to starting that in July!

How can our readers get started if they are interested? What do you recommend?

If you want to get started in microscopy, I highly recommend getting an OMAX, Swift or Amscope microscope on Amazon. You can also get a pocket scope (like a Carson pocket scope, or a Celestron pocket scope). If you want something with a bit more options, get a microscope with a double-mechanical stage. That will make life much easier, as it will allow you to move your samples around with knobs instead of moving them around with your hands (making it all shaky when you're viewing them). There are all kinds of fancy microscopes, made by companies like Olympus, Motic, Zeiss, Nikon. But, they're really expensive, so consider getting them used or wait until you really want to upgrade. Starting small and simple is always best.

Once you do have a microscope, get yourself a phone attachment on Amazon and use your phone for pictures and videos. It's the easiest way to do things, and the quality will be great! From there, experiment! Soak some dust in a bit of water and put that in a petri dish to see what you'll find. Go hunting for Tardigrades in moss (soak the moss in a bit of water, drain the moss and then observe the water under the microscope).

Watch my Twitch livestream and ask as many questions as you'd like. I will always take the time to answer them. And, connect with people on Twitter. There is a large science community on Twitter, and many scientists are very generous with their knowledge to help you identify what you're looking at.

What is the last book you enjoyed?

What a Plant Knows: A Field Guide to the Senses by Daniel Chamovitz. And now, I'm in the middle of reading *Coraline* by Neil Gaiman, and it's absolutely charming!

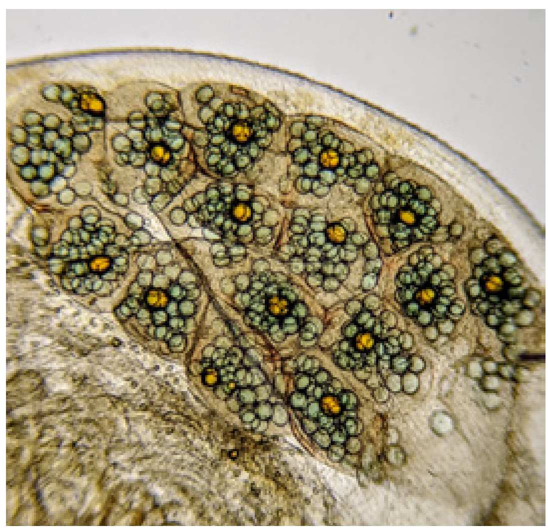
What's your favourite motto or quotation?

My mother tongue is French, so my favourite quotation is in French (please feel free to translate!):

"Quand on a envie de faire un truc, il faut plonger comme un fou, et le faire." (When you want to do something, you have to dive in like crazy, and do it.) - Jacques Brel ×

For more: http://atinyworld.org
https://www.twitch.tv/atinyworld
https://twitter.com/atinyworldorg
http://julielaurin.com

We would appreciate your feedback on this article:



Copepod | Photo: Julie Laurin

Copepod larva (*nauplii*) | Photo: Julie Laurin

Minh Ly (Neverland) | Photo: Julie Laurin

Minh Ly (Neverland) | Photo: Julie Laurin

Nematode (roundworm) | Photo: Julie Laurin

Copepod (with eggs) | Photo: Julie Laurin

Clara Cloutier (Neverland) | Photo: Julie Laurin

Daina Ashbee (Neverland) | Photo: Julie Laurin

Diatom | Photo: Julie Laurin

Copepod | Photo: Julie Laurin

Clara Cloutier (Neverland) | Photo: Julie Laurin

Daina Ashbee (Neverland) | Photo: Julie Laurin

Tardigrade (*Milnesium*) | Photo: Julie Laurin

Tardigrade (*Ramazzottius*) | Photo: Julie Laurin

Benjamin Maitre (Neverland) | Photo: Julie Laurin

Clara Cloutier (Neverland) | Photo: Julie Laurin

Rotifer (Bdelloid) | Photo: Julie Laurin

Stentor | Photo: Julie Laurin

Benjamin Maitre (Neverland) | Photo: Julie Laurin

Natasha Modelo (Neverland) | Photo: Julie Laurin

Daphnia | Photo: Julie Laurin

Bugaboos | lichen
Photo courtesy of CHM Bugaboos


Interview
Jamie Miller

Interview
Jamie Miller

Jamie Miller is an award-winning designer and the founder of Biomimicry Frontiers. He was the director of OCAD University's biomimicry program and obtained a Ph.D. in engineering from the University of Guelph, focusing on systems-level biomimicry and resilience theory. In 2019, Biomimicry Frontiers was named a "World Changing Idea" by Fast Company for their collection of services in consulting, education, incubation, and investing. Their mission is to make it better, naturally.

Jamie Miller

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

There is unlimited potential for biomimicry. I am happy to see more platforms, educational spaces, and funding being directed to its pursuit but I also see an opportunity for more businesses in biomimicry that are committed to its application. With the economic shift taking place, we need more entrepreneurs - pioneer species - jumping in to build a service or product that shares the story of biomimicry. That's where the hard work needs to be done.

What do you see as the biggest challenges?

I believe that the biggest challenges will be in our collective shift from a status-quo that seems to disregard the deeper value of nature. Paradigm shifts can be difficult to coordinate. Especially at a systems level, where they can be fiercely resisted because of their disruptive nature. And naturally, humans avoid disorder.

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

Honestly, whatever area you are passionate about. I believe we need multiple small-scale revolts that are based on the principle

Bugaboos | Photo: Jesse Tamayo, 2018 | CHM Bugaboos

Interview
Jamie Miller

of nature. It could be in creating disruptive technologies, new policies, circular food economies. Whatever area is of interest to you is the best place to start.

Personally, I focus on systems-level biomimicry and specifically in land-use planning and design. My understanding is that the most effective thing we could do for climate change is to create more intact ecosystems and limit the destructive influence of our development practices (i.e. continuing to separate and control nature from our built environments).

The other, more recent interest, however is in exploring what I call "Inner Biomimicry". Inner biomimicry is an exploration of the thoughts and assumptions that inform our designs. It's about understanding a person's biases, interests and assets, and leveraging those in the application of biomimicry. The key to Inner Biomimicry is to make sure that we focus on the mindsets of our next generation of inventors because our thoughts are the foundation of what we build, and it is human nature to want to use older thinking to innovate and design.

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

My interest in biomimicry is based on a continual pursuit of wanting to find a deeper connection to nature. This includes teaching the biomimicry program at OCAD University, focusing my PhD research on systems-level biomimicry, working early on with Janine Benyus and Dayna Baumeister at Biomimicry 3.8 and now, founding Biomimicry Frontiers and the Biomimicry Commons.

Perhaps most influentially, I have been lucky enough to work with several Indigenous Communities who have shown me a deeper understanding of biomimicry. Specifically, they have given me a new perspective of how to relate to nature and to understand our place within it.

What is your best definition of what we do?

Biomimicry is a way of viewing the world. It's about uncovering the genius of nature.

By what criteria should we judge the work?

As Janine Benyus outlined, we should always ask ourselves, does it create conditions conducive to more life? This is a layered and very powerful metric.

What are you working on right now?

Our current focus:

- Guelph circular food economy (Our Food Future) project in which we are re-imagining food production and delivery for the City of Guelph and County of Wellington. https://www.youtube.com/watch?v=5RPyTlyqYm4
- Biomimetic planning and design. We are helping an architect firm design an innovative airport master plan in Saudi Arabia. We are designing a "biomimetic" home in India. And we are currently working on some innovative master planning for a redevelopment in Ontario.
- An online course for building a biomimetic business. This course is an evolution of the OCAD University courses I taught and is an intro to becoming a biomimetic entrepreneur. It is for those who want to put biomimicry into practice - either creating their own company or approaching your business with this new lens, which may lead to new opportunities. The course has three modules: Module 1 focuses on the mindset required to effectively "do" biomimicry, Module 2 focuses on the techniques we've developed

Bugaboos
Photo: John Entwistle, 2015 | CHM Bugaboos

Bugaboos | Photo: John Evely, 2018 | CHM Bugaboos

Bugaboos | Photo: Lyle Grisedale, 2016 | CHM Bugaboos through our consulting and courses, and Module 3 provides students with the opportunity to find a niche based on their skills and purpose and to use those to build out a biomimetic business. The course is the entry point for coaching, incubation, and excursions - which all lead to a deeper connection with nature and a more impactful product.

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

My passion for the concept really started in a Math & Poetry course at Queen's University in 2004. We learned about the Fibonacci sequence and the idea that nature could be a source of inspired design. The class fundamentally shifted my interpretation of engineering, which I was studying at the time, and inspired me to apply biomimicry to my master's work in Indonesia and Sri Lanka. I worked on tsunami relief from 2005-2006 and lived in Indonesia with an environmental consultant, who taught me about permaculture, ecological engineering and the general ideas surrounding biomimicry. However, it was not until I got back to Canada and connected with Norbert Hoeller in Toronto that I got more deeply involved with biomimicry and the Biomimicry Guild/Institute (at the time). He suggested I read *Biomimicry: Innovation Inspired by Nature* and to join Janine Benyus and Dayna Baumeister in Costa Rica for one of their early workshops, which I did in 2007. This experience in Costa Rica catalyzed my passion for the idea and later I was lucky enough to teach OCAD University's biomimicry programs for several years. Recognizing that there weren't many places to do biomimicry, I started a Ph.D. in engineering research to focus on systems-level biomimicry and urban resilience, which led me to today, where I have been running Biomimicry Frontiers since 2017.

We are a small team at Biomimicry Frontiers but are always interested in hearing from top candidates who can make our company better - we also have some job postings coming soon.

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

I found this article by Anna Lenzer in *Fast Company* very interesting: https://www.fastcompany.com/90475368/to-avoid-climate-catastrophe-its-going-to-take-a-revolution-of-the-mind

In it, she explores the mindset of environmentalism and the necessary paradigm shifts that need to occur for us to have a significant positive impact. She references Naomi Klein's book *On Fire: The (Burning) Case for a Green New Deal* and ties that in to the relationship between death and environmental degradation.

This to me is a big part of Inner Biomimicry. It is important to understand the barriers and motivations of how we think, behave and create and our relationship to uncertainty - especially to the uncertainty of death. Much of my Ph.D. research was on uncertainty, change and cycles. So this interest in death (the ultimate uncertainty) seems like a natural next step in my research and excitement.

What is the last book you enjoyed?

Currently enjoying *The Invention of Nature* by Andrea Wulf

Previously enjoyed *Braiding Sweetgrass* by Robin Wall-Kimmerer

Who do you admire? Why...

Yvon Chouinard, Founder of Patagonia.

I appreciate his conviction to his values, his business sense, and his ability to push our interpretation of a sustainable brand. I loved that he brought in a day-care to his company because he said that the most important product was the kids of his employees. I also appreciate how he blurs the lines between business and outdoor adventure, and found a way to do both.

What's your favorite motto or quotation?

Einstein - "A new type of thinking is essential if mankind is to survive and move toward higher levels."

What is your idea of perfect happiness?

A combination of community, family, and nature. Playing outdoors on a mountain bike, or skiing, paddling, or climbing. As my friend says, "dancing with nature and letting nature lead."

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

I would run a sustainable ice cream parlor. ×

Jamie will be runnning a biomimicry workshop August 14-17, 2021 at CHM Bugaboos - for more: https://www.cmhsummer.com/biomimicry-workshop/

We would appreciate your feedback on this article:

Snowpatch Spire (Bugaboos) | Photo: Laurel Fan, 2011 | Flickr cc

Oribatid Mites.
Photo courtesy of Jay Taylor and Sofía González Salazar.

The Science of Seeing

The Mighty Mite

Adelheid Fischer

The Mighty Mite

Adelheid Fischer

In terms of size, mammals are an anomaly, as the vast majority of the world's existing animal species are snail sized or smaller. It's almost as if, regardless of your kingdom, the smaller your size and the earlier your place on the tree of life, the more critical is your niche on earth: snails and worms create soil, and blue-green algae create oxygen; mammals seem comparatively dispensable, the result of the random path of evolution over a luxurious amount of time.

Elisabeth Tova Bailey

Jay Taylor brushes away a few pebbles and twigs before stuffing a topdressing of dry leaves from the base of an oak tree into a plastic bag. Just as he is about to sink a trowel into the cleared patch of dirt, Taylor, an evolutionary biologist at Arizona State University, hears a sound that some have described as a cross between a dog bark and the oinking of a pig. It is the call of the Elegant Trogon. Delighted, he jumps to his feet, grabs his binoculars and begins to scan the tree tops. Even for an experienced birder like Taylor, catching a glimpse of the showy male, with its harlequin patchwork of metallic green, gray, black, white and blitz-red colors, would make the nearly five-hour drive from Phoenix worth the effort.

Trogons are a big draw to the Chiricahua Mountains of southeastern Arizona, as are other fancy-pants critters like warblers, owls and, depending on the year, a whopping fifteen species of colorful hummingbirds. But they are vastly outnumbered by what the great biologist E.O. Wilson calls the "little things that run the world." Little things like the hundreds of species of ants, spiders, dung beetles, wasps and moths here that probably won't be coming to a Facebook post near you anytime soon. It may be the "vertebrates [that] catch your eye most of the time," Wilson observes, but whether you're on land or in the sea "you are visiting a primarily invertebrate world."

No one knows this better than Taylor and his graduate student Sofía González Salazar, a Ph.D. candidate in the Evolutionary Biology program at ASU. The Chiricahuas are part of an archipelago of isolated mountains in the Desert Southwest, known as the Madrean Sky Islands, which rise from the desert floor and stretch to snow-covered peaks. For decades, they have been a magnet for scientists. But while "there has been a lot of research on the ecology and biodiversity of the Sky Islands," Taylor observes, "most of it has focused on the larger organisms that live above ground."

Taylor and Salazar are taking a different approach. They're exploring the often-overlooked world under their feet. Since summer 2018 they have been scooping soil and litter samples from the mid-elevation oak woodlands of the Sky Islands in Arizona and Sonora, Mexico. It's ground-breaking

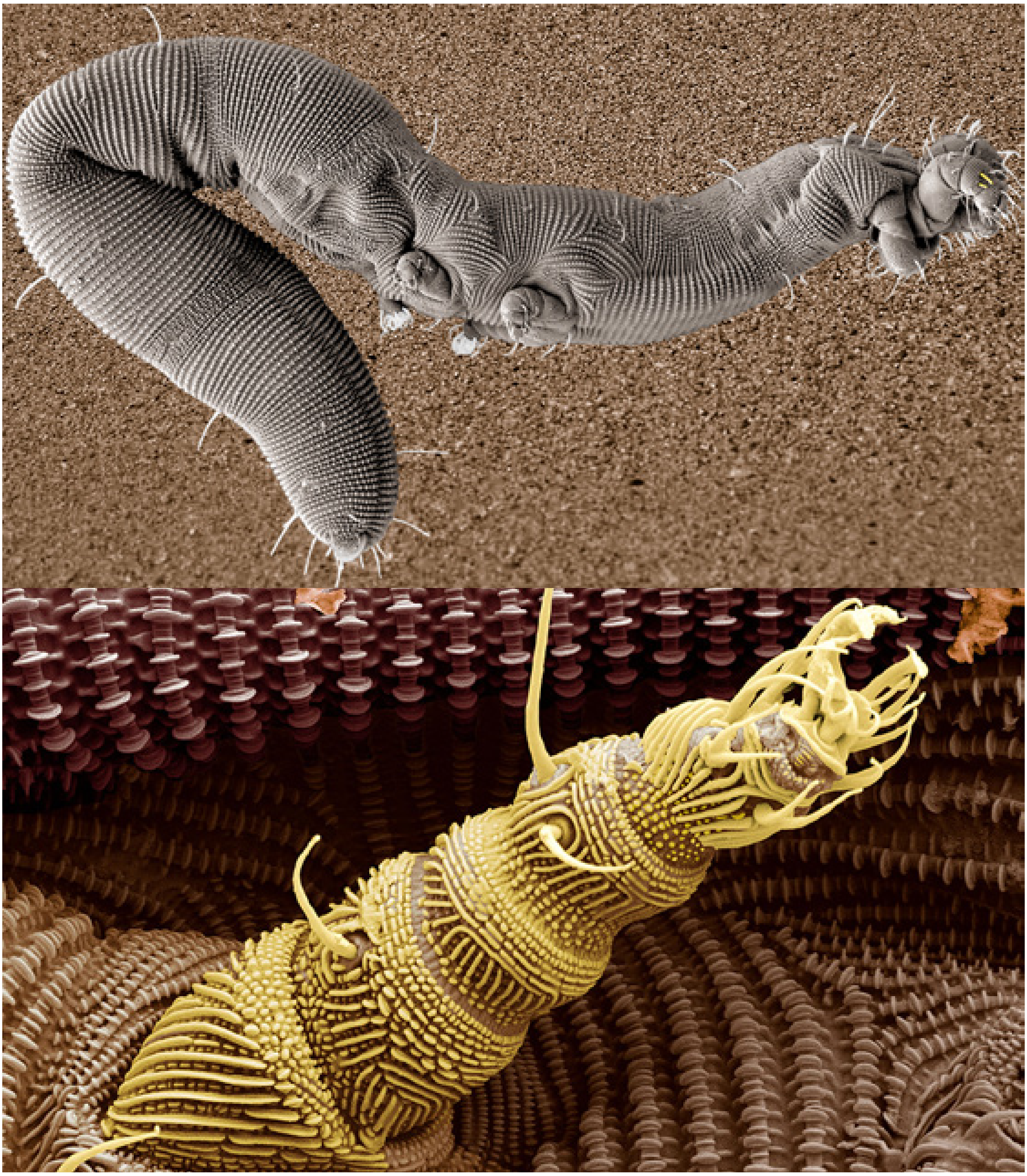
Soil mite *Nothrus* sp. (ventral | 200 μm). | Photo courtesy of Jay Taylor and Sofía González Salazar.

The Mighty Mite
Adelheid Fischer

work—literally. Though not readily apparent to the unaided eye, the tiny pores between soil particles are home to a surprisingly diverse community of organisms. And most of it is terra incognita, especially when it comes to soil mites, the focus of Taylor and Salazar's research. Their goal is straightforward: to compile an inventory of the mite species that occur across the Sky Islands of southern Arizona. They are especially interested in one group of armored mites, known as the oribatids, which includes a multitude of species that graze peacefully on decaying leaf litter, bacteria and fungi, tasks that are critical to breaking down organic matter and releasing valuable nutrients into the soil. From there Taylor and Salazar hope to tackle a few bigger questions. Do similar suites of species turn up over and over again in each isolated mountain range or does the community structure of mites vary depending on their geographical location?

Soil mite *Nothrus* sp. (dorsal | 200 µm).
Photo courtesy of Jay Taylor and Sofía González Salazar.

Their goals may be straightforward, but assembling something as basic as a catalogue of the Sky Island oribatids involves hundreds of hours of painstaking work. After their annual summer collecting trips, Taylor and Salazar will transport coolers packed with litter and soil samples back to their lab at ASU, where they sift their field booty through a low-tech device known as a Berlese-Tullgren funnel. The process involves loading the litter and soil into a funnel whose narrow end fits into a container filled with liquid preservative. A lightbulb is placed over the funnel causing the soil organisms to dive ever deeper into the lower reaches of the funnel to avoid desiccation from the bulb's drying heat. Eventually they tumble into the preservative. Then begin the long hours at the microscope during which the researchers will identify and sort the individual specimens. Each specimen undergoes a final genetic barcode test that validates its identity as well as provides insight into the evolutionary relationships



The Buckeye Dragon mite, *Osperalycus tenerphagus* (top) and a colorized LT-SEM image of its back leg.
Photo courtesy of USDA Agricultural Research Service.

Peacock mite, *Tuckerella* sp (300 µm). | Photo courtesy of Christopher Pooley, USDA Agricultural Research Service.

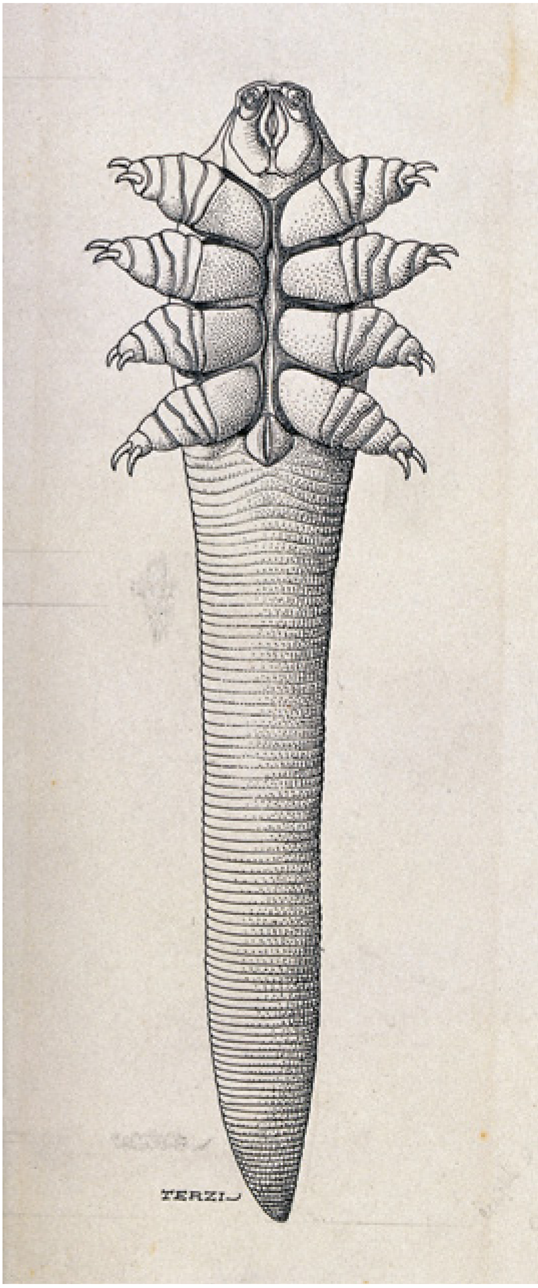
among populations of species found on multiple mountain ranges.

Laboring in the obscurity of a basement lab with study animals so miniscule that many of them could group dance on the head of a pin may not seem like headline-grabbing work. But scientists like Taylor and Salazar are pushing the boundaries of what Ronald Ochoa of the U.S. Department of Agriculture calls "one of the last great unknown frontiers of biology." Ochoa conservatively estimates that there are between three and five million species of mites. With the exception of mites that harm agricultural crops and human health, we know very little about most of them. It turns out that mites can be found in just about every corner of the world, from the depths of the ocean to the tops of a rainforest canopy and even in more specialized habitats closer to home such as the base of the human eyelash. According to Ochoa, the availability of high-powered microscopes, along with abundant opportunities for online photo sharing, are stimulating a brisk new interest in the field of acarology (the study of mites). Increasingly, scientists are drawing back the curtain of anonymity on a whole new world of strange and beautiful creatures.

And you don't have to go far to create an Internet sensation. In 2010, for example, spurred by the question, "What's in my backyard?" Ohio State University acarologist Samuel Bolton crossed the street behind his lab, retrieved a soil sample and examined its occupants under a microscope. The result? *Osperalycus tenerphagus*, a bizarre new species with a kind of chainmail cladding that expands and contracts like an accordion as the mite wends its way through grains of nutrient-poor sandy soils. Bolton speculates that the lineage of *O. tenerphagus* may be several hundred million years old, its ancestors having inched along in this wormlike fashion as the footsteps of dinosaurs thundered overhead. Even stranger, although *O. tenerphagus* sports genitals and lays eggs, this all-female lineage has dispensed with the need for mating and fertilizing eggs.

Then there's *Tuckerella japonica*, the Japanese tea mite. Until recently, it had been hiding in plain sight on the surface of tea leaves ever since the ancient practice of tea drinking began between 1066 and 771 BC. *T. japonica* is festooned with setae, tiny structures that are likely used for defense as well as for aiding wind-borne dispersal. The swirling pattern of winglike setae that cover the mite's body, as well as the delicate hairlike strands that trail from the back of the mite, create a design that rivals that of the frilliest haute couture party dress.

The Mighty Mite
Adelheid Fischer



The follicle mite (*Demodex folliculorum*) | Pen and ink drawing by A.J.E. Terzi, ca. 1919 | Wellcome Collection. Attribution 4.0 International (CC BY 4.0).

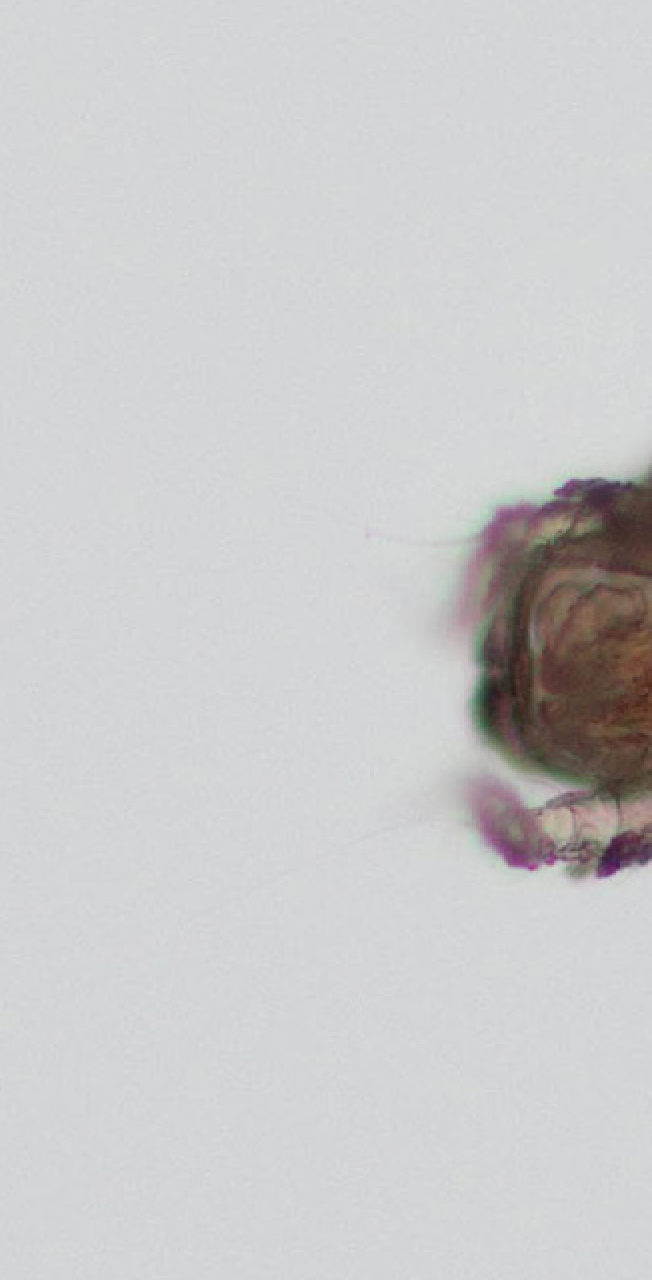
No mites, however, could have been hiding in plainer view than the two species of *Demodex* mites that are affectionately known as eyelash mites because they exhibit a particular fondness for holing up in the hair follicles surrounding the nose, eyebrows and eyelashes. By some estimates, an army of 1.5 million mites or more emerge from their hideouts at night to feed and mate on the surface of the skin. But what has made *Demodex* mites the darlings of cocktail-party chatter is their excretory habits. As writer Jess Zimmerman exclaimed in *Grist*, "They don't just poop willy-nilly, oh no. Because *Demodex* don't have an anus. So they just poop right inside their bodies, and carry on doing that until they die and explode into a pile of mite-shit in your pores. Hooray!"

But for every mite that graces the cover of a science magazine with its exotic good looks or startling behavior, there are millions more that labor unheralded in places like the Sky Islands. They're doing the yeoman's work of breaking down plant matter so that scores of other beneficial critters can eat, enriching the soil and keeping populations of their fellow organisms from building to damaging levels. If tiny invertebrates like them and others "were to disappear," writes Wilson, "I doubt that the human species could last more than a

Soil mite *Sphaerochthonius* sp. (dorsal | 100 µm).
Photo courtesy of Jay Taylor and Sofía González Salazar.

few months. Most of the fishes, amphibians, birds and mammals would crash to extinction around the same time. Next would go the bulk of the flowering plants and with them the physical structure of the majority of the forests and other terrestrial habitats of the world....Within a few decades the world would return to the state of a billion years ago, composed primarily of bacteria, algae, and a few other very simple multicellular plants."

Given their critical work, the least we could do then is to get to know the service workers under our feet, find out what our neighbors need in order to make a living and honor their good deeds and extraordinary talents by calling them by a proper name. ×



We would appreciate your feedback on this article:

Soil mite *Sphaerochthonius* sp. (ventral | 100 µm).
Photo courtesy of Jay Taylor and Sofía González Salazar.

Lower Antelope Canyon
Photo: Sandrine Néel, 2018 | Flickr cc

Article

How Can We Drive More Success in Bio-Inspired Design?

Ben Morgan

How Can We Drive More Success in Bio-Inspired Design?

Ben Morgan

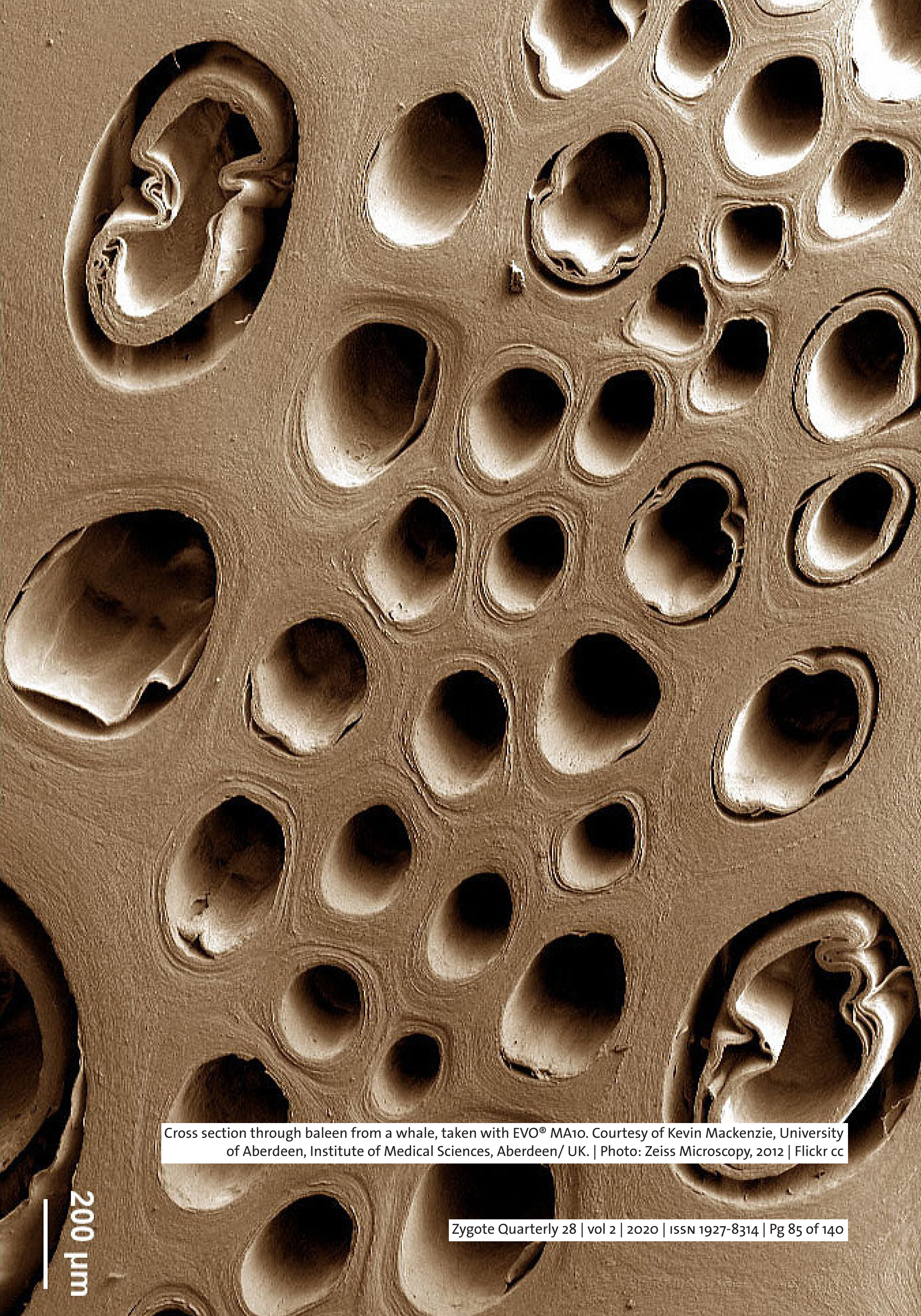
Between 2000-2010, wind energy capacity in the United States grew from 2.5GW to 40GW. Investment in wind turbine research and development (R&D) increased with new companies proposing efficiency improvements and more cost-effective energy production. Mechanical, Energy, and Civil engineers developed technologies for the field, but unexpectedly, so did biologists. WhalePower developed a bio-inspired design (BID) that mimicked the tubercles on humpback whale fins to decrease drag and claimed to increase energy outputs of rotating wind turbines by 20%. Not only was WhalePower proposing to benefit sustainable energy, the technology also promised to showcase biomimicry globally. A tangible benefit could be employed in a large scale, society changing industry.

"Stories from the Trenches" [1,2,3] in Zygote Quarterly discussed the business strategy that limited commercialisation, and WhalePower remains as an example of how biomimicry must connect more appropriately with business in order to deliver value. Bio-inspired designs come from both industrial and academic settings, and it is the latter in which business considerations during development are often overlooked, which can prevent promising ideas reaching the market.

This could partly be because there is ambiguity in what academic researchers define as success, and this may be influencing the market success rate of bio-inspired designs. Shoshanah Jacobs' BioM Innovation Database [4] showed only 32% of projects reached the market, and only 21% of those came from academia. Promising lab results, working prototypes, or an accurate replication of biology may be reported as success for research teams within an institution, but it doesn't mean biomimicry is being successful as a practice for sustainable design,

To increase the efficiency of the practice, bio-designers need a better definition of success. Success cannot mean "an accurate replication of the biology" if it does not bring positive change by delivering meaningful benefits. If a bio-inspired design is to be deemed successful, it must be a 'bio-inspired product/service being implemented in society or industry while creating the desired benefit'. By including a focus on implementation within the definition of success, designers are encouraged to consider their work in three domains: technological, market, and business.

- Is the BID an improvement on current designs?
- Is this improvement a societal need?
- Can the BID work within a business context?



Cross section through baleen from a whale, taken with EVO® MA10. Courtesy of Kevin Mackenzie, University of Aberdeen, Institute of Medical Sciences, Aberdeen/ UK. | Photo: Zeiss Microscopy, 2012 | Flickr cc

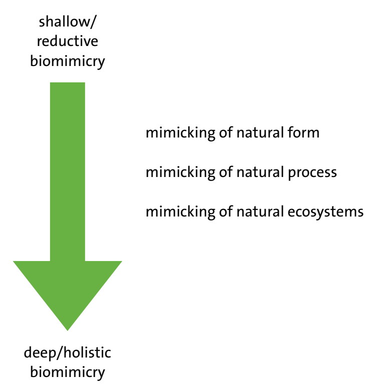
Magnified view of ocean clam shell construction | Photo courtesy of Brook Kennedy

The business segment is often overlooked during bio-inspired development and only becomes a consideration later in the product timeline. This article examines case studies at different lifecycle stages and refers to these questions to understand how bio-inspired designers are developing their ideas. Similar to other studies on biomimicry, such as Fu [5] and Volstad [6], the goal of this work is not to criticise, but to bring attention to different working methods and ultimately open questions on how more societal, environmental, or economic benefits can be provided via the inspiration of nature.

Corlayer3d, Brook Kennedy

Fused Deposition Modelling (FDM) is an additive manufacturing technology that extrudes material through a heated nozzle to deposit 2D layers that build 3D shapes over time. Mechanical failure below expected operating stresses is common due to the printing direction causing reduced strength in the z-axis. Additionally, FDM employs inferior mechanical forces, rather than chemical, to create bonds between layers. An article by Kennedy on his Corlayer3d innovation in ZQ19 [7] proposed a biomimetic solution that promises enhanced mechanical properties in any additive manufacturing technology.

Corlayer3d mimics the pattern of a seashell's external wall by raising printed layers in the z-axis to become 3D structures. Although heat transfer and interlayer bonding issues remain, the newly defined boundaries block crack propagation along the plane. According to its patent, Corlayer3d "provides resistance to shear force", "increases the structural strength of an object" and "can be included in any additive manufacturing technology on any scale". Considering that the function of a shell is to "mechanically resist failure under environmental stress" [8], Corlayer3d was able to use the biology and create an improvement to 3D printing technology. However, it remains a foundational research project and the development process offers lessons for bio-inspired designers



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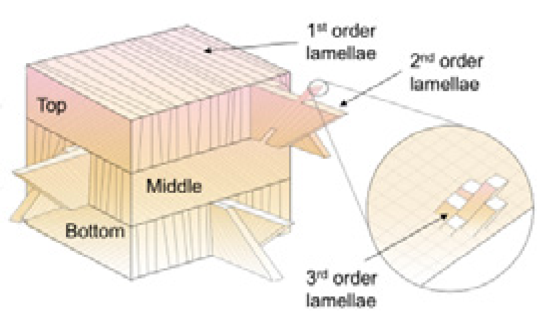
Benyus' levels of biomimicry [9] class Corlayer3d as reductive, meaning a natural form is imitated. The depth of biological modelling depends on the designer's knowledge and experience, but with only a small team of mechanical engineers and students contributing between other projects, advancements were difficult. Kennedy mentions "the idea is based off macro-scale observations of the material", and says biological insights were gained from an expert in Australia, but collaborative work was difficult.

Laboratory trials revealed increased stiffness of printed parts, though no quantitative measurements were collected, making it difficult to convince investors of the value. Corlayer3d proposed a biomimetic solution in 3D printing but couldn't progress from experimental stages.

Nature continued to inspire Kennedy's work which delivered contrasting results. His Fog Harp is a fresh water-harvesting device for arid climates based on pine needles. Unlike the low interdisciplinary collaboration in Corlayer3d, some of Fog Harp's success is attributed to cooperative work with a fluid physicist. According to Kennedy, "A more fundamental understanding of the system and its relationship to the problem allowed progress to be made quickly", though a botanist could have added knowledge on the structure of pine needles to allow functional characteristics to be modelled.

The Fog Harp demonstrated positive results in prototype testing, and subsequently gained media attention when PBS News Hour, CNN, and The Washington Post reported on the sustainable technology. Investor interest followed, which facilitated planning of large-scale production and applications.

Corlayer3d and Fog Harp highlight how slight variations can impact the overall success of a project. A diverse team can provide a stronger link between biology and engineering, and showcase value through positive results, which is ultimately what investors seek. Additionally, a sustainable solution solved a critical societal problem which invites media attention and conversation on the project. The Fog Harp must now discover how it fits into the broader



Conch shell hierarchical structure adapted from Gu, Grace & Takaffoli, Mahdi & J Buehler, Markus. (2017). Hierarchically Enhanced Impact Resistance of Bioinspired Composites. Advanced materials (Deerfield Beach, Fla.). 29. 10.1002/adma.201700060.

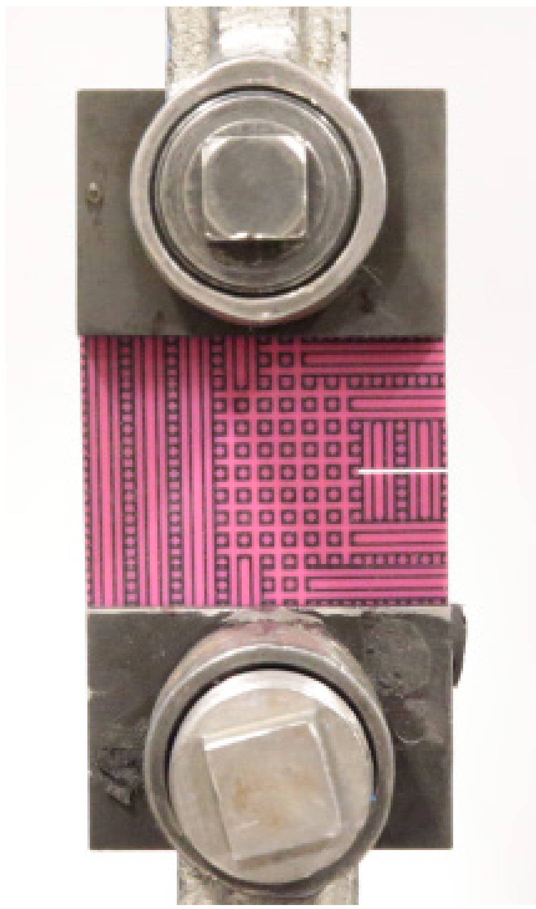
business world with up-scaling manufacturing being critical.

3D Printed Composites, Dr. Grace Gu

The examination of seashells and other Mollusca account for roughly 5% of the BioM Innovation Database [4]. Similar to Kennedy's endeavour for mechanical strength, Gu is also inspired by seashells to develop novel materials. Where Kennedy is an Industrial Designer within the Architecture Design School at Virginia Tech, Gu holds a Mechanical Engineering PhD from MIT and now leads a research group at Berkeley. Kennedy is focussed on creativity, where Gu investigates physical principles. Her methods allow for a deep understanding of a topic and have produced synthetic materials comparable to their natural counterpart in appearance and performance.

ZQ24 [10] showed how Gu and her team are utilizing machine learning to model the hierarchical structure of conch shells to a high level of detail. Unlike Kennedy, who took inspiration from the physical form, Gu emulates the process through which strength is provided. Scanning Electron Microscopy (SEM) teaches Gu how these materials behave and interact, rather than what they look like. A diverse team including Civil and Mechanical Engineers helped translate the biology into engineering models, though Gu didn't directly collaborate with a biologist. Instead, her team is encouraged to develop their biological understanding through research and conversation.

Increases in toughness and strength of 3D printed structures were demonstrated through Gu's work, though the push for



Conch shell inspired material testing adapted from Gu, G. X., Chen, C. T., Richmond, D. J., & Buehler, M. J. (2018). Bioinspired hierarchical composite design using machine learning: simulation, additive manufacturing, and experiment. Materials Horizons, 5(5), 939-945.

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commercial backing is not evident. Gu embodies the patience of an academic researcher, and fully admits that, “although early technical success is apparent, the materials are not ready for the market”. Gu is also expanding her research into highly accurate, self-correcting 3D printing systems.

A long-term approach may not be suitable for industrial researchers that aim for a quick turnover of ideas, though this urgency can also result in products that have a shallow understanding of the problem and inferior performance. For example, Speedo’s Fastskin swimsuit, previously discussed in ZQ8 [11], claimed to be biomimetic, but either missed or deviated from the science behind high-speed sharks. Biological researchers found shark skin denticles increase swimming speeds by up to 12% [12]. Surface denticles create negative pressure at the front of the shark which enhances propulsion. Speedo used hydrophobic materials, innovative fabrication techniques, and shape forming characteristics to reduce drag. However, it would not be appropriate, by definition, to label the Sharkskin a biomimicry success - positive results were delivered, but biological traits were not the cause.

Gu proposes to apply her research methods to ideas similar to Fastskin. By investigating a wide range of parameters such as denticle size, width, angle, and frequency, she believes an improvement on the current design can be found that could benefit any industry dealing with hydrostatic drag.

Targeting products in the real world enables key technical decisions during early phases, which can save time, money, and facilitate future product marketing. A holistic approach during development may allow for greater technical success; to allow true value to be created, market and business aspects must be major considerations. Without taking the risk of bringing a product to market, the value of biomimicry cannot be recognized.

Ginger Dosier, Bio-MASON®

The ocean depths, although largely unexplored, are an attractive location for bio-inspired designers. Seashells have demonstrated their contribution to mechanical performance, but benefits to material sustainability have also been observed. Ginger Dosier was fascinated in how bacteria can aid the formation of some sandstones and wanted to apply this to architecture. Her interest in sustainable alternatives led to development of a cement brick produced from bacteria.


Lower Antelope Canyon | Photo: DJ McCrady, 2019 | Flickr cc

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In 2012, Dosier started bioMASON®, a biotechnology start-up based in North Carolina, after formulating a recipe for lab grown bricks using a mixture of sand, calcium chloride, urea, water and Sporosarcina pasteurii, a calcite precipitating bacteria. Creating solid bricks without the need for heat treatment is a significant improvement on traditional production techniques, which accounted for 8% of all global CO2 emissions in 2018 [13].

BioMASON®'s message is clear: "greener building materials." Providing benefits to a genuine, quantifiable problem attracted early stage investors, and start-up/small business awards delivered essential funding and exposure. BioMASON® is part of a collective of "greener building material" start-ups looking to enter an established market with a new product, which is often the case for bio-designers. Dosier's experiences can provide valuable business execution insights for biomimicry proponents.

BioMASON®'s message of sustainability has allowed Dosier to develop a very promising and exciting business, but the next stage of bioMASON®'s development must now consider how factors such as material regulation, supply chains, manufacturability, and cost can allow the bioinspiration to create value in the construction industry. Goldenburg [14] reports that new products in an established market have a higher probability of failure, and coming from a biotechnology background to tackle a construction problem is an ambitious challenge. If a product doesn't fulfil key performance and aesthetic characteristics, then it cannot compete against current materials. The Brick Development Association in the UK (https://brick.org.uk) pointed out that a customer's main concern is appearance. If the brick doesn't look pleasing, then it will rarely be used to build homes.

BioMASON®'s future now depends on its ability to translate technical success to a market. If scalability can be achieved in 2020 and the cost of their product can compete with current materials, then it is likely that bioMASON® will be a biologically inspired design providing decreased carbon emissions within the construction industry. Conversely, if it is unable to address key market and business concerns, it will invite questions regarding the integration of BIDs into business.

Terrapin Bright Green and Harbec
Academia is a large source of bio-inspired designs, with nearly half of all projects in Jacobs' database being directly or indirectly

from educational institutions. Jacobs' database shows 67% of industrial BIDs examined reached the market, compared to 14% of academic BIDs. Industrial solutions can focus directly on creating value for the company and its customers, and this results in a much greater market success rate. It is therefore valuable to observe how businesses conduct biomimicry, and what lessons this approach can provide for academic researchers.

Terrapin Bright Green and Harbec Inc., a metal and plastic parts manufacturer based in Ontario, NY, teamed up to apply biomimicry to additively manufactured tools, and this example highlights how industrial and academic bio-inspired projects differ.

Harbec uses injection moulding and additive manufacturing to meet customers' demands. In 2015, they collaborated with Terrapin Bright Green, an environmental strategy consulting firm, and professors from Cornell University and Rochester Institute of Technology to provide biomimetic solutions for heat transfer in additively manufactured injection moulded cavities.

Injection moulding heats polymers to a molten state inside shape-forming moulds. Only after the mould has cooled can the part be removed. The process of heating, cooling, and removing the part makes up one process cycle. The team's goal was reducing cycle time, and the cooling phase was seen to be a promising area.

Cooling often involves circulatory systems, suggesting collaboration with vascular experts. Natural heat dissipation systems were explored and narrowed down to elephant ear vessels, termite mound channels, and vascular structures found in dicot leaves. Selecting the natural model was one of the biggest challenges in Harbec's work, and digital simulation was used to assess several factors. Dicot leaves contain a main trunk with interconnecting branching channels which carry fluid through the leaf, a model that Harbec could easily manufacture.

Keith Schneider of Harbec remarked that, "the mix of academic insights and manufacturing knowledge allowed the biology to be translated into engineering models." Academics provided expertise in natural systems, but on its own this did not provide a valuable solution. Harbec's experience with manufacturability and performance allowed the biology to be incorporated into the designs. Ensuring the solution was cost-effective and technically realistic was a key project feature for Schneider. He noted that start-ups or early stage projects may need to focus more on manufacturing than they currently do.

African bush elephant with ears spread in a threat or attentive position; note the visible blood vessels | Photo: Mister E, 2008 | Wikimedia Commons

Although Harbec had already developed circulatory cooling systems, the dicot vascular model delivered an additional 4% reduction in cycle time compared to previous, non-biomimetic solutions. The project delivered cost savings of $7 over 100,000 cycles against previous solutions for low volume production runs. [15]

When presented with the question, “What would Harbec do if they were a start-up?”, Schneider emphasised the importance of interdisciplinary collaboration. Admitting that his team do not know everything, they welcome insights from various fields, in particular from the client industry. “Someone who understands price points would be critical.”

Biomimicry allowed Harbec to decrease cycle time and they continue to use the practice.

Closing

It’s not surprising to see engineers and designers turn to biology for inspiration. but the question is, how can this intelligence create a positive impact in the world? Tools such as AskNature along with software, databases and processes support problem and function definition, comparing biological processes, and functional model validation, but the commercial success, and consequently the true value of BIDs has remained relatively low.

It may now be appropriate to introduce new steps in the biomimicry design process that allow human and market needs to be evaluated during development. Questions that move beyond how biology relates to technology can allow designers to view their products in the real world. Is the proposed design tackling a critical societal problem? Are the materials used in this solution economically viable, and can we work with current suppliers to allow up-scaling? Is the manufacturing process time effective against current solutions?

By exploring how designers make the transition from idea-to-prototype and prototype-to-business, we have gained some understanding of the industrial experiences and challenges faced in creating a commercially viable BID and what it takes for a product to have real value. ×

We would appreciate your feedback on this article:

Ben Morgan is a Materials Engineer at heart, though a passion and curiosity for sustainability sees him branch out to a variety of topics such as urban renewable energy, advanced composites, and biomimetic design. He received a 1st Class Hons in Sports Materials BEng from Swansea University in 2016 and graduated from a dual MSc in Chemistry and Materials Science as part of the European Institute of Technology's AMIR Master in 2019.

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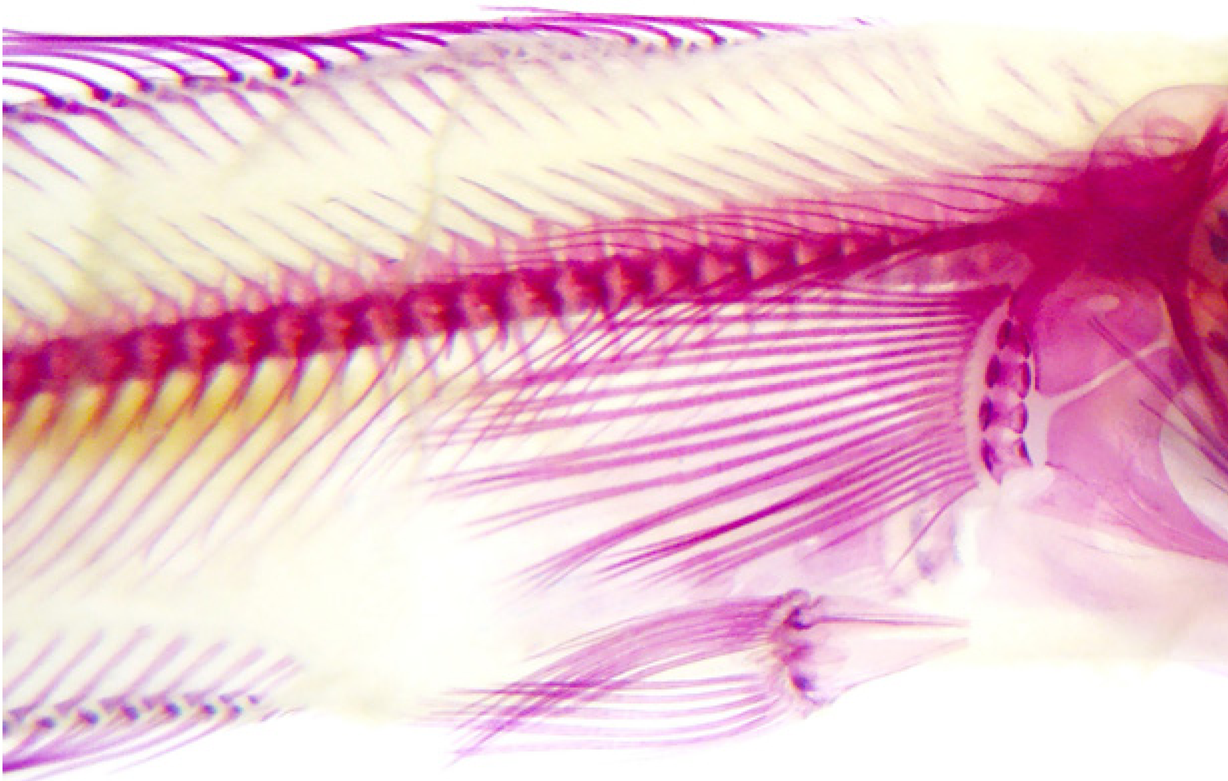
Permukkale pools (travertine), Turkey | Photo: Ray Wewerka, 2004 | Flickr cc



Channa argus

Portfolio

Noah Bressman

Portfolio
Noah Bressman

Originally from Chappaqua, New York, I got my bachelor's degree from Cornell University in 2016. Currently, I am a PhD candidate in Miriam Ashley-Ross' lab at Wake Forest University in Winston-Salem, North Carolina. If all goes according to plan, I will have passed my defense and have my PhD by the time this is published. My dissertation research at WFU focuses on amphibious fishes. In May, I will be moving to California for a postdoctoral scholar position at Chapman University to study how hagfish slime could be used to safely stop small boat propellers at high speed. When I am not researching, I am most likely fishing or creating biological fish art. My art uses photography, digital image manipulation, and a biochemical technique known as clearing and staining using whole organisms of fish. It involves using a series of chemicals to stain certain tissues certain colors (i.e., staining bone red and staining cartilage blue), while dissolving other tissues or making them transparent. This technique is great for studying morphology and skeletons, but also creates beautiful images in the process.

Noah Bressman

Please tell us about your research and how you got into making art.

My research is on fish functional morphology, biomechanics, and behavior. I have a special interest in amphibious fishes, studying why they emerge onto land, their morphological and behavioral adaptations for terrestrial locomotion, and their terrestrial orientation. Many of the amphibious fishes that I study are also invasive species, such as snakeheads, walking catfish, and suckermouth armored catfish (plecos). By learning why these invasive species go onto land, how they move around on land, and where they go while on land, I hope to better inform management of these ecologically harmful species.

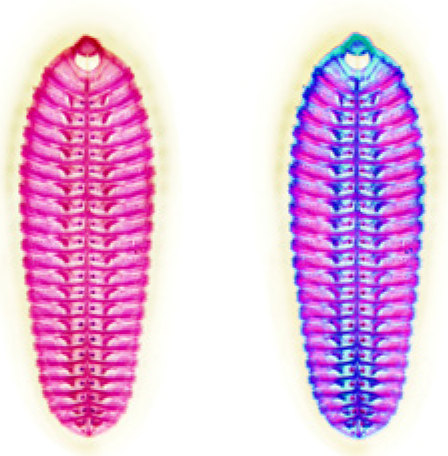
I got into making art completely by accident. It started after I took a fish functional morphology course the summer of 2016 at Friday Harbor Labs on San Juan Island, Washington State. One of the instructors, Adam Summers of the University of Washington, is renowned for his fish skeleton art using a technique known as clearing and staining. Adam taught me clearing and staining as part of the course and I used it to study fish functional morphology.

When I started my PhD program in the fall of 2016 at Wake Forest University in Winston-Salem, North Carolina, the walls of my house were pretty empty and boring. I went to a local art gallery to get some decorations. That's when I realized that art is expensive, at least on a graduate student budget. I had a lot of cleared and stained fish, so I decided to try to make images like Adam's to decorate my house. Unfortunately (though now I see it as fortunate), I didn't have a nice camera, light table, or set-up like Adam, so my images were not as great quality. To fix that, I tried to Photoshop my images, and discovered cool effects in the process. Instead of simply taking photos, I started creating pieces of abstract and modern art for my walls.

I went to Kinkos to print out my first pieces for my house, and was excited about how they came out. With the art in my car, I went for lunch across the street at a restaurant called Vin205. I noticed they were taking the art down, and asked if they put up work from local artists. They said they sometimes do, so I went and brought in my artwork. They loved it - I later found out that one owner used to be an underwater photographer and the other is an avid fisherman, so it happened to be a perfect fit. They put my art up in their restaurant – which is still there – and that's when I realized that I was an artist.

Any interesting fish functional morphology, biomechanics and/or behaviour stories you can tell us?

The best story I have for this is probably how I got into the field. I was born a fish biologist. I always had an inexplicable passion for fish, but thought I would get into some flashy aspect of it like studying the predatory behavior of shark and big game fish. This changed when I was taking a course the summer after my first year of college at



Remora Disks

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Noah Bressman

Shoals Marine Lab in Maine. The two-week course was on the anatomy and function of marine vertebrates, which required a week-long research project. During that course, I noticed a fish on the ground in the lab.

It was a small intertidal killifish called a mummichog, which must have jumped out of a tank in the lab overnight because a predatory sculpin was chasing it. If a fish were to jump out of the tank, you would expect it to randomly flop around on the floor and stay somewhere close to the tank. This two-inch fish, though, was ten feet away from the tank. I thought this was unusual, but still within the realm of possibilities. The next morning, I found another mummichog in the exact same spot ten feet away from the tank. This could not be a coincidence.

The teaching assistant for the course, Stacy Farina, had a high-speed camera with her, so we put mummichogs on a table and filmed them to see what they were doing. In the slow-motion videos, it was clear that these fish were not moving randomly; they had a very stereotyped behavior. They would perform a tail-flip jump from their side, land on their side, and then upright before

Searobin 5

rolling back on their side to perform another tail-flip jump. This uprighting behavior is so quick – lasting a tenth of a second – that it is almost impossible to even notice without a high-speed camera. Because they jump from their side, uprighting was unnecessary to perform consecutive jumps. However, after a series of behavioral experiments, we found that this uprighting behavior was used by mummichogs to get a better look around, allowing them to reorient between each jump.

Stacy and I, along with the help of Alice Gibb, an amphibious fish biologist, applied and received a grant to further study this fish the next summer. After more experiments, we found that they use vision to find their way around on land. When on land, they look for the most reflective surface in their environment. This is usually water, which they then move toward. This made me realize that the spot where those two mummichogs went was where the sunlight first shone each morning on the shiny tile floor. The fish, which had jumped out of their tank at night, move toward that spot in the morning thinking it was water. It was such a cool 'aha' moment to be able to be

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able to figure out why those fish went to that spot, and launched my career in studying amphibious fishes.

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

Photography makes me more aware of the shapes around me. It really helps me understand form, and the subtle differences in the structures of the world. I find myself staring up at the trees at different angles or even just looking closely at the bark to really understand their shapes and why those shapes exist. Photography has really given me an appreciation for every kind of shape, as they all have their functions. I enjoy staring at forms until I can understand their functions.

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

Fish (and vertebrate) diversity inspire me most. I love capturing the organizational and structural beauty of every species of fish. Because there are so many species, I will not run out of creativity for a long time. Each species, by definition, has its unique characteristics, so I have as many potential pieces to create as species. As I learn more techniques, gain new ideas, and understand Photoshop better, I find that I can enhance the forms of each fish in new and different ways. Even with a limited number of species, the possibilities are endless.

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

I have four exciting projects that I am working on right now. The first is a project that got started because of my art. I was clearing and staining a bunch of different fish, and noticed something interesting about the mouths of armored suckermouth catfishes (aka plecos). I found the clearing process did not work well on their mouths, which is unusual. Through additional staining, I found out that they have large amounts of collagen in their lips. Through the help of my collaborators Jonathan Armbruster and Nathan Lujan, I found that the amount of collagen in their lips varies between species, but thicker, more collagenous lips have evolved multiple times in the species that live in fast-flowing, rocky rivers. We think the additional collagen helps these fish hold onto rocks with their oral suction cups while experiencing high drag forces. Because of the clearing and staining nature of this project, I am working on a funky artistic piece to submit as the cover of the Journal of Morphology once the revisions are done (which should be shortly).

The next project is on walking catfish terrestrial behaviors. These fish are invasive in Florida and around the world and are renowned for their amphibious behaviors. Despite this, not many people know about their amphibious natural history, so I did a series of experiments and crowd-sourced information to learn more about this unusual species. I will not say much about this project until it passes peer review to ensure my science is sound, but our findings are crazy. Basically, these fish taste the air to find new bodies of water while on land, live in the sewers, and come out of storm drains when it rains to feed on terrestrial vertebrates.

The third project started by accident. While doing experiments at the University of Florida's Tropical Aquaculture Lab, a person came in to warn me that one of my catfish got out, and that I need to be more careful about my invasive species getting loose. After apologizing profusely, I went outside to retrieve my fish... but it was not

Nanjemoy Natives

Portfolio
Noah Bressman

a walking catfish. It was a different catfish species, an armored suckermouth catfish. They can breathe air and I had everything with me to study terrestrial locomotion, so I looked at how well they could move around on land. It turns out, very well. They are among the fastest fish on land using an asymmetric form of locomotion completely unlike any other animal. They also have super unique morphological adaptations that both allow these fish to move so well, but also restrict them into moving in such an unusual way. I hope to submit this research soon for publication.

The last project I am working on is a review paper on how performance and behavioral data on invasive amphibious fishes can be used to better manage these species. Very little of this information is either available or used to inform management. I am consolidating all of the available information on invasive amphibious fishes and adding some new information in order to prevent the spread and introduction of these ecologically harmful species.

What is the last book you enjoyed?

Animal Weapons: The Evolution of Battle by Douglas Emlen. It is an interesting book about why and how weapons and defenses in animals arose evolutionarily, and draws parallels to human weapons and defenses.

What are your favourite 3 websites, and why?

The USGS flow data website (https://waterdata.usgs.gov/nwis/rt) is probably one of my favorites because it helps me know when the fishing in the rivers is good. I enjoy https://viz.com. I am an avid manga reader and it is my main source. I also like Instagram because in these crazy times, I like looking at pictures of fish and dumb memes to keep me distracted.

What's your favourite motto or quotation?

"The sea, once it casts its spell, hold one in its net of wonders forever." – Jacques Cousteau. It is such a great quote because I really connect to it. The sea (and particularly the fish within it) caught me in that net early on and I have been passionate ever since. ×

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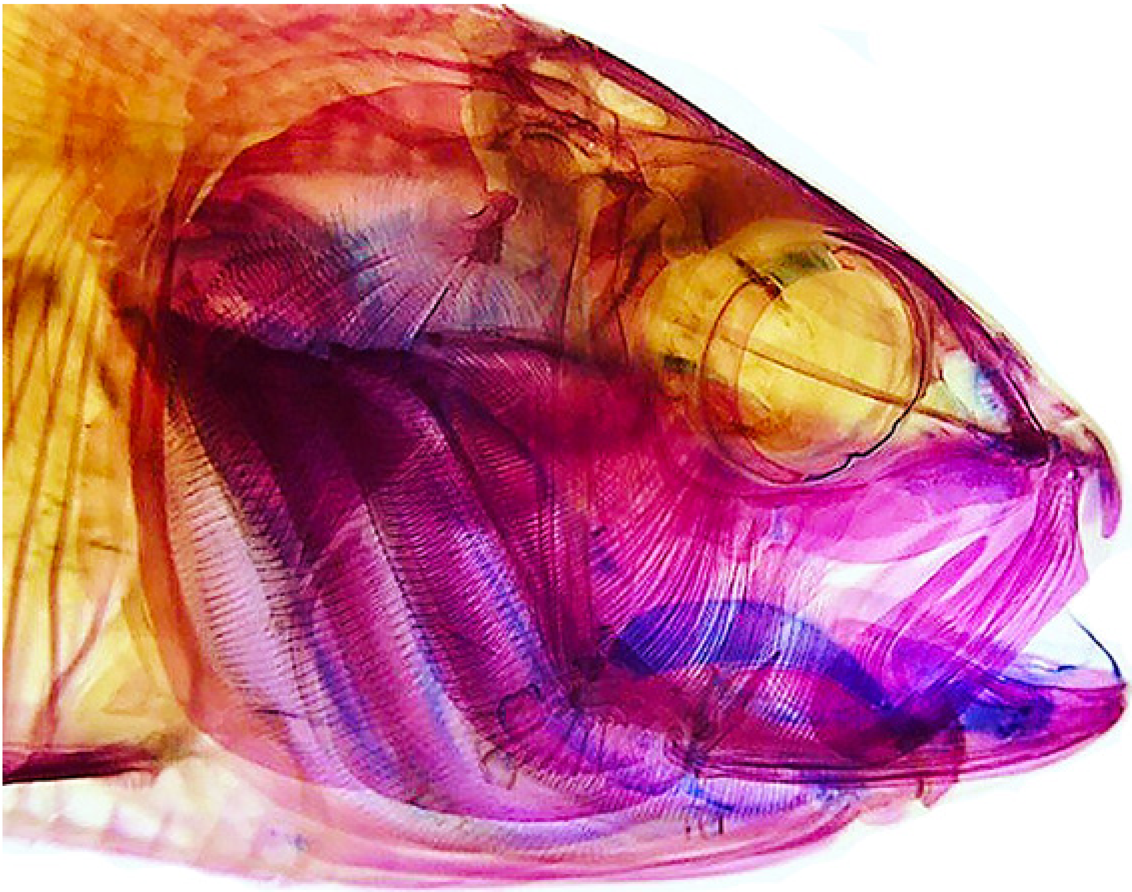

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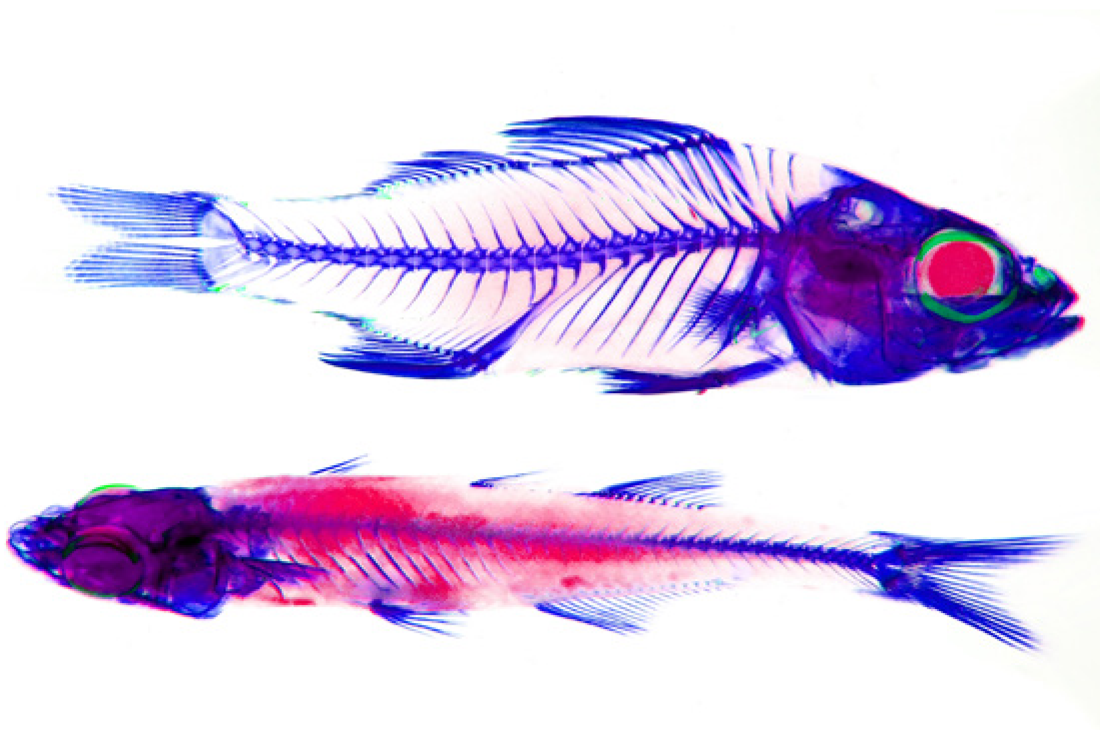

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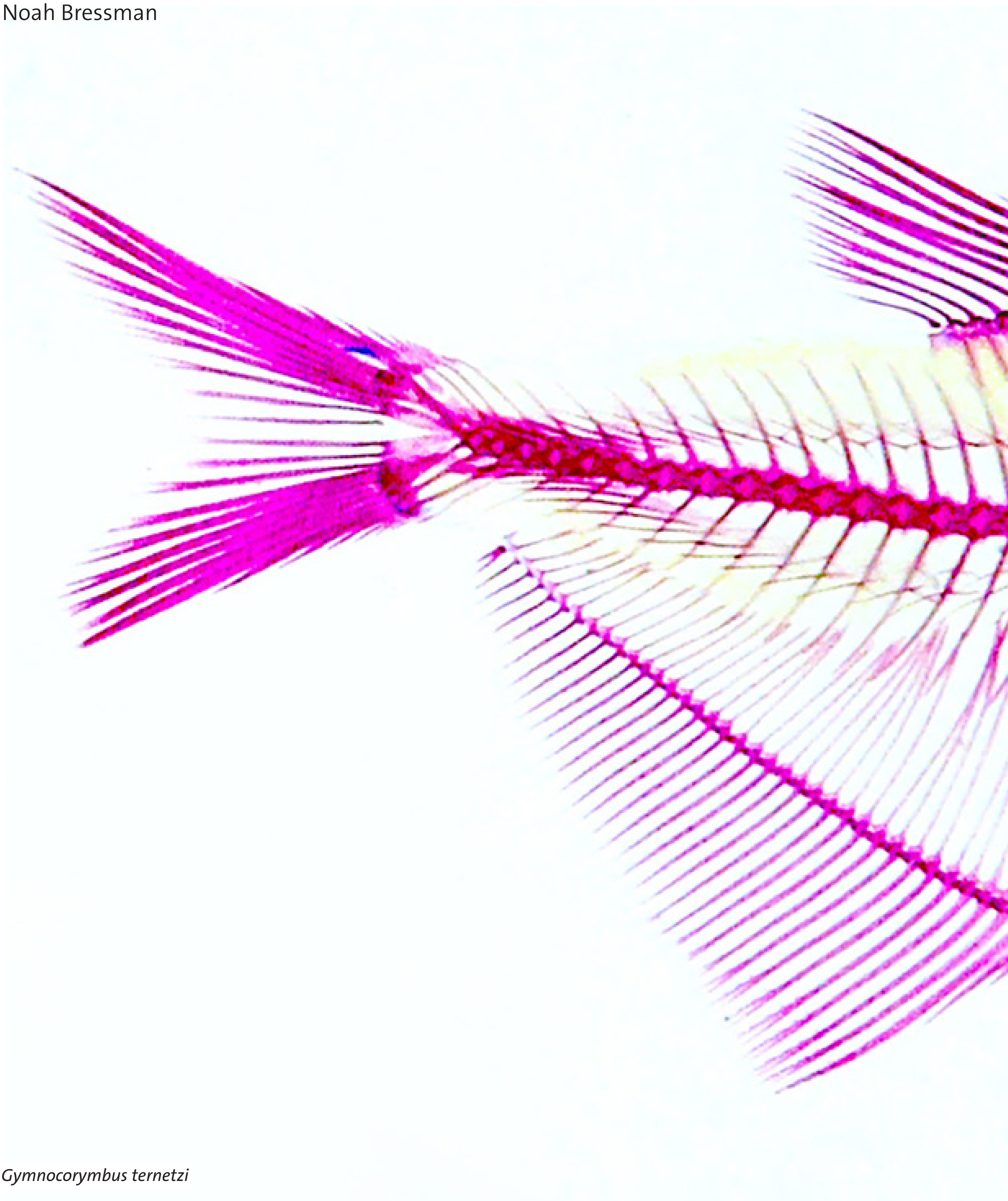

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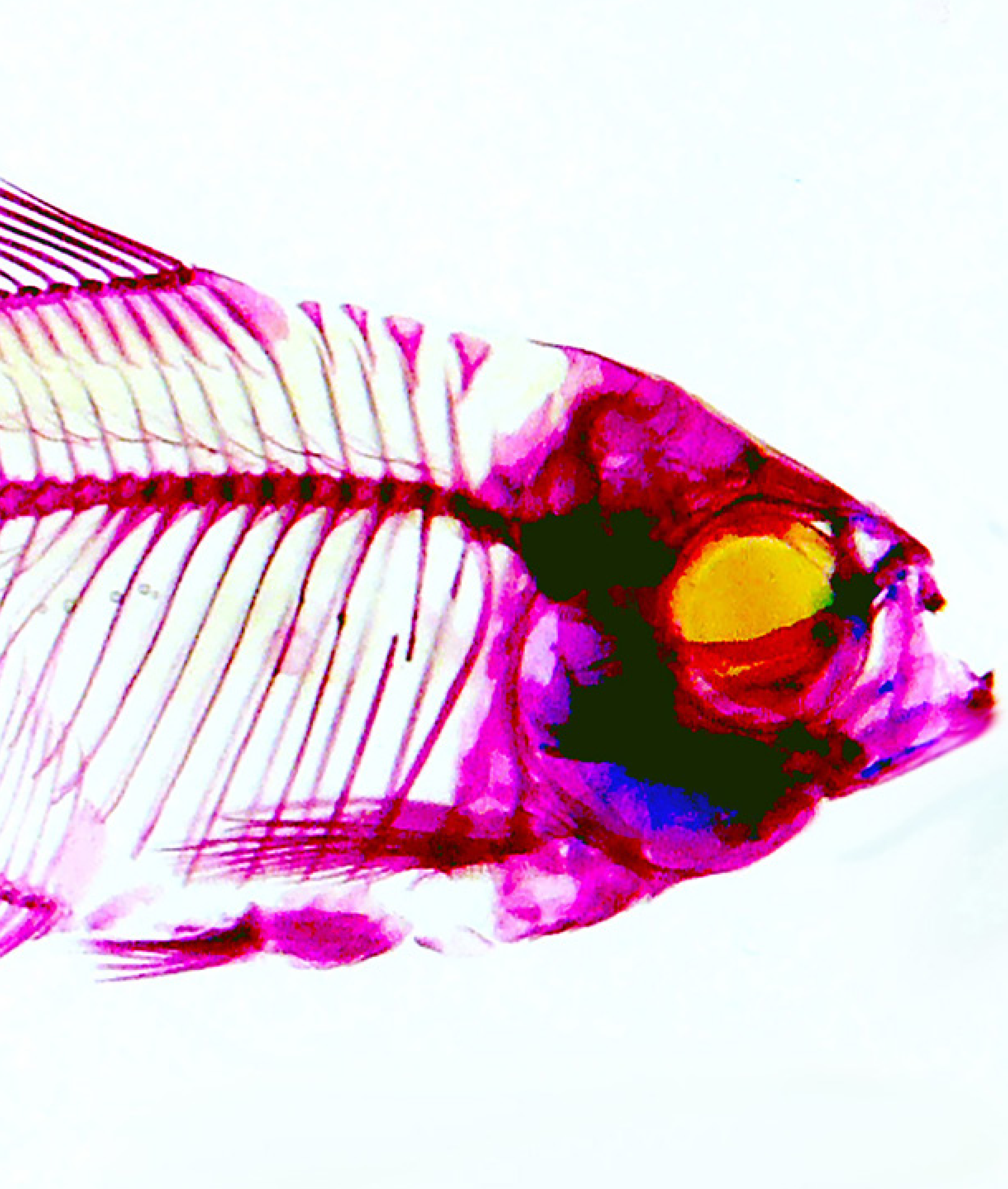

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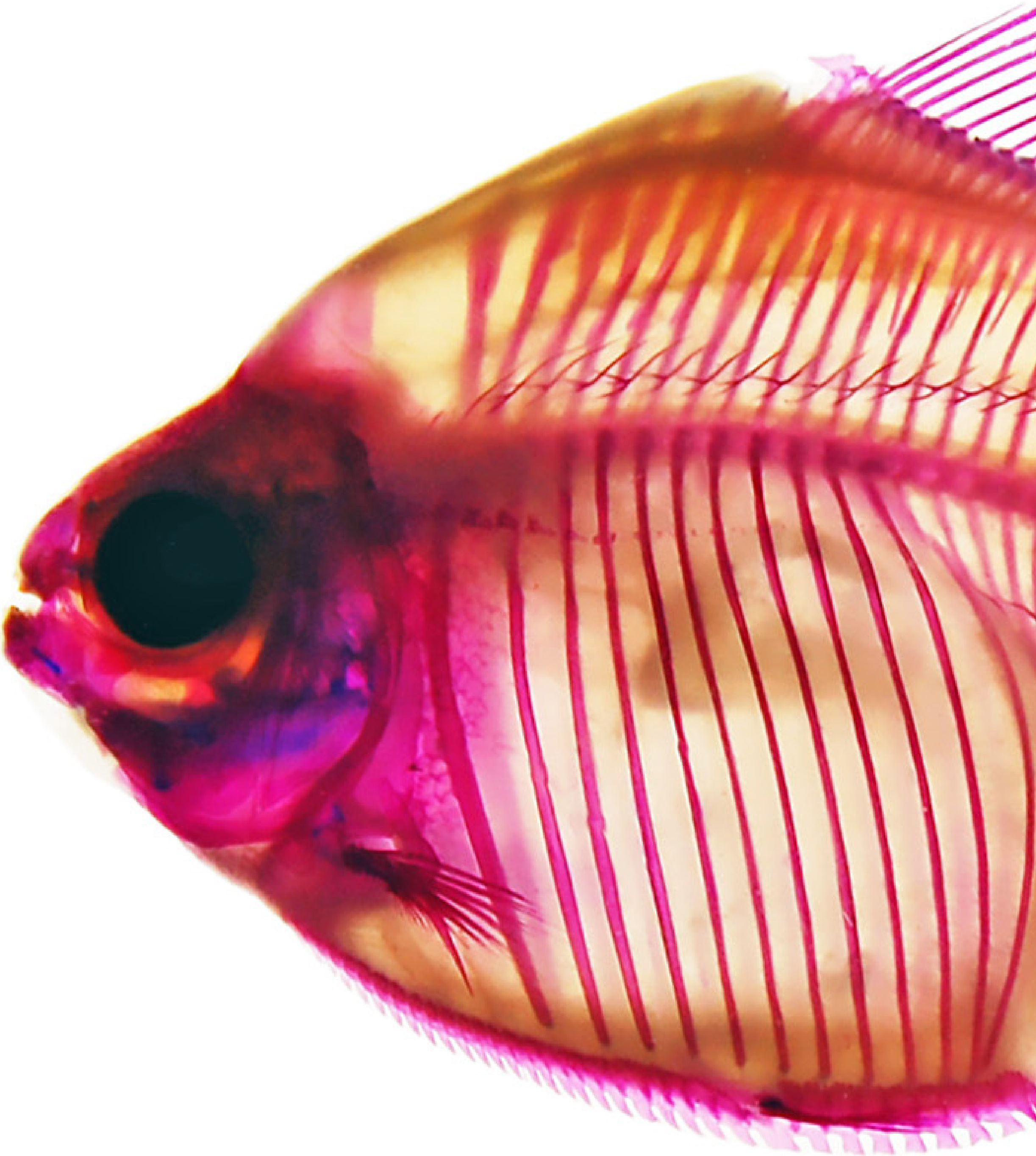
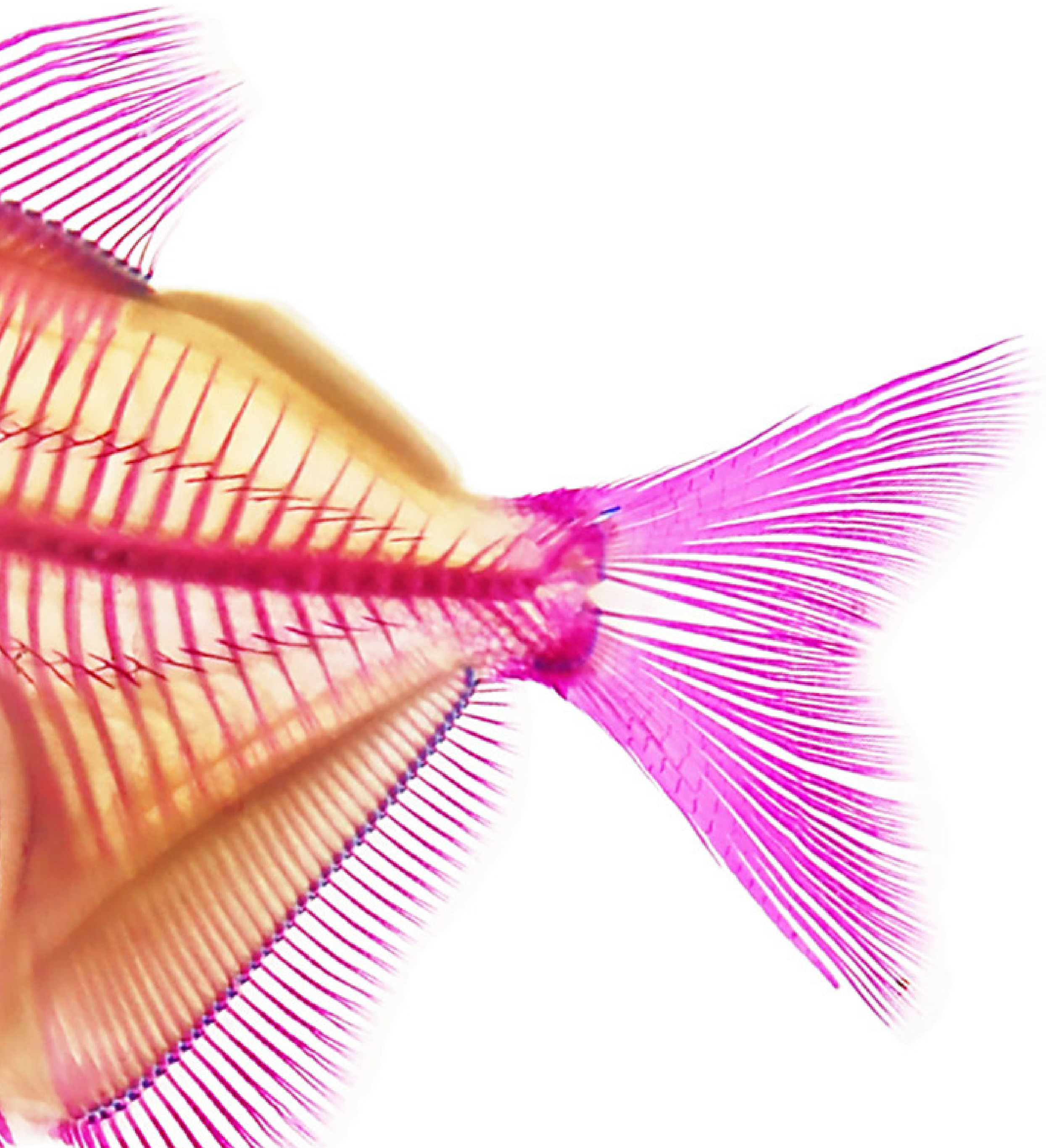
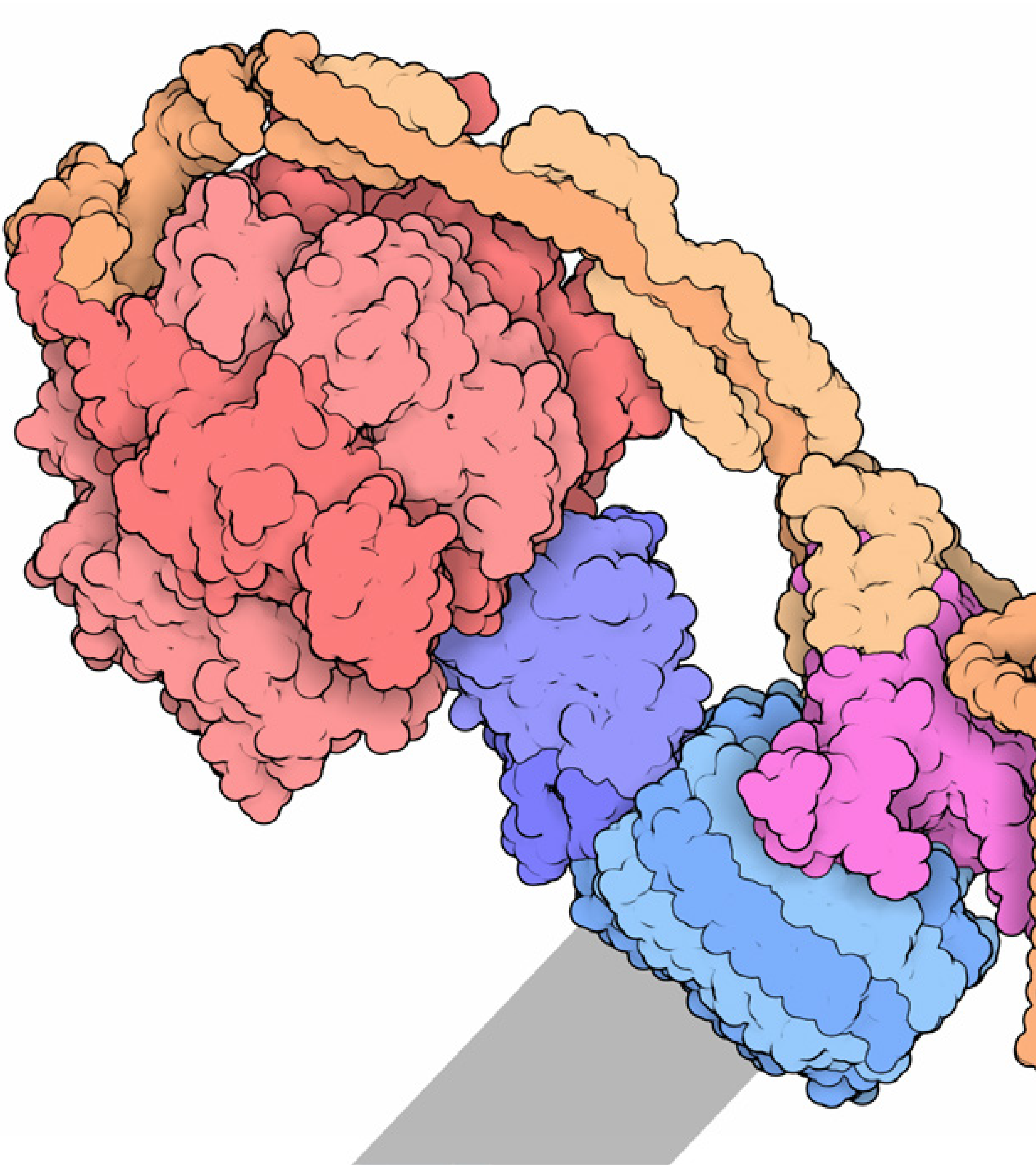
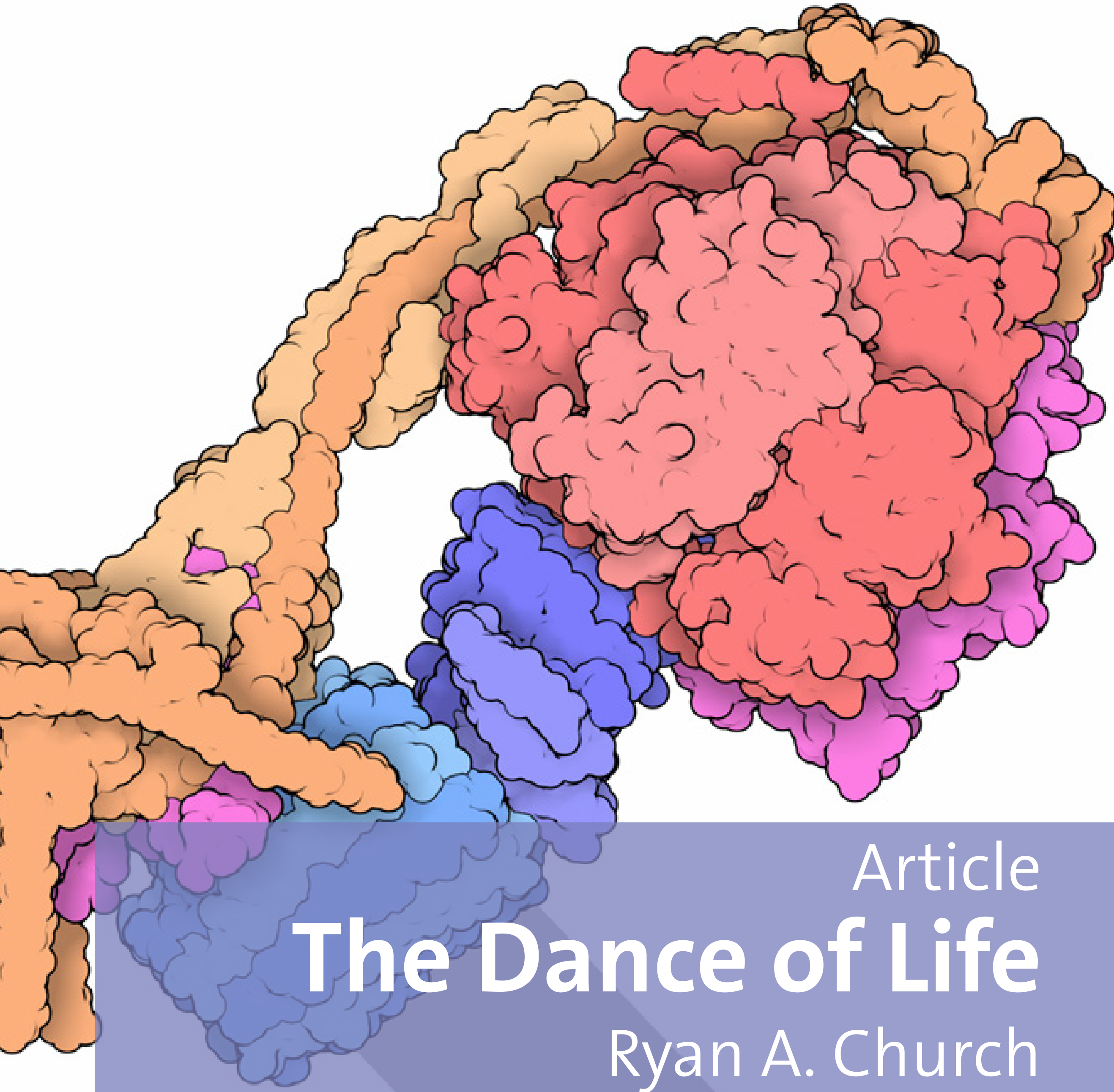




Silver dollar



Dimeric complex of ATP synthase
December 2005, David Goodsell | doi:10.2210/rcsb_pdb/mom_2005_12 | RCSB PDB, CC-BY-4.0



Article

The Dance of Life

Ryan A. Church

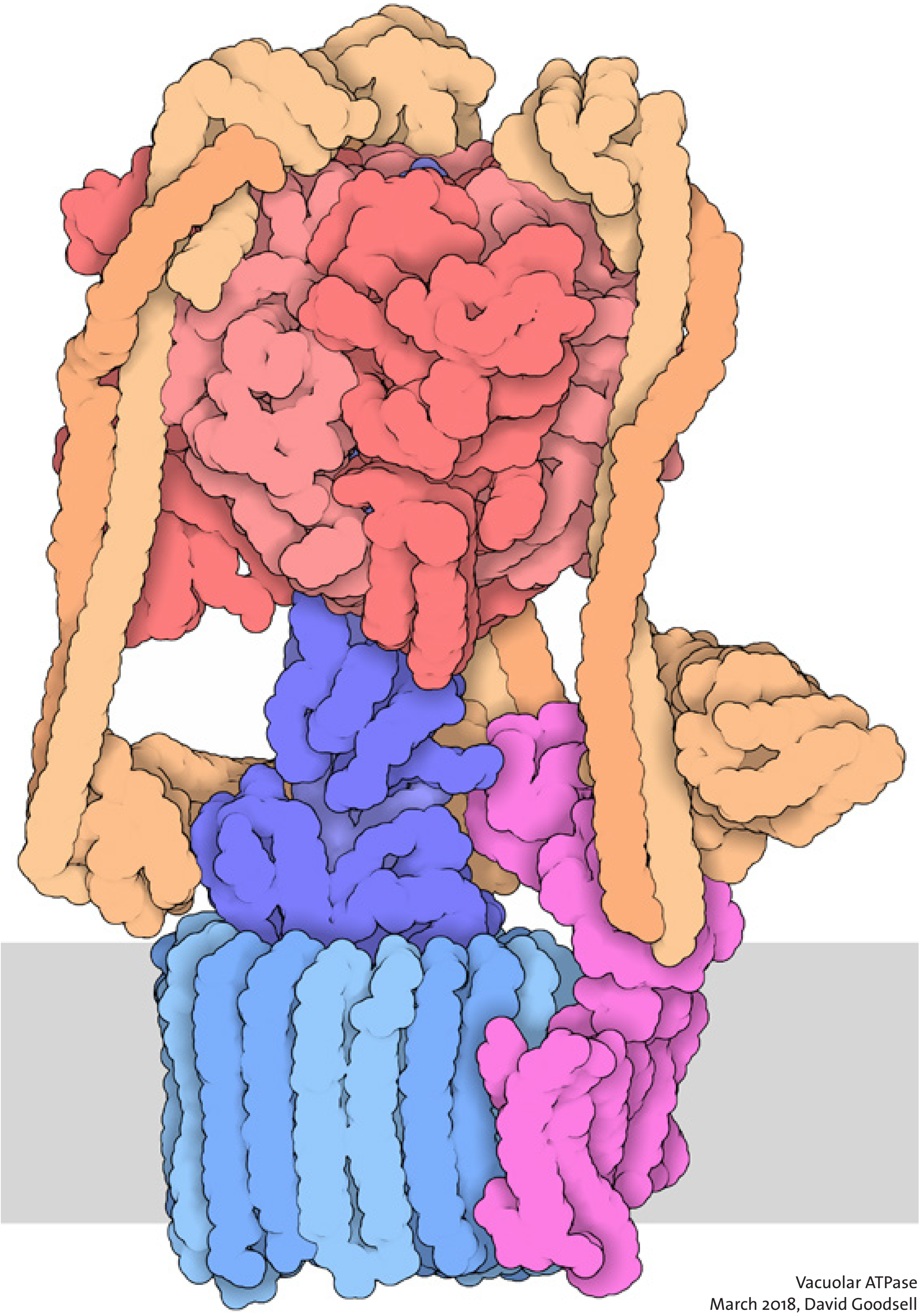
The Dance of Life
Ryan A. Church

The Dance of Life: How Green Chemistry can inform the Green Revolution

With COVID-19 shuttering the world economy, there is talk about a green resurgence. The concept is to build the economy back up using green energy infrastructure and green jobs. Examples of this include The Green New Deal [1] in the United States. The argument is that we can battle both the current economic crisis and the environmental crisis of climate change together, with one united burst of spending. Champions of this concept say this is just the sort of thinking that could spark a Green Revolution.

Nature might have some suggestions for achieving a green revolution that is sustainable and in harmony with the natural world. The previous sentence is slightly circular, but that is the point. Nature is best at highlighting how to create batteries that aren't manufactured from toxic components like lithium, or solar panels manufactured from toxic silicon tetrachloride [2]. The vast majority of the natural world is made from carbon, hydrogen, oxygen, nitrogen, phosphorus, and silicon, collectively referred to as CHONPS by the organic chemistry community. The way we harness, transmit, and use energy can also stay true to these tenets, and use these basic building blocks. Life on Earth is a dynamic dance: an intricate system of energy gradients, thresholds, and set-points that have evolved over time to revolve around points of dynamic equilibrium. These gradients invoke energy cascades and the transformation of these CHONPS molecules from lower energy states to higher energy states, and back again. This can be thought of as the Dance of Life [3].

As researchers investigate chemical energy generation and energy storage as the areas of largest potential commercial impact for the energy industry, understanding green chemistry will play a large role in how we transition away from fossil fuels, and create an era of energy technology that is in sync with the natural world. This article will look at how microorganisms, plants, and animals make, store, and use energy in a dynamic system, and what strategies and processes are used. Through the process of evolution, waste has all but been eliminated, which is what makes natural models so interesting to examine. In doing so, the article will highlight several advances in chemical energy generation and energy storage, and where we might go next to advance clean energy.



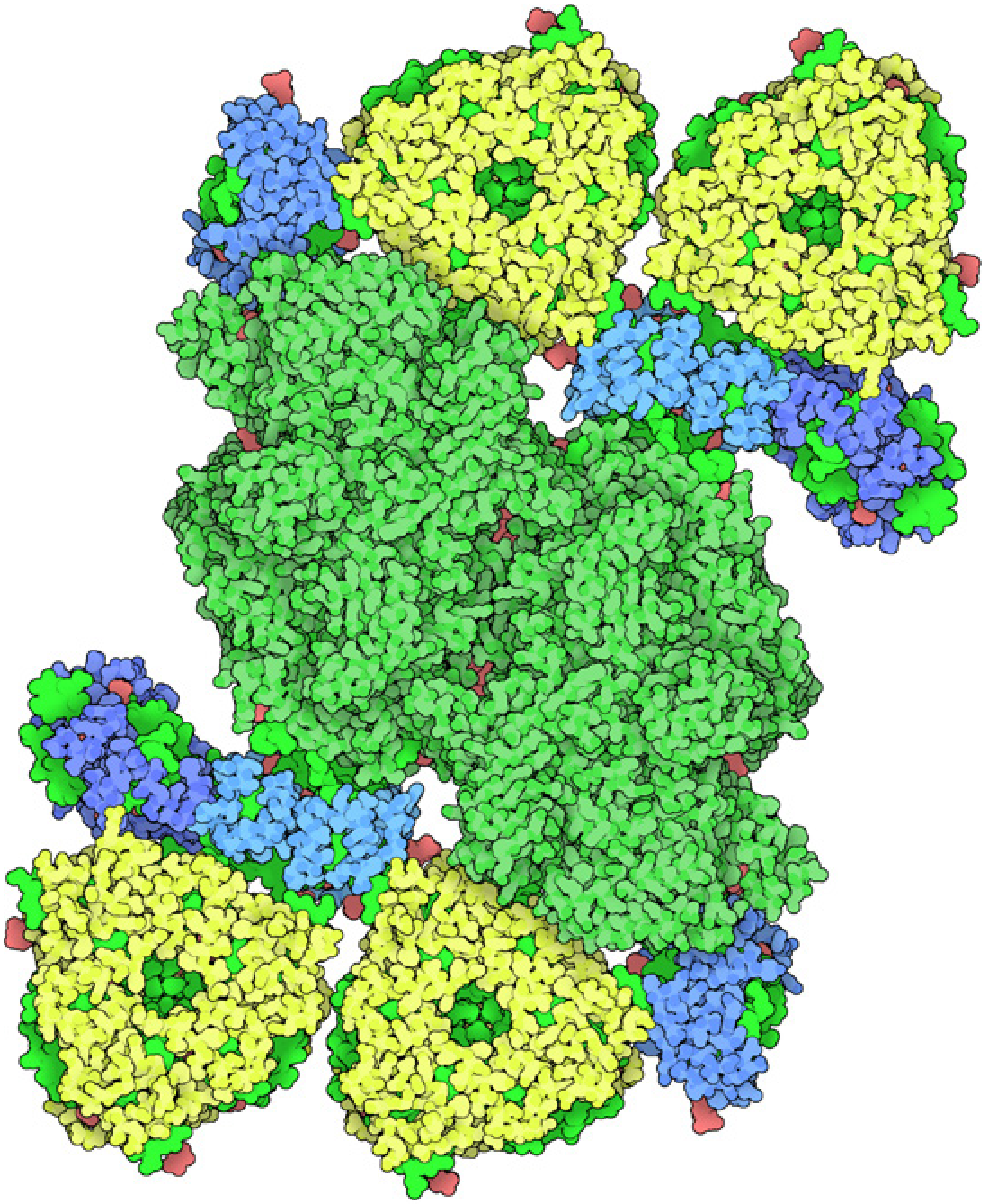
Vacuolar ATPase
March 2018, David Goodsell
doi:10.2210/rcsb_pdb/mom_2018_3 | RCSB PDB, CC-BY-4.0

The Dance of Life
Ryan A. Church

Photosynthesis: Green Energy Inspiration in Energy Generation and Storage

Plants use a process called photosynthesis, from the Greek 'light' and 'putting together', to transform simple building blocks into more complex building blocks with higher energy states. As this energy gradient is 'uphill', the products of photosynthesis can be thought of as a battery: chemical energy stored in the form of chemical bonds. A battery is just that of course: a store of potential energy in a higher energy state than its surroundings. The main machinery of photosynthesis in plant cells is the chloroplast, which has evolved over billions of years to transform CO2 and water into oxygen and sugars through the input power of solar energy, using light-based and dark reactions in a series of cascading events.

The architecture of chloroplasts in plants is striking. Composed of multiple disk-shaped membrane-bound sacs called thylakoids, they are stacked on top of one another and connected to each other through another thylakoid structure that is helical in its geometry, acting like a wrap-around staircase, connecting to each disk through a bridge-like structure. In this way, the thylakoid system, known as a granum, is completely interconnected and geometrically adaptable and mobile within the cell, responding to light conditions to either increase its surface area or adjust its orientation. Think of it like an accordion constantly on the move to achieve the optimal orientation for the light available. Within the membrane, the real magic happens. Light energy striking the thylakoid membrane hits embedded protein complexes, known collectively as photosystem II, and splits water into oxygen and hydrogen, releasing an electron in the process. The oxygen is released, exiting the cell and creating our atmosphere in the process. The positively-charged hydrogen ions generate a charge gradient across the membrane, and are joined by other hydrogen ions generated by protein complexes employing the energy of the free electron. The end result is up to a thousand times more hydrogen ions within the thylakoid space than outside the membrane. This is in effect a flexible battery, and creates the proton-motive force which produces adenosine triphosphate (ATP) to power the dark reactions, which in turn make the sugars. Light also strikes another protein complex in the membrane called photosystem I, the ultimate product being nicotinamide adenine dinucleotide phosphate (NADPH), an electron transport molecule needed for the dark reactions.



Photosystem II supercomplex from pea plants. The photosystem is in green, LHCII in yellow and minor antenna complexes in blue. The many cofactors are in bright green and red.
April 2020, David Goodsell | doi:10.2210/rcsb_pdb/mom_2020_4 | RCSB PDB, CC-BY-4.0

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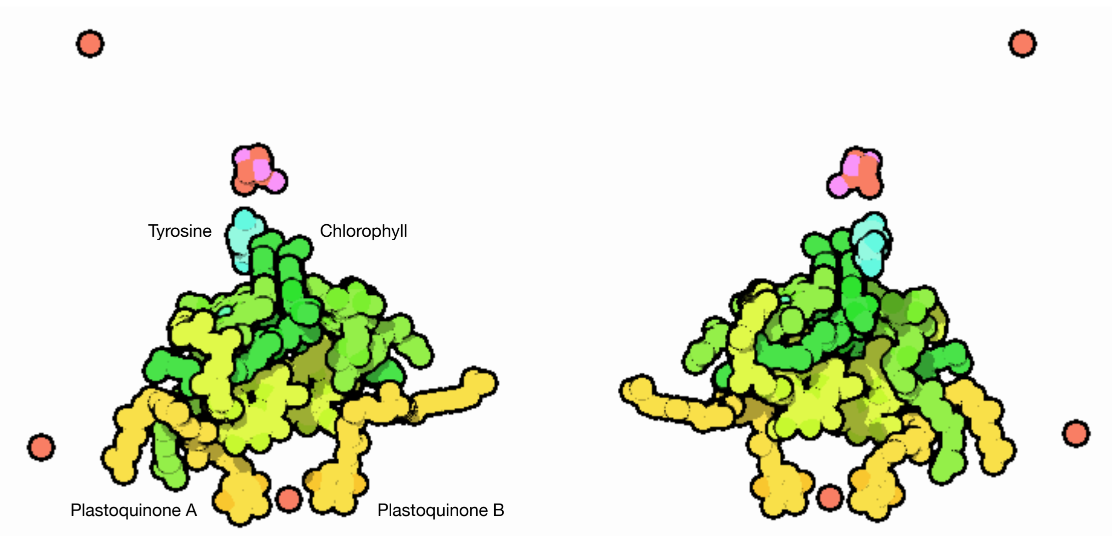
Globally on land and sea, photosynthesis produces about 130 terawatt hours (TWh) of energy per year [4] through light-dependant reactions, which was about 7.6 times the power consumption of the entire world in 2015. [5] That pales in comparison to the total energy potential falling on the earth from the sun in a given year – a whopping 122,000 TWh, of which 35,000 TWh strikes land. [6] However, it might surprise you to learn that photosynthesis isn't an efficient process. Only around 1% of the energy from the sun is converted into the useful form of glucose [7], partially because there are so many conversion steps along the way. As LaVan and Cha [8] pointed out, these losses include incomplete absorption, absorption as heat, and a limited light spectrum range for conversion. This might leave you wondering if this process is worth emulating. While the overall energy yield is very low, nature allows for this because there is such an abundance of energy coming from the sun. Given the abundance of solar energy, perhaps our focus on conversion efficiency might be overblown, however there are certainly ways to improve our current designs.

One issue in photosynthesis as it applies to would-be biomimetic engineers is the light saturation characteristics of the photosynthetic apparatus, driven largely by the green pigment chlorophyll and associated catalysts. This should be avoided rather than mimicked in artificial systems. Light saturation is often already reached at 10-20% of the maximum solar power because the high absorption and fast primary reaction steps are not matched by the capacity of the subsequent redox chemistry. Redox reactions combine reduction (where a molecule/atom/ion gains an electron) and oxidation (where a molecule/atom/ion loses an electron) – other examples include combustion and battery technologies. The trick is to design chemical systems that can react quickly to light stimuli and have a broad absorption range. The absorption peaks of chlorophyll a are at 465 nm and 665 nm, while chlorophyll b has approximate maxima of 453 nm and 642 nm. [9] Other pigments around 300-400nm would balance out the spectrum of any would-be biomimetic design.

Photosynthesis is a very complex process found in nature, and many attempts have been made to try and emulate it. Its complexity highlights one of the issues of trying to mimic it, in that many researchers focus at the wrong level of detail. Perhaps a more practical approach is to leverage the process and strategy, rather than concentrating on the efficiency. One example of a venture trying to exploit the high-level concept of photosynthesis is Sun Catalytix, [10] led by MIT professor Daniel Nocera. The concept is to use sunlight to split water into hydrogen and oxygen, which are collected for later use. This is the battery. Then, when energy is required, these two gases can be combined in a fuel cell to produce water and an electric current. This system works because hydrogen and oxygen gas on their own are in a higher energy state than water. Unlike photosynthesis, sugars are not created in this process. The trouble with devices such as these is that they use cobalt and nickel as the catalysts and silicon, which have global sustainable supply chain issues and use toxic processes in refinement. One of the Holy Grails of research are improved catalysts which do not denature over time, are easily synthesized, and composed of organic building blocks.

One line of research is to explore the use of materials other than cobalt and nickel that readily accept electrons, such as iron or copper, which might be cheaper to produce and better for the environment. The chemical structure of chlorophyll is an organic ring structure with four nitrogen atoms bonded to magnesium at its centre. Its structure is remarkably like another of nature's carrier and translocation molecules, namely hemoglobin, which uses iron in the center of a nitrogen ring structure for rapid bonding and debonding of oxygen. The magnesium within chlorophyll isn't used to bind oxygen.



The reaction center of photosystem II.
November 2004, David Goodsell | doi:10.2210/rcsb_pdb/mom_2004_11 | RCSB PDB, CC-BY-4.0

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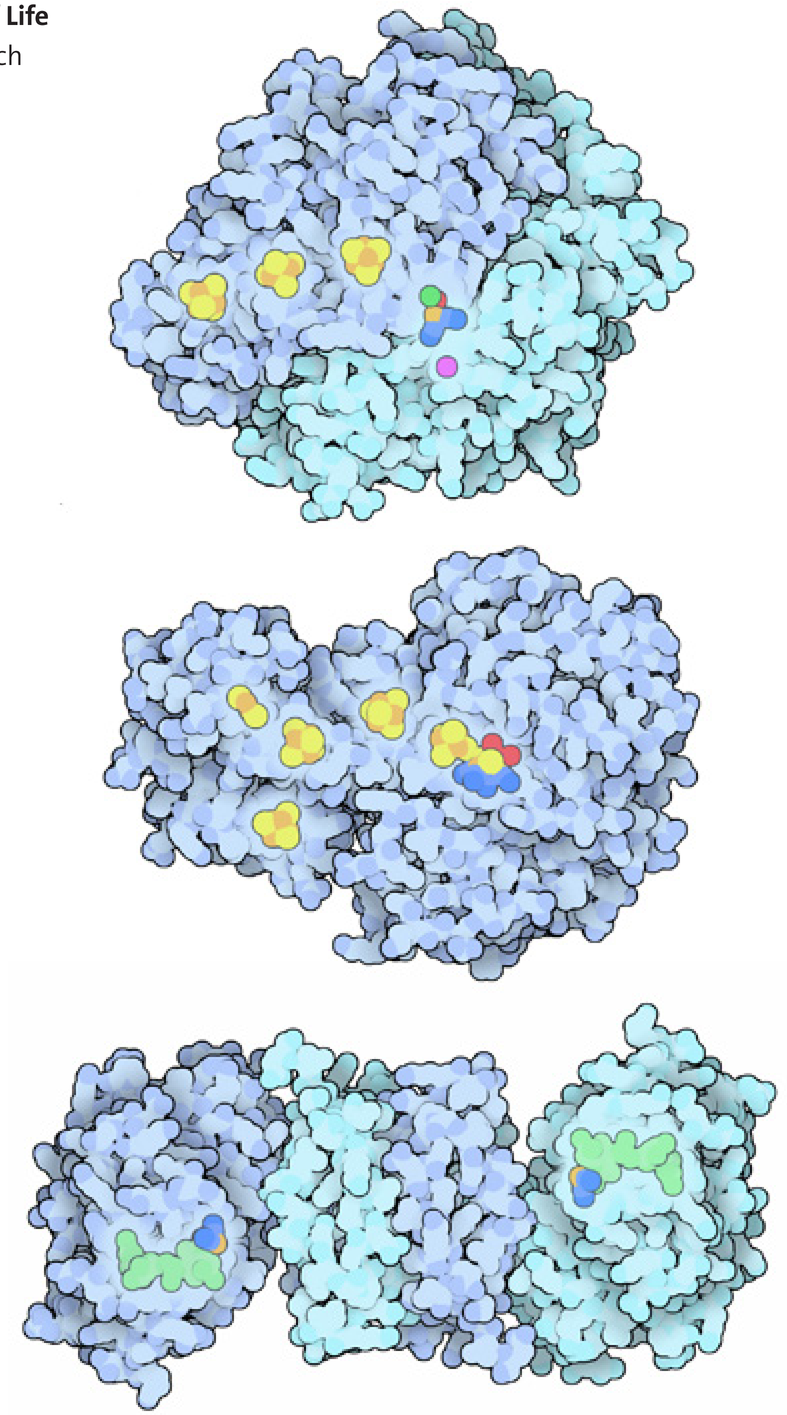

Nickel-iron hydrogenase (top), iron-iron hydrogenase (center), and iron hydrogenase (bottom).
March 2009, David Goodsell | doi:10.2210/rcsb_pdb/mom_2009_3 | RCSB PDB, CC-BY-4.0

Instead, it is used to stabilize the molecule, allowing it to be a very strong oxidant. In fact, the molecule is the strongest biological oxidizing agent known, with a redox potential of 1.3 volts. As you'll see, everything happens in pairs. The process goes like this:

The reaction center within Photosystem II is composed of two chlorophyll molecules. Once light energy is absorbed by these two chlorophyll a molecule dimers, known together as P680 (Pigment absorption at 680nm), charge separation and excitation occurs, releasing two electrons. Pheophytin and quinone molecules catalyse the reaction by accepting these electrons and taking them away from the reaction that happens next with P680. Quinones in particular are known to be very mobile – like the FedEx of the Photosystem, they scoop up the electrons and take the negative charge away, acting like a mobile battery. Meanwhile, P680, which sits on top of a protein with four magnesium binding sites, is in the perfect location and electrical state to react with water. The oxygen in water is strongly attracted to these magnesium sites and two water molecules are held in place right above the reaction center of the two chlorophyll molecules of P680. Each chlorophyll molecule then strips an electron away from each water molecule, freeing the hydrogen ions, before the two oxygen atoms fuse to form stable oxygen. At this stage, you are left with electrons, hydrogen, and oxygen. As explained above, the hydrogen charge differential creates potential energy away from a point of equilibrium - another battery. The electrons also create potential energy away from a point of equilibrium. This is in effect also a battery, though this free radical is not as stable as a chemical bond. In essence, these steps produce diversified energy generation in the form of hydrogen and electrons through one of the most elaborate dances of life in nature.

The Electron Hot Potato: Energy Storage and Distribution

Quinones are interesting molecules for research. Once two electrons are taken from P680, the electron 'hot potato' is passed down a series of mediators until eventually consumed in the dark reactions described previously. These mobile electron mediators are a promising area of energy storage research. Researchers discovered that the physical properties of these structures can be tuned in specific ways to maximize capacity, voltage, and other parameters. For example, plastoquinone, one of the cofactors in photosystem II, carries electrons and protons in chloroplast through a redox reaction. The redox center of quinones is a

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carbon-oxygen (C=O) double bond, which has a very high bond energy of 803 kJoules/mol (12 grams could power a 100 watt lightbulb for an hour) Further, there are usually two or more C=O bonds in quinones, which come in four different geometries (Fig. 1), so multiple charges can be stored in a relatively compact structure, resulting in a high charge capacity. Quinones are attractive candidates for electrode materials compared with conventional electrode materials that contain heavy metal elements, though stability issues remain [11].

Chemical Origami: Energy Generation and Storage

The shape and geometry of molecules determines much of their functionality.

In plants, adenosine triphosphate (ATP) is a largely linear molecule at its activation site. Synthesized from the building blocks of adenosine diphosphate (ADP) and inorganic phosphate (P), they are joined to form ATP. The reverse process (hydrolysis) of ATP into ADP and inorganic phosphate releases 30.5 kJ/mol of energy by breaking the linear phosphate-oxygen bond. ATP is ubiquitous in nature, and is often referred to as the energy currency of nature [13], because it exists in both plants and animals, and its transition from ATP to ADP+P and back to ATP again is the main dynamic dance of life. In fact, people will transform their own body weight in ATP every day, just in their daily routine. ATP is used as a short-term energy storage mechanism, as thousands of molecules are transformed every second in your body.

Molecules that provide longer duration forms of energy storage include carbohydrates, which are branched in geometry and more compact. In plants, starch is another carbohydrate that also has a highly branched geometry, allowing for compact long-term storage of energy. In animals,

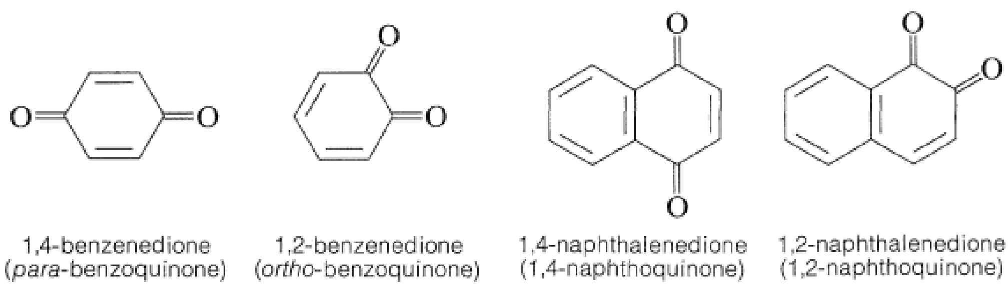

Figure 1: Four different geometries of Quinones [12]

glycogen and triglycerides play the role of long-term energy storage and are formed and stored in fat tissue. Triglycerides cannot pass through cell membranes, but can be converted at the cell wall into free fatty acids and glycerol by lipoprotein. Fatty acids can then be taken up by the cells by the fatty acid transporter. This requires multiple steps and makes it a slower process than the energy obtained from glucose, however triglycerides have a number of benefits.

- They can grow very large in size and they can be packed closely together, and can increase or decrease in size according to needs.
- They are more energy dense.
- They are hydrophobic, so they do not include water weight when being stored.

Triglyceride carbons are all bonded to hydrogens, unlike in carbohydrates which are linked to water, so they lend themselves to long-term compact stores of energy. Unlike glycogen, they allow for complete oxidation of the fatty acid from the hormone-sensitive enzyme lipase to provide high caloric content, about 414 kJ/mol.

The chemical structure and physical form of these bio-molecules play a large determining factor in their role within the dance of life. Molecules with easily accessible bonds, fewer bonds, and molecules that are more linear, lend themselves to short term energy storage, with rapid use and re-use – take ATP as example, compared to the highly branched nature of glycogen (Fig. 2). These molecules typically have

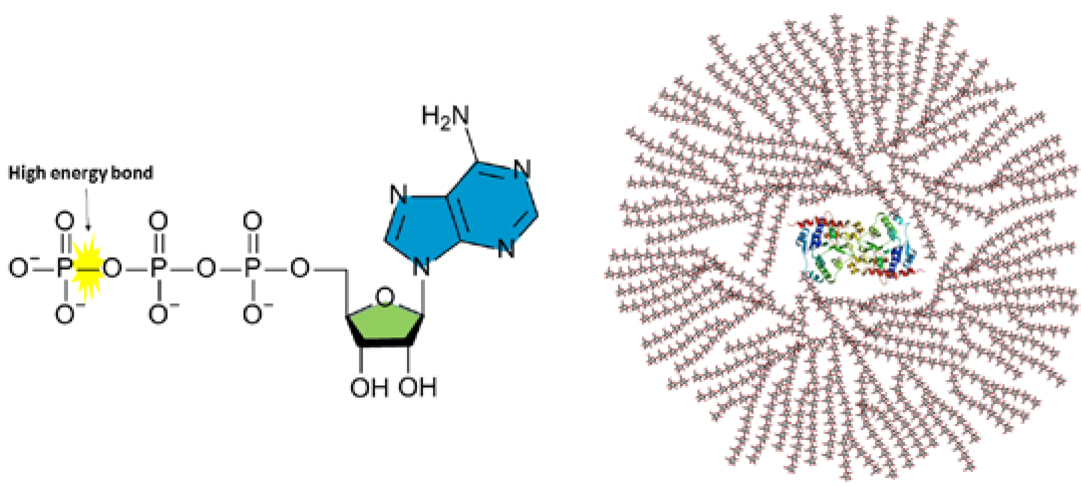

Figure 2: ATP [14] *left* (Short Term Use) | Glycogen [15] *right* (Long Term Storage)

lower energy bonds. The phosphate-oxygen bond of ATP, as example, produces about 30 kJ/mol, while the carbon-oxygen bond of animal fat releases a whopping 326 kJ/mol of energy per bond. The length of a chemical bond and the number of bonds between various atoms affects the amount of energy between two atoms. As the number of bonds increases, the bonds become shorter and higher energy, thus leading to more bond energy. If you were designing a molecule for quick energy storage, you'd likely want a lower bond energy with fewer bonds. If you were designing a molecule for long-term energy storage, you'd want the opposite. This is the cross-over where physics and chemistry come together to form biology. These principles of biological energy storage and use are translatable to technology. Thus far, glucose has received more research attention, yet triglyceride chemistry promises to be an interesting research direction for the production of bio-batteries.

Another promising candidate for long-term energy storage exists with non-immobilized enzymatic fuel cells (EFCs), where enzymes can move around. In 2014, researchers Z. Zhu *et al*. published a paper in Nature [16] showing how a fuel cell containing a 15% maltodextrin solution (a highly available, cheap polysaccharide that has 11% higher energy density than glucose) had an energy-storage density of 596 Ah/kg (Ampere-hours per kg), which is one order of magnitude higher than that of lithium-ion batteries at 42 Ah/kg. As such, sugar-powered biobatteries could serve as next-generation green power sources, particularly for portable electronics and electric vehicles. [17] A key takeaway is that sugars like maltodextrin are appealing fuels for EFCs because they are abundant, renewable, inexpensive, non-toxic, safe for storage and distribution, and carbon neutral over the entire life cycle. [18]

Polysaccharides like maltodextrin and bio-enzymes like quinones show potential as elements of next-generation battery technology. From a chemical and physical point of view, their storage capacity far exceeds that of lithium. A futuristic maltodextrin battery-pack of the equivalent weight of current lithium-ion batteries in an electric vehicle could unlock seven times the range of current battery technology. The key to unlocking this range will be to ensure complete oxidation of these organic fuels, reduce degradation of EFCs through repeated use, and combine this in a system with high Faraday efficiency (the efficiency with which charge (electrons) is transferred in a system facilitating an electrochemical reaction). Research [19] suggests that non- immobilized enzymes (like those found by Z. Zhu *et al.*) can also improve battery lifetime. This research was also able to show far greater energy density than lithium-ion equivalents *in vitro*; the next challenge is to scale this up and commercialize it, while proving the reliability benefits of EFCs.

Bacteria to the rescue?

Although an example of bio-utilization, there has been some good research done on using photosynthetic processes of algae and other organisms to produce electricity. This is often called biofuel-cells.

Optical Bio Microsystem lab have invented and developed micro-photosynthetic cell technology [20] that can harness electrical power from the photosynthesis and respiration of blue-green algae [21]. Shelley Minteer and a group from the University of Utah have similarly looked to blue-green algae . Benefits include a long life – biofuel cells can last years – however they have a low power-density. This may not be an issue, depending on the application, but must be considered. Previous research focussed on the creation of fuels from blue-green algae, which is inherently inefficient because multiple conversion steps are required, with energy losses at each step. These processes produce electricity and mimic the way these cells keep their sensitive metabolic enzymes confined in membrane-bound vesicles, which prevents denaturation.

This area of research is promising, and is warranted for future research, especially around the area of targeted fuel sources and improvement of catalytic efficiency. The use of redox polymers as mediators is also a promising concept to facilitate electron transfer and improve operational performance of bio-electrochemical systems, which of course can draw upon the principles of photosynthesis, and the characteristics of quinones and other charge-mediation molecules.

Bacteria can also be utilized in other ways. Bacteria naturally harvest electrons by oxidizing carbon in organic materials and then converting this energy into forming ATP. One group [22] used bacteria and the salinity differences of fresh and salt water to produce hydrogen. If bacteria don't have a convenient electron acceptor, they'll use one outside the cell, which is where a cathode or fuel cell can substitute. Just as some researchers are using algae to make fuels, bacteria can be used to make hydrogen. In both cases, you are harnessing complex cellular machinery to produce desired end products.

Combining Efforts: Generation, Storage and Distribution

In February 2020 [23], the RIKEN Center for Advanced Photonics [24] in Japan combined PV devices and electrochemical cells to design a plant-inspired system that consisted of:

- A photovoltaic power-generating device
- An electrochemical unit converting electric power into chemical energy
- Storage of hydrogen, and,
- Polymer electrolyte cells converting hydrogen back to electricity to meet demands on site.

In 2015, this group reached the highest solar-to-hydrogen conversion efficiency of 24.4%. This is an impressive achievement, especially noting the efficiency of photosynthesis at around 1%. This shows that harnessing multiple biomimetic principles can improve efficiency in man-made systems.

Conclusion

The current technological landscape is bound to see a push for clean technologies as we enter into the 2020s. Emulating natural models of energy generation and storage 'to the last detail' can be misguided. What is more practical and fruitful for energy researchers and technologists is to understand the underlying mechanisms at play, and emulate these pieces of biological wisdom. Nature does not separate energy storage from generation, so the study of one should lead to the other, and vice-versa. A systems level approach is likely to be more beneficial in future research. Emulating the chemistry of chemical bond formation and decomposition strategies in photosynthesis and polysaccharide formation appears to be a very fruitful area for exploration, especially in chemical energy storage to electricity. Utilizing nature's recipes that revolve around CHONPS will increase compatibility with the nature world. Major barriers for technologies that involve catalysts have always been decomposition of these molecules over time – this will continue to be a major area of focus, as this underlies a number of issues with commercializing battery technology and energy production. Non-immobilized EFCs could be a promising field in this respect. It is unlikely we will find a one-size fits all model, or one 'ultimate enzyme' of the future, but if we pick the right combination of approaches, green chemistry can inform the green revolution. ×

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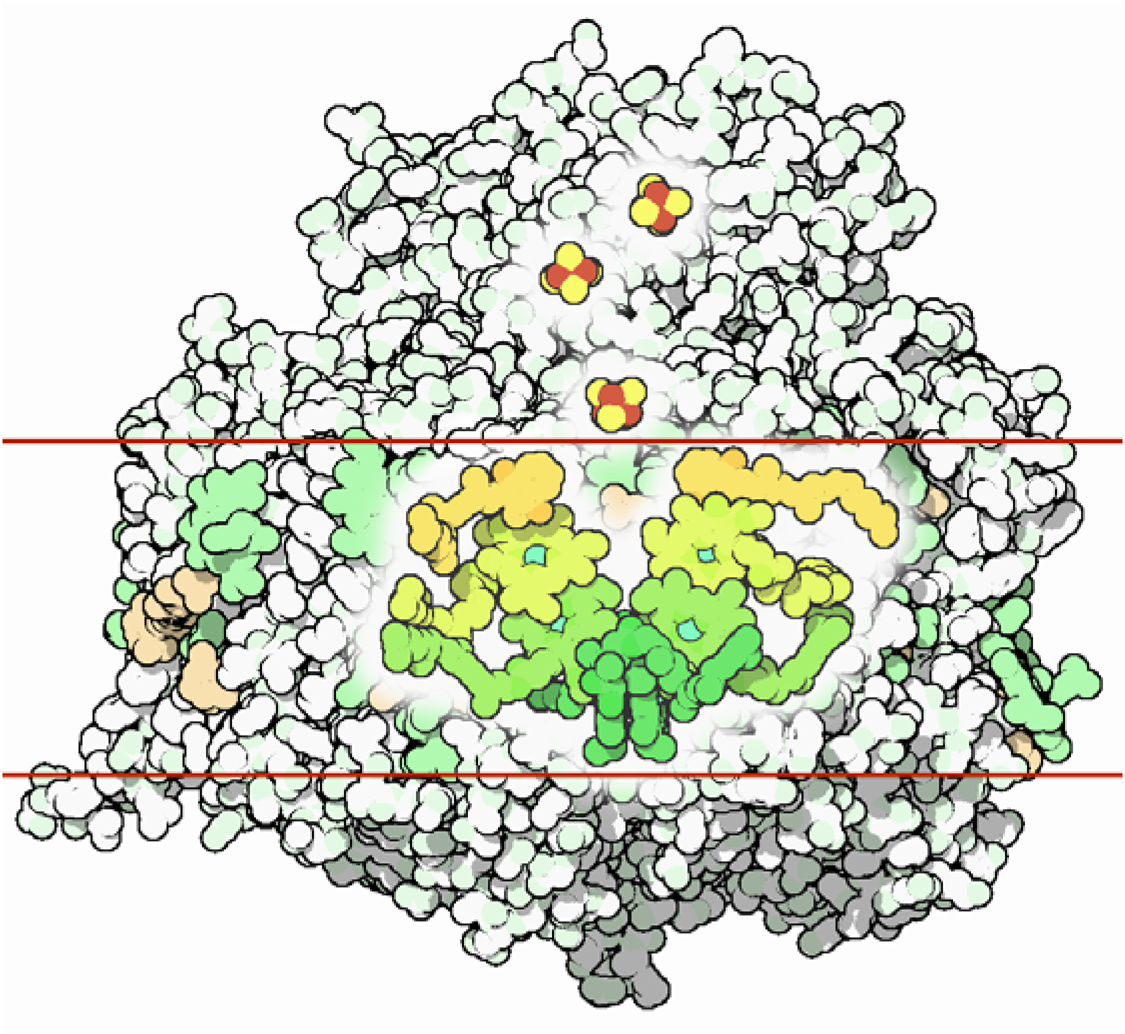

Electron transfer chain of photosystem I. The heart of photosystem I is an electron transfer chain, a chain of chlorophyll (shown in green), phylloquinone (shown in orange) and three iron-sulfur clusters (yellow and red at the top). These cofactors convert the energy from light into energy that the cell can use.
October 2001, David Goodsell | doi:10.2210/rcsb_pdb/mom_2001_10 | RCSB PDB, CC-BY-4.0

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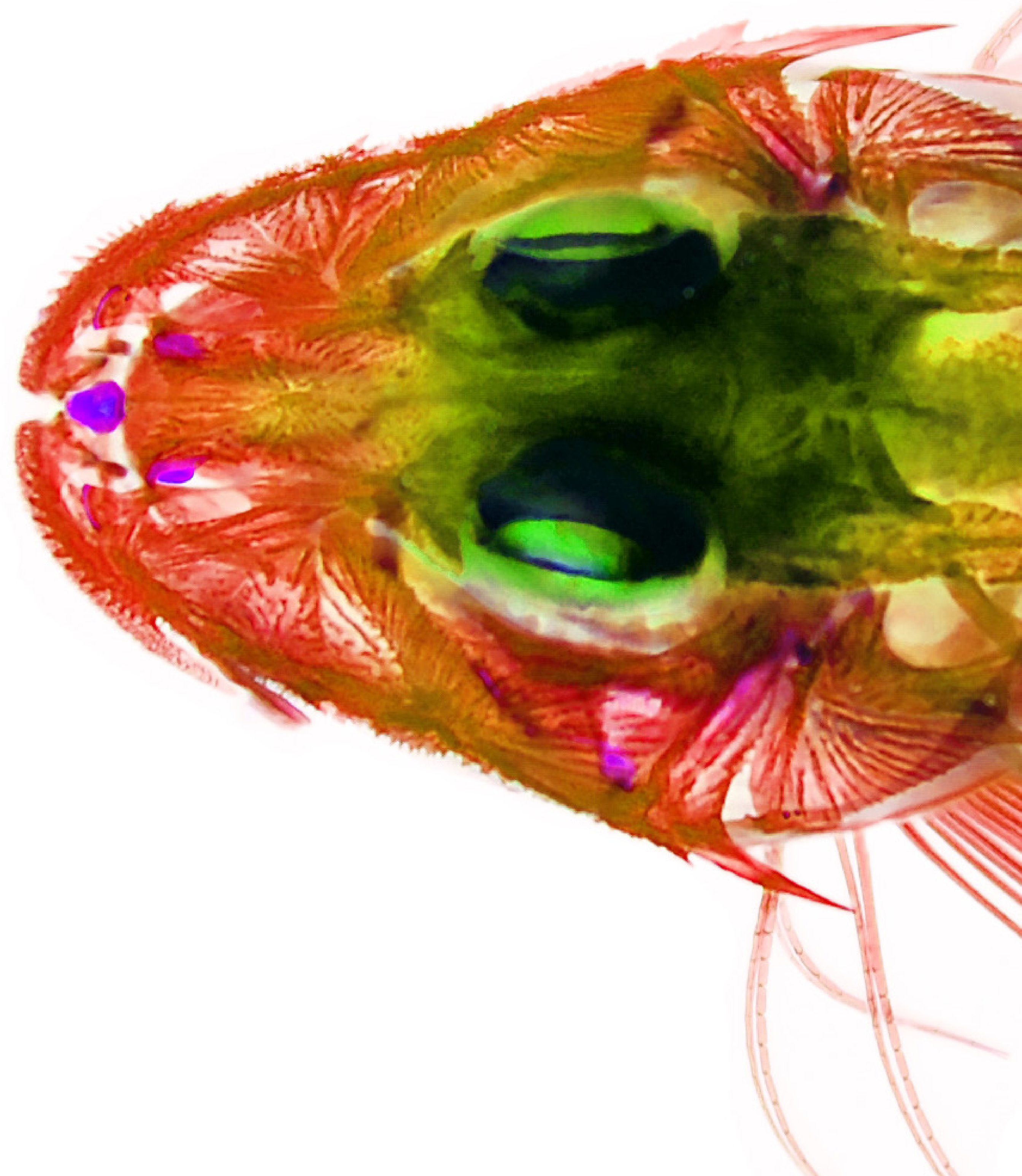

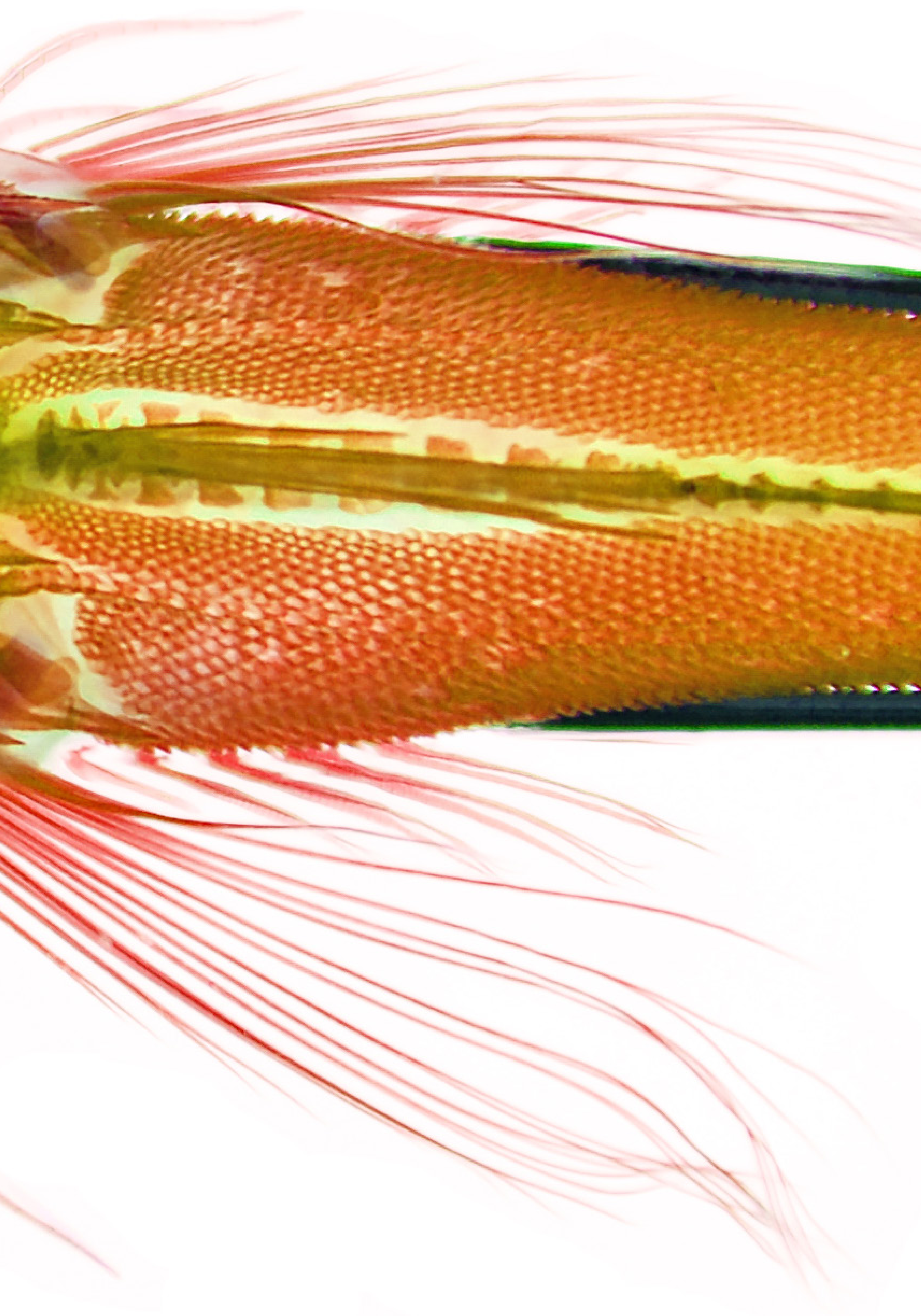

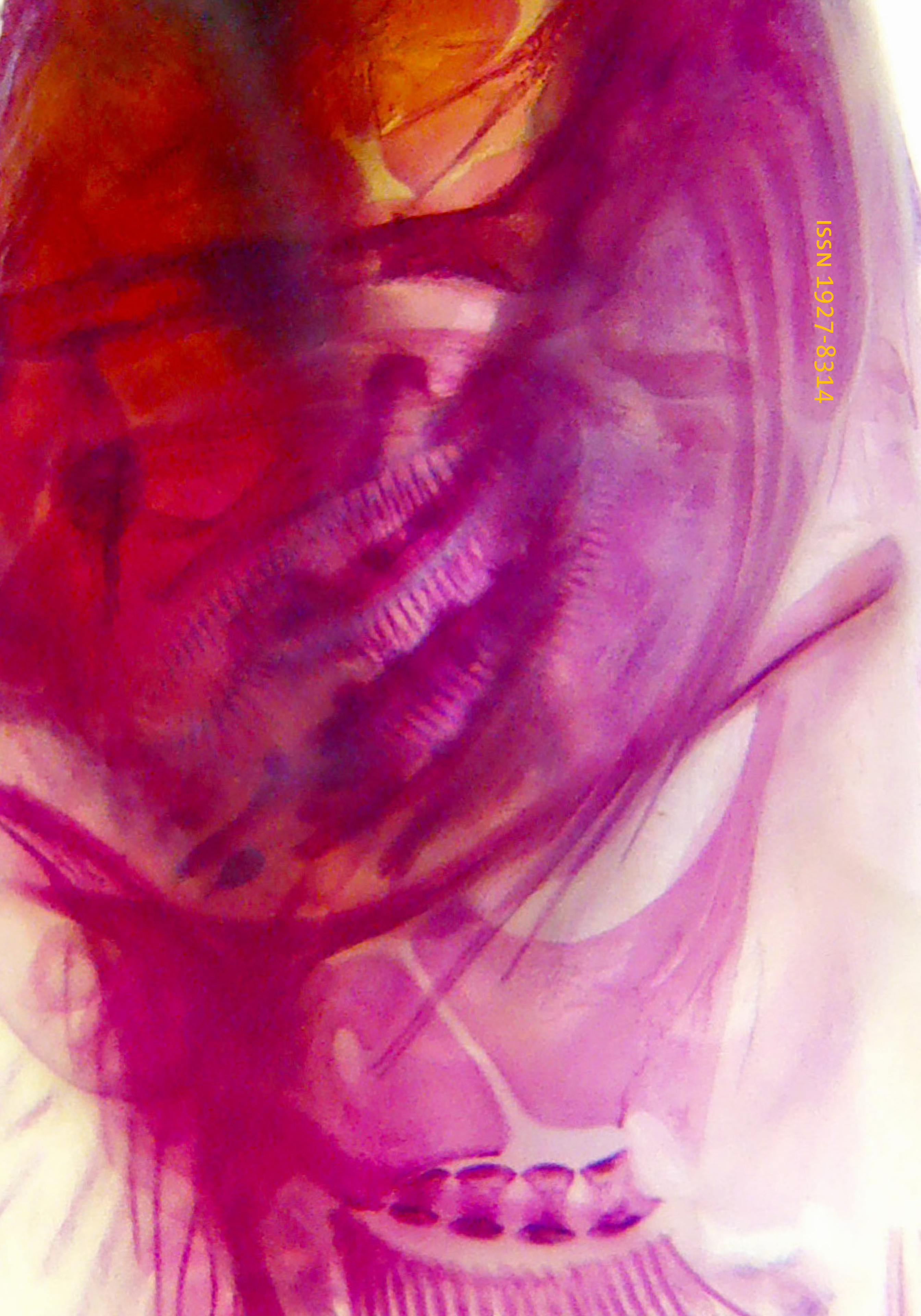

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