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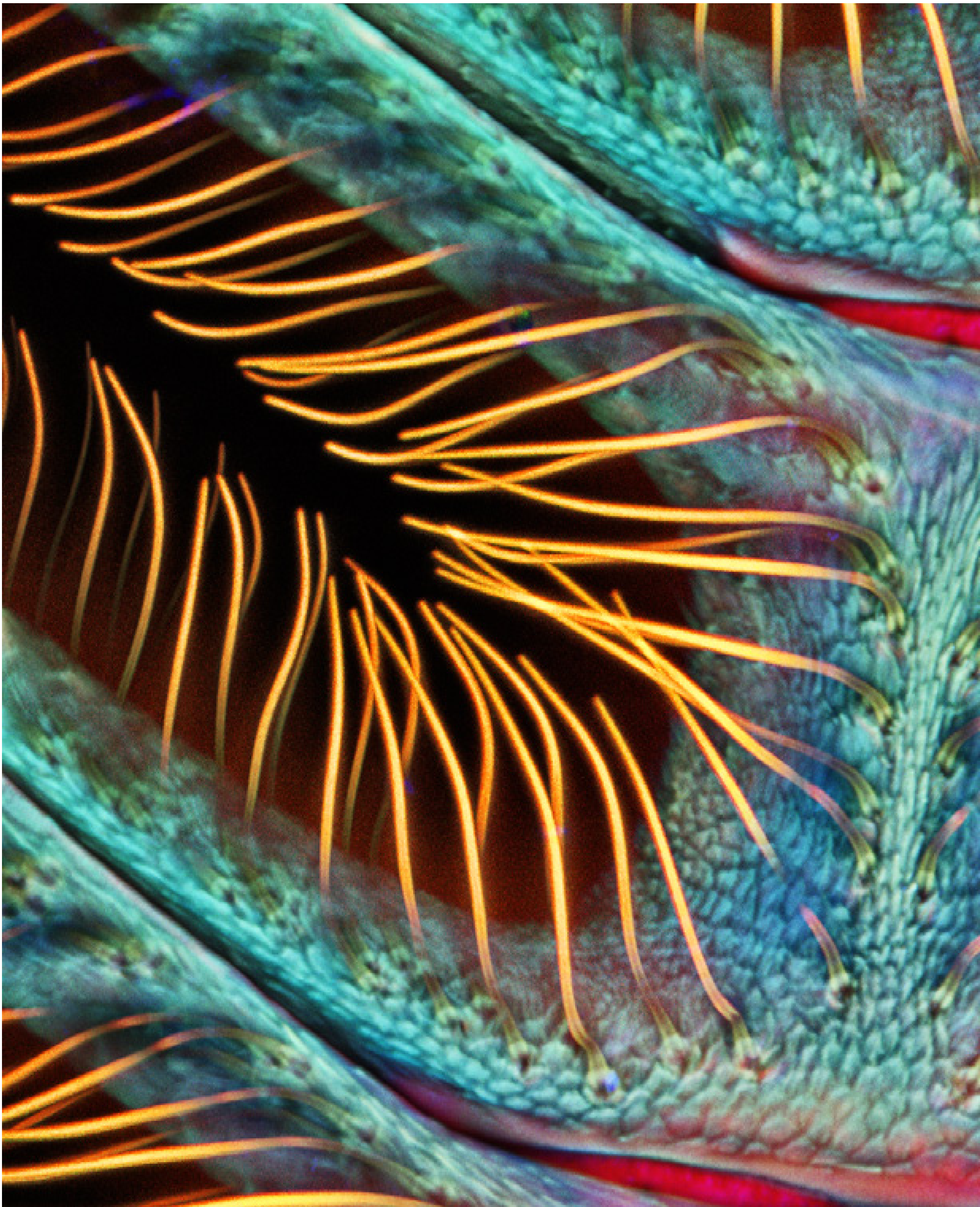

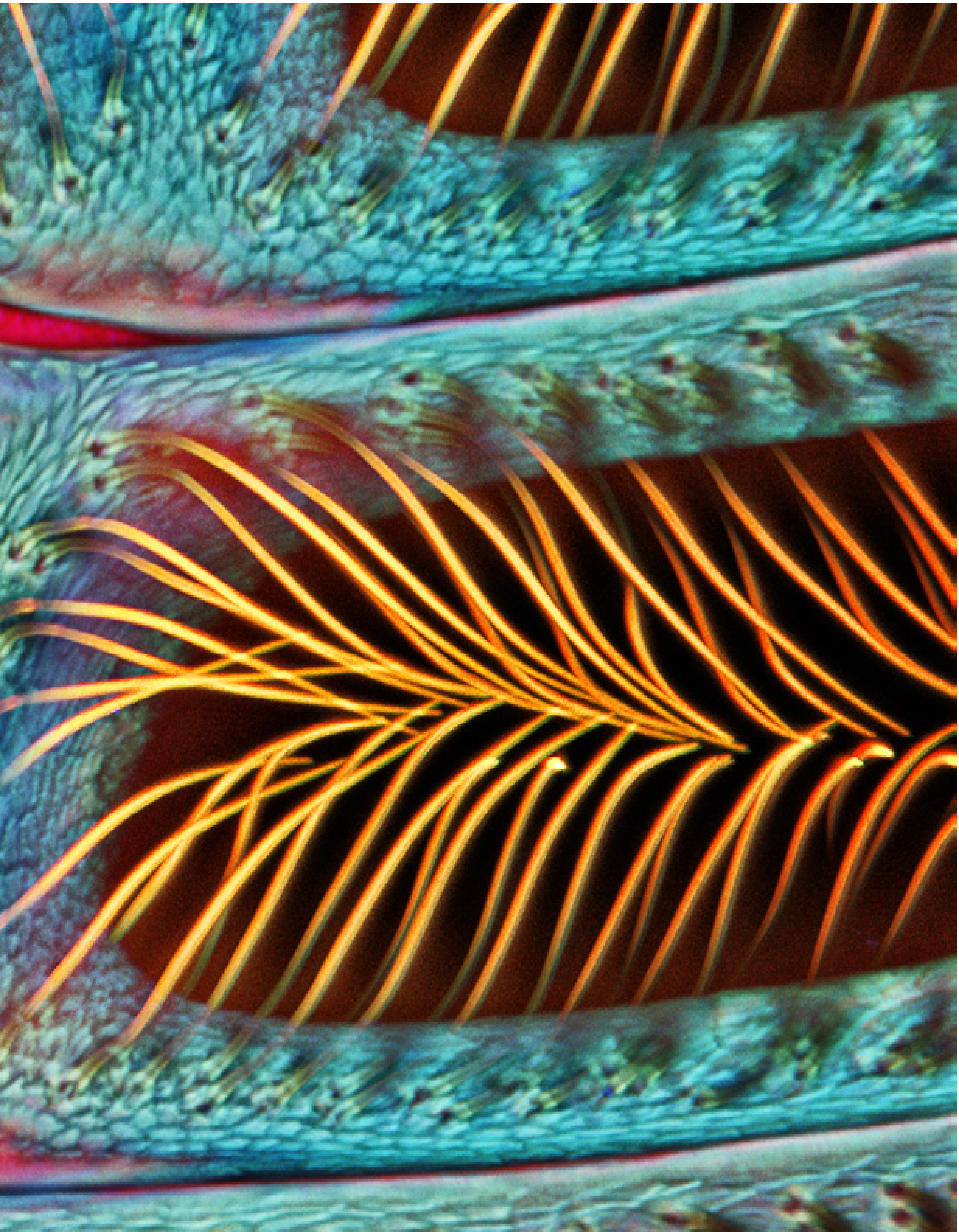

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Igor Siwanowicz | 2012

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Polyphemus Moth (*Antheraea polyphemus*)

Photo: DaveHuth, 2012 | Flickr cc

Beyond Metaphor

One of the goads for starting this magazine was the plethora of popular press articles trumpeting the dubious qualities of certain inventions based allegedly on nature. You have, perhaps, seen some of them: giant artificial lily pads as solar collectors on rivers (surrounded by acres of empty rooftops), metal solar stanchions masquerading as trees in greenless downtowns, giant office towers sporting faux mangrove roots simply because they are on the waterfront. From a functional standpoint many of these are no less laughable than leopard skin pumps or cell phone towers dressed up to look like redwood trees.

Rather than rail against this hot wind of misplaced and fleeting celebrity, we thought it better to reflect on what we considered worthwhile in the field of bio-inspired design, and to then highlight the work we thought important. In addition to showcasing individuals and companies who are advancing the field, this forum also gives us an opportunity to express what it is that we stand for.

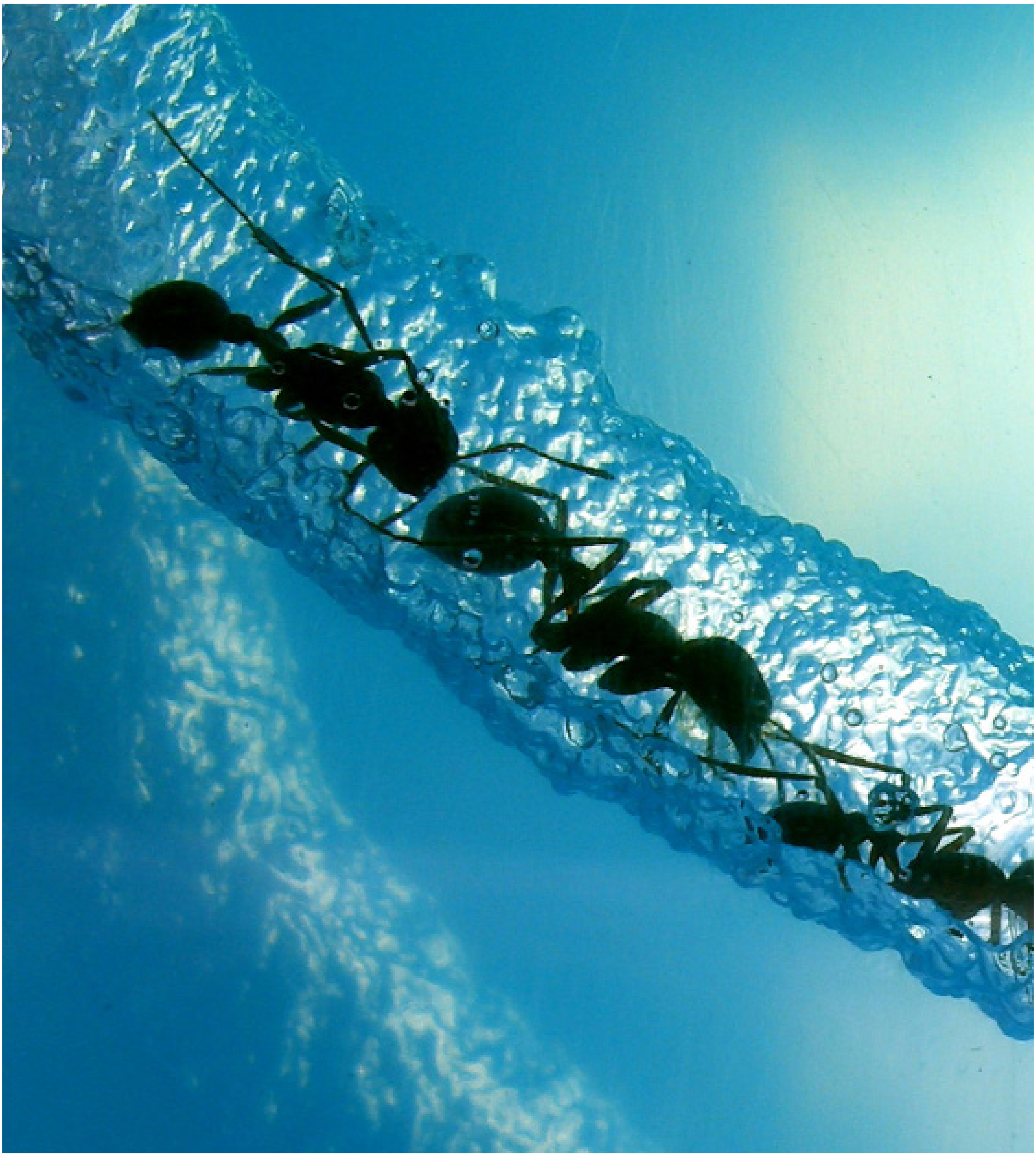
In previous issues we have written about the importance of inspiration and observation and the collaborative effort needed to bring an idea to reality. We should also mention the vital importance of analytical thinking to the field and the men and women of both science and design who practice it. Two such persons are Steven Vogel and Julian Vincent, who have exhibited this thinking throughout their long careers and in welcome contributions to this issue.

"Beyond Metaphor" is a phrase that sums up our opinion about what constitutes a worthy bio-inspired design process. This is one that goes beyond the superficial mimicking of a form, process or system that gains no real functional advantage or results in the misinterpretation of established scientific principles. A worthy process, in our opinion, extracts a basic biological principle, abstracts it to a level that is common to the fields of knowledge involved, and then translates it to the appropriate methods and materials at hand or on the horizon. After that, an actionable plan for a product or service is necessary and, as you will read in this issue's case study, no plan is a guarantee against the vagaries of the public marketplace.

We believe that there are many ways to practice this basic process and, because bio-inspired design is a critical tool for solving some of our most pressing challenges, there are many more reasons for doing it. The outcomes of this process should be as worthy of our world as the process. Therefore we support all that contribute to the health and well-being of our planet. We will happily continue to aid those working hard to bring sound, nature-based solutions to our society.

Tom Norbert Marjan

Tom McKeag, Norbert Hoeller, and Marjan Eggermont

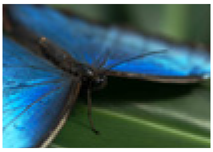


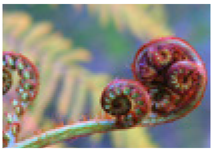
MIners

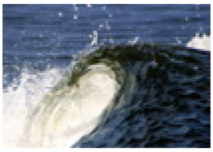
Photo: jurvetson, 2005 | Flickr cc

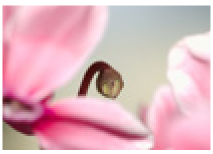
In this issue

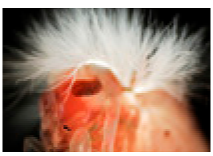
In this issue we bring you some of the best images from the world of the very small, submitted to the annual Bioscapes competition sponsored by Olympus. We also learn more about one of their star photographers, Igor Siwanowicz, and the contest itself from its coordinator, Laura M. Ferguson. Dayna Baumeister of Biomimicry 3.8, and Larry Stambaugh of the Centre for Bioinspiration at the San Diego Zoo tell us about themselves and their respective work in our interview section. In our tool department, we explain Georgia Tech's Structure-Behavior-Function model and walk you through an example from the built world. We give you a sneak peak at Jay Harman's new book, *The Shark's Paintbrush*, due to be published in June (special thanks to our guest book reviewers!). We are honored to have Steven Vogel and Julian Vincent both return to our pages to offer some useful thoughts about appropriate design and research: why thoughtful abstraction is superior to mimicry, and how information management may make a difference in what you find. Our case study follows the difficult market path of a well-known product, Qualcomm's Mirasol display technology, and how a brilliant idea and lots of money do not always augur success. We wish you, of course, the best of success, and enjoyable reading.

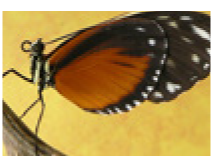


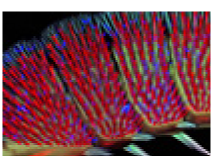


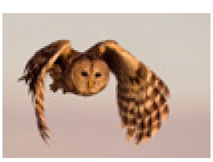












Blue Morpho

Photo: Pantheroux, 2011 | Flickr cc

Case study

Requiem for a Butterfly:

Mirasol's Market Meltdown

Tom McKeag

Requiem for a Butterfly: Mirasol's Market Meltdown

A Change in Course

In July of 2012, Qualcomm CEO Paul E. Jacobs arranged a teleconference with several communications industry analysts to give them rather startling news. Qualcomm, the powerhouse chip maker, was holding its quarterly investor meeting and the mood was ebullient: chip sales were booming and the company was expanding its reach in one of the most mercurial markets in the history of technology. Jacobs had some sobering news from another part of his company, however. Qualcomm would no longer manufacture its Mirasol eReader display screen, but would license its technology to interested parties instead. Qualcomm would still make and sell Mirasol technology as certain other, unnamed applications, but the company's high-stakes bid to capture the eReader/tablet display market seemed over. This change in strategy was, in Jacobs' words, better aligned with "addressable opportunities".

The Mirasol display technology had been one of the most visible examples of bio-inspired design in the technology sector. Based on the principles of structural color, and manufactured using traditional silicon chip methods, the reflective display had been marketed as an energy saver that would yield a rich color display when used in full sunlight. Industry insiders had watched for years for the product to break out of its demonstration phase box and gain market share in the fiercely competitive personal device industry. The news that Qualcomm would no longer make its own innovative product was a shock.

What happened to the promise of this biomimetic technology is a lesson in the challenges faced by any who introduce innovation into a dynamic, consumer market. The story holds particular instruction for those whose inventions are based on nature.

The Inspiration

Structural color is formed from the diffraction of select, colored light waves off a nano-surface, rather than the absorption and reflection of so-called white light by a colored pigment. In structural color, natural light is broken up or diffracted by a surface and the jumbled wavelengths of the constituent colors in the light are bounced away at different angles. Some of these wavelengths interfere with each other and some do not. The resultant color that one sees is from those wavelengths that were not cancelled out by this interference.

This kind of color can be seen in many examples in nature: peacock feathers, beetle thoraxes, seashells, and oil slicks. One of the champions

Blue morpho butterfly coming out

Photo: Petr Kosina, 2009 | Flickr cc

Rainbow shield bugs on Jatropha
Photo: tonrulkens, 2012 | Flickr cc

of this natural brilliance is the Morpho butterfly, *Morpho rhetenor*, an insect with shimmering, electric blue wings. The intense color of its wings is directly attributable to the geometry of their surfaces, and so is known as “structural color”.

The Morpho butterfly wing surface is anything but uniform. It is made of tiny scales, which have ridges with sloping shelves or ridge lamellae. The patterns formed on the cuticles of the scales are various series of ridges and cross-ridges with as many as 10-12 layers of shelves. The spacing between the ridges is in the range of 0.5 to 5 microns, while the gaps in the lamellae are measured in the nanometers. The scale of these gaps is a critical match to the color wavelengths. The visible range of light extends from the red wavelength of 700 nm to the violet wavelength of 400 nm, when measured crest to crest.

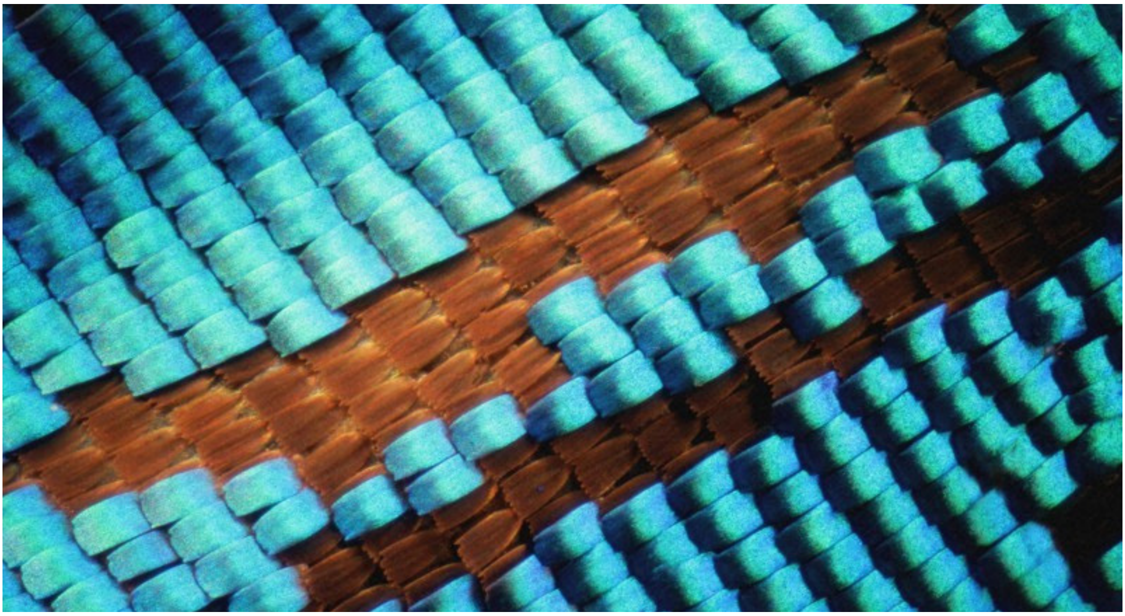
Natural white light hits this nano-stack of shelves at different depths, and so its different component colors are bounced back different distances, and therefore arrive back at different times. Like the jump ropes in a game of Double Dutch, some of the reflected colors are in sync, or phase, and some are not. Those that are not will cancel each other out; this is called “destructive interference.” Those that are in phase will make an even brighter color. The intensity of the color on Morpho’s wings is a result of this in-phase reflection of the blue light broken up by the grating (see pp. 20-21).

The layers of overlapping scales have been formed from individual cells in the wing’s epithelium, starting in the larval stage. These cells flatten, elongate and then develop patterned structures on their surfaces. The growing cell secretes these cuticle structures as a liquid that hardens as the cell dies back into the epithelium of the wing. Researchers believe that elastic buckling is key to achieving the period necessary to interfere with the wavelength in some species. Other species grow a three-dimensional network of endoplasmic reticulum to form a photonic crystal. The general results are the same. Chitin, by the way, is the hard material of choice for this kind of work in the invertebrate world; a long-chain polymer derived from glucose.

Sexual selection and reproduction, intra-species communication and camouflaging appear to be the main functions of butterfly color. For example, in some species color signaling is in the eye of the beholder. The same wing is perceived as background green by predators limited by their range of sight, while other butterflies can see a bright (linearly polarized) blue from as far as a half-mile away.

The Translation

The hardware engineer’s goals, of course, are very different from the butterfly’s. In the highly competitive visual display market competing technologies all seem to sit on the edge between runaway success and obscurity. Advantages of one system seem to be balanced with limitations. For example, Liquid Crystal displays (LCD’s) are bright but power hungry. Electrophoretic (E-ink) displays use less power, but are slow to refresh, and it is not certain whether they will be able to support video color on low power. Key concerns for the developer are energy use, visibility, and consistent color for both still and moving images; all must be in a user-accepted form at low cost.



The signaling requirements are also different. Rather than a field of color that changes with the random incidence of light, the device display has to control color to the pixel size and convey it in patterns that can be interpreted within the range of human eyesight.

Similarly, the methods and materials for achieving comparable color results are different. The form of the Morpho's light-bending shelves is quite complex and precise, and the living cellular material allows for a "bending into precision" type of fine-tuning at a scale still uncommon in most manufacturing.

Although the ultimate solution known as Mirasol technology has been generally compared to the butterfly, its technological development had come from the adaptation of silicon chip manufacturing technology to microelectromechanical (MEMS) devices and the study of the basic physics of light wave interference. The form of the butterfly's stacked shelves was not mimicked, nor was its hierarchy of scale, but it was a model that showed that the color effect could be achieved at the nano-scale.

Qualcomm uses a so-called IMOD (interferometric modulation) technology to create its color. The technique adjusts precisely the color wavelengths that will be cancelled out by interfering with each other. The remaining color is what one sees. MEMS structures are key to producing the effect.

To do this two plates are sandwiched with a tiny separation between them. A thin-film stack on a glass substrate is above a suspended reflective membrane. When an electrical charge is run

Butterfly wing scales

Photo: wellcome images, 2011 | Flickr cc

through the array electrostatic attraction brings the plates together. All the light colors except ultraviolet are absorbed and one sees black.

When the charge is released, however, one of three width gaps results, corresponding to the red, green or blue wavelengths. Combining these shown colors in a pixel array can create any color desired. These plate gaps can be adjusted one thousand times a second. The technique is bi-stable and therefore uses low power; energy is used to make changes but not maintain the states of “on” or “off”.

The History of an Idea

The technology for the Mirasol color display was not developed originally by Qualcomm but by Iridigm, a small startup that Qualcomm bought in 2004 for $170 million. Iridigm was founded, circa 1995, by Mark Miles and Erik J. Larson, two former classmates at the Massachusetts Institute of Technology.

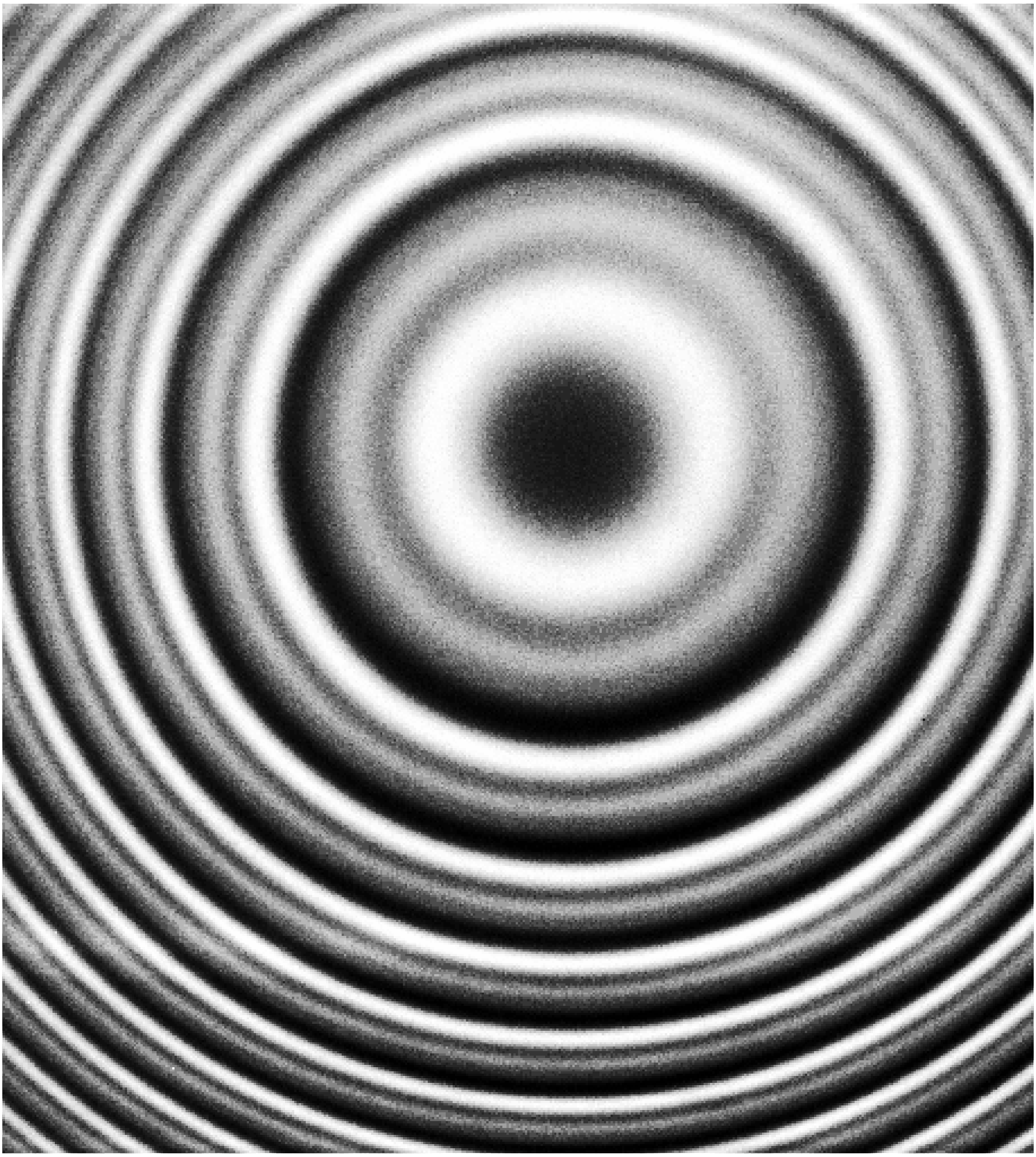
Miles had had the original idea for the technique in 1984, but had needed to school himself in the various technological components necessary to make a working prototype. He had become fascinated with the idea of using tiny arrays of antennae to capture sunlight for direct conversion into electricity. He had reasoned that if he could capture sunlight this way, and could manipulate the reflection and absorption rates, then he could make a new color display panel to replace the bulky cathode ray tube screens then in use.

As Miles continued to educate himself, two pieces of information became critical to his eventual success. First, he learned of an optical device called the Fabry-Perot interferometer, or etalon, that diffracted natural light to make light of one color. Second, he studied microelectromechanical systems (MEMS) fabrication. It was putting these two techniques together that yielded what would be called the Interferometric modulator (IMOD) display, the technology that would become the Mirasol product.

The etalon is a mirrored box where white light enters the top, is reflected from the bottom and bounced between two parallel, mirrored sides. The bouncing of the light cancels most wavelengths of light, except for those that happen to fit precisely between the two mirrored sides. This wavelength is reinforced and the box emits it as a color. While this was exactly the kind of control of light that Miles was searching for, the lab variety of etalons was of a scale much too large to serve as a pixel generator for a display screen.

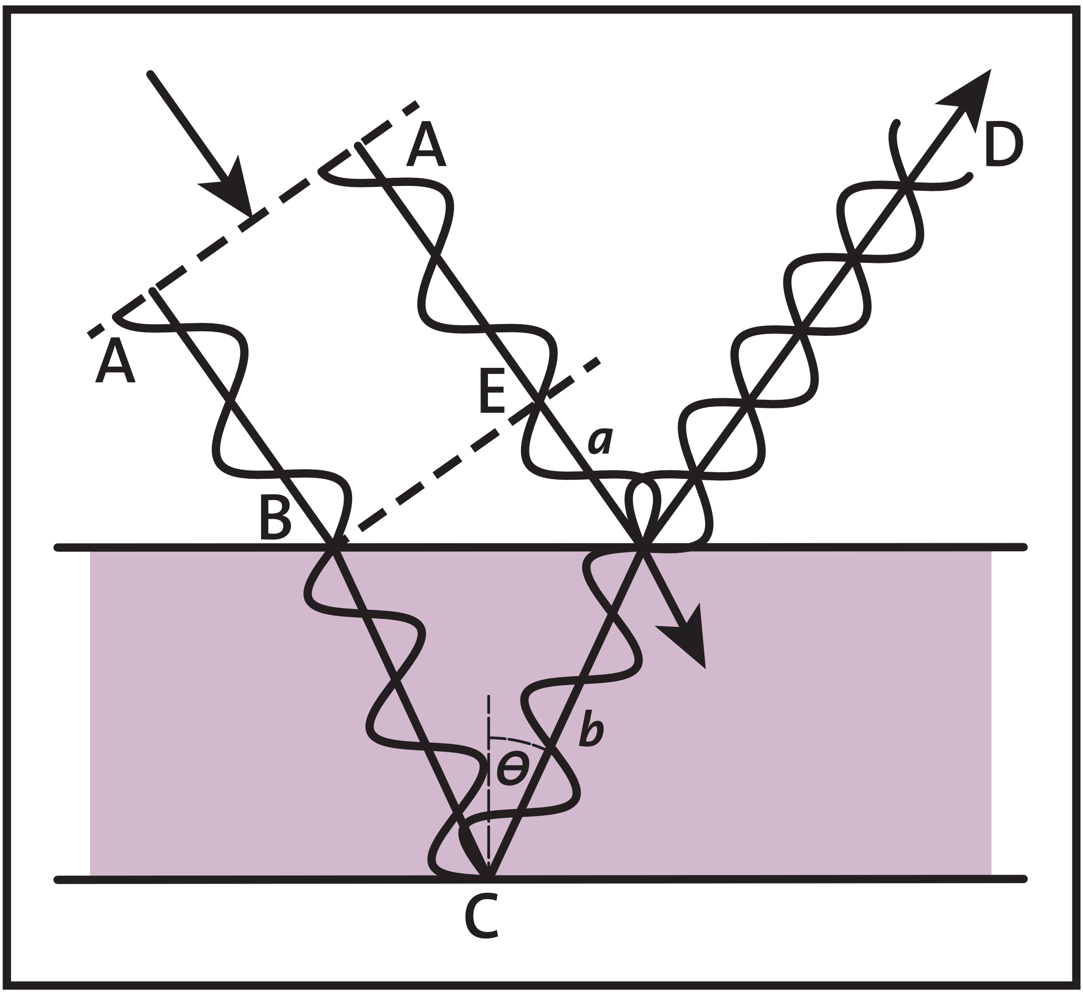
As it turned out, nature had been using etalons for a very long time, for the nano-scale ridges on the butterfly wing scales were indeed both trapping light and reinforcing wavelengths that fit the geometry of the declivities. It was not until Miles had discovered MEMS technology, however, that he realized how he could construct an etalon at that scale. These devices were made from etching the surface of a silicon wafer to produce microscopic mechanical devices. He now saw how he could construct what was an adjustable etalon at a scale sufficiently small to serve a display screen.

The result was two parallel, thin-film reflective surfaces, one above the other, that were fabricated precisely to maintain a gap corresponding to the wavelength of the desired color, red, green or blue. Light hitting the structure would



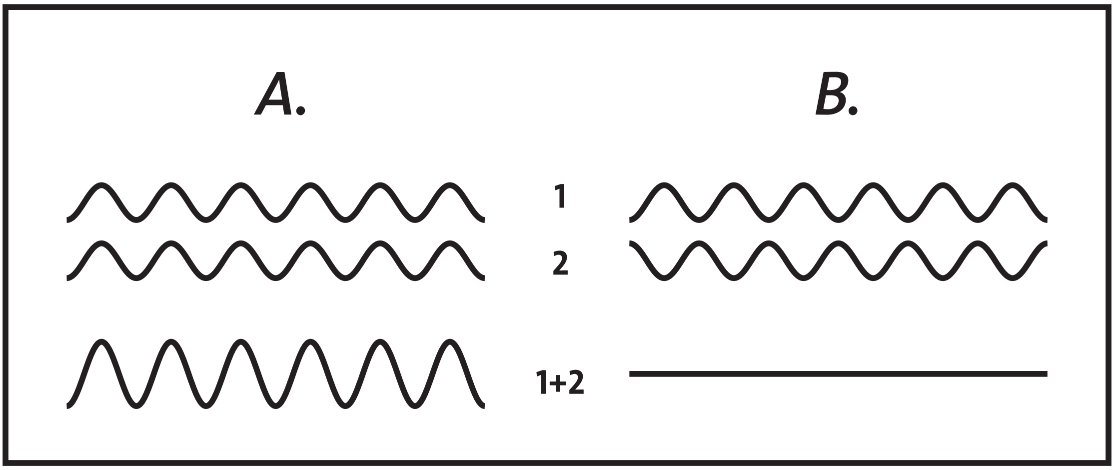
Fabry-perot interferometer/etalon fringes produced using a supercooled, deuterium light source, showing fine structure

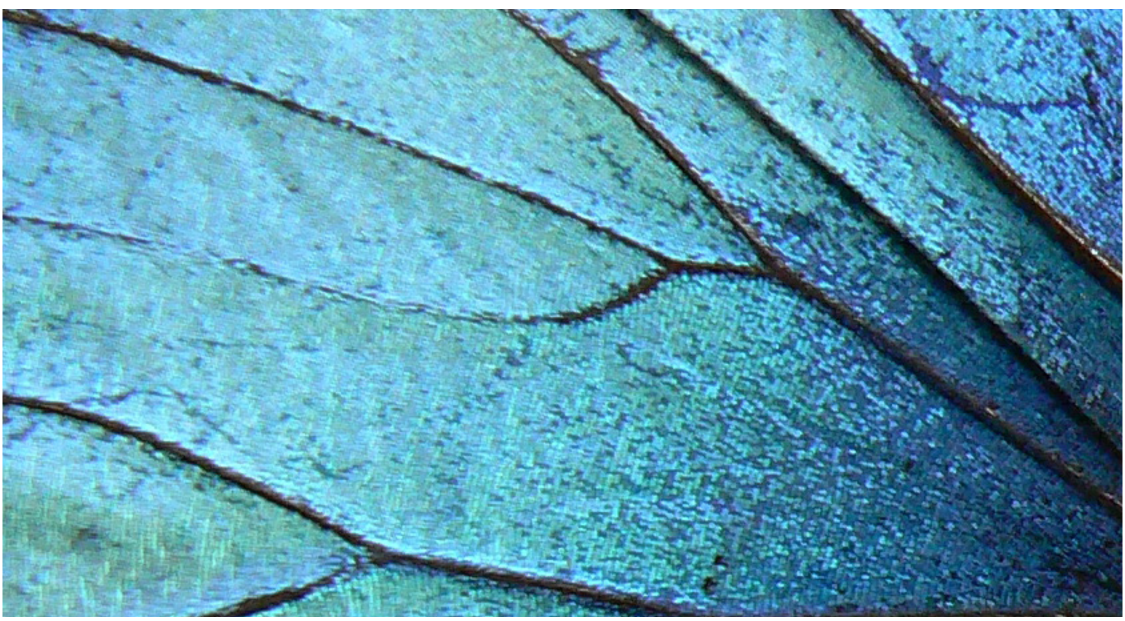
Photo: Johnwalton, 2007 | Wikimedia Commons



Interference of light waves reflected from front and back of thin parallel film

Image: Colin McDonald, 2013





A = two light waves in phase (reinforcement)

B= light waves out of phase (cancellation)

Image: Colin McDonald, 2013

Morpho

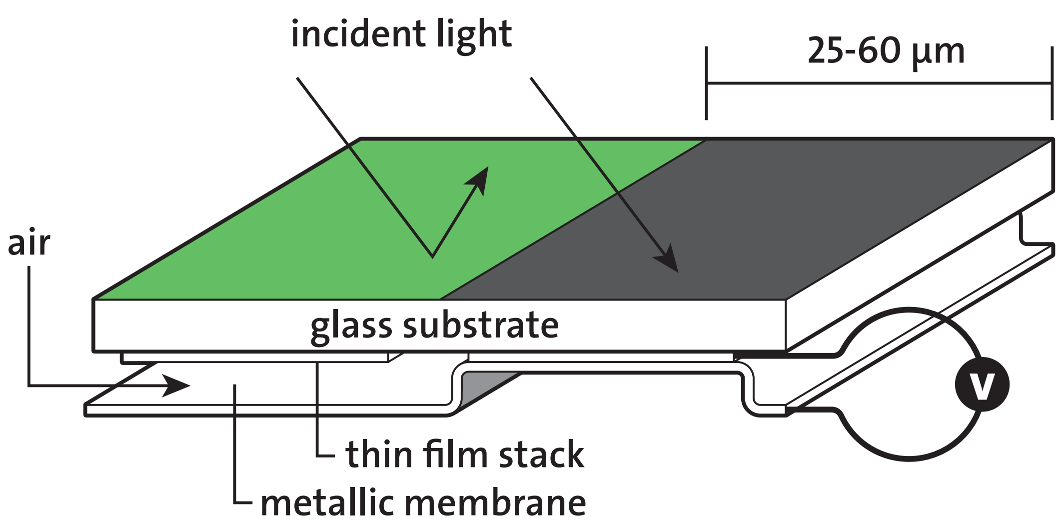
Photo: e$^{3\circ\circ\circ}$, 2007 | Flickr cc be both reflected off the top and penetrate into the gap, where it would be bounced about. The wavelengths not in phase with the gap would be cancelled out via interference. The designed wavelength would escape the gap through the upper film and be seen as a color. The films were flexible, so that when an electric charge was applied the bottom layer would bulge up to meet the upper, close the gap and create a black tone. The unit cell would remain black without any energy draw until another charge released the film and the unit reverted back to its original color.

Iridigm had developed a workable, paradigm-busting innovation in the form of some crude prototypes, but, after several years of bump-along development with very little capital, was making slow progress. One of their investors from San Diego offered to buy the company outright. It was Qualcomm.

The Market Field of Play

Qualcomm renamed the operation the Qualcomm MEMS Technologies unit and spent nearly four years developing its screen technology, now dubbed Mirasol. It was presented as an alternate to Pixel Qi and Color e-Paper, competitive technologies based on entirely different paradigms. The plan was to introduce an era of low-power color displays for smartphones, tablets and e-readers that could be read in full sunlight.

It was a crowded and dynamic field with a range of competing technologies typifying a new industry with clear profit potential. In 2009, ap-



Mirasol color sub pixel showing two states

Image: After Mirasol, Colin McDonald, 2013

Blue Morpho Butterfly, Santa Elena
Photo: ClifB, 2009 | Flickr cc

Barboleta (*Morpho rhetenor*)

Photo: Roberto Mourão, 2012 | Wikimedia Commons proximately 4.9 million e-readers were sold and the projected compound annual growth rate was reckoned at a saliva-inducing 58%. The introduction of the Apple iPad in April, 2010 made the trend toward an integration of capabilities seem inevitable. Consumers now expected what manufacturers would soon be able to deliver: internet, video, color graphics, text, all delivered with speed on a mobile, intuitive device. Market acceleration was being driven by the widening availability of content and the software and hardware to access it.

With this trend toward capability convergence came a shifting in the criteria for success. Users now wanted to read, browse the web, watch a movie, and communicate in voice and text on one device that would also tell them where they were and how to get to where they were going. Balancing these capabilities in a successful, optimized package seemed to have become the game. Within this technology-driven market the contention was fierce because no one technique could do it all: provide low cost, long life, rich color, viewability and speed. There were six main competitors:

Liquid Crystal Display (LCD)

LCD technology was the clear leader in the overall display market. The technique used a type of liquid crystal known as a twisted nematic (TN). In LCD's each pixel was subdivided into red, green and blue units and these colors were polarized and filtered for the ultimate image. In active matrix LCD's, each subunit had its own transistor. The iPad was introduced with a type of this thin-film transistor (TFT) enhanced with in-plane switching (IPS). IPS was an improvement over the twisted nematic approach; it aligned the liquid crystal in a horizontal direction and allowed the switching voltage to be applied through each end of a crystal. LCD's performed well overall; in color, video rate response time, but used a lot of energy because the transistors were continually pulsing. Moreover, the backlit screen became washed-out in direct or bright sunlight.

Electrophoretic Display (EPD)

Typically, EPD's employed millions of charged capsules suspended in a clear fluid between two parallel electrode plates. When a charge was applied to the pixels within the plates, positively charged capsules would show white and negatively charged capsules would show black. Alternately, white capsules were suspended in a black-dyed oil and selectively electrifying the plates would cause a migration of reflective white to the top, pixelated plate, where it would be read against the lower background of black. The advantages of this system were that it was bi-stable, and did not require energy to maintain states, only change them. The drawbacks were in the lack of color and the disproportionate amount of energy needed to refresh video. Most e-readers, including the Amazon Kindle, the Sony Reader, and the Barnes and Nobel Nook, used this technology. E-ink has since developed the E-ink Triton, an EPD with the addition of a color filter.

Transflective LCD - Pixel Qi

This was a traditional LCD with an additional operating mode, a low-power, reflective monochrome display. The device used a backlight and polarizer when in LCD mode or reflection when in the so-called e-paper mode. Each sub-pixel, then, was able to toggle between modes, but while the e-paper mode relied on reflectivity, the device was not stable in each mode and therefore drew power to maintain the modes as well as to change them.

Organic Light-Emitting Diode (OLED)

An OLED was a light-emitting diode made up of multiple layers of different organic semiconductor materials with electroluminescent properties. These semiconductors were sandwiched between two conductive layers. OLED's emitted red, green and blue visible light from individual LED's at each pixel. A typical OLED required an anode, cathode, a substrate, an injection layer and an emissive layer. The anode, typically indium tin oxide, was transparent. The power draw of the display was directly proportional to the brightness of the image and the need for several transistors at each pixel reduced the light aperture and increased the need for power and a more complex design. OLED's were used in a variety of cameras, phones and small televisions.

Interferometric Modulator (IMOD) - Mirasol

IMOD combined thin-film optics and MEMS to create an optically resonant cavity that included an air gap separating a stack of optical thin films from a moveable reflective membrane. The optical gap selected between the moveable membrane and a partial reflector within the thin-film stack caused both destructive and constructive interference. The wavelength of the constructive interference determined the color reflected. Adjusting the gap determined whether the color was red, green, or blue. The IMOD technology was a reflective method that was bi-stable and required natural light to work. In situations with low light, front-lighting was needed.

Electrowetting (EWD)

EWD used three optical modes (transmissive, reflective and transflective) and colored oil as an optical switch that moved with changes to electric potential across two electrodes for each pixel in a display. When not electrified, the oil spread into a continuous film that was viewed as a color. When charged, the oil was pulled into a droplet that contracted into a shielded edge of the pixel, so that it appeared transparent. An active matrix of transistors was needed as a backplane to retain the colored oil films' optical state for each pixel. Liquidvista was the industry leader in this technology, but was still planning commercial products in 2010.

The Mirasol Campaign

When Qualcomm acquired Iridigm it had what it thought was a disruptive technology that would be both cheaper to operate and to make. "The convergence of consumer electronics products, including cameras, MP3 players, camcorders, GPS receivers and game consoles, into wireless devices is driving the increased adoption of 3G CDMA," said Paul Jacobs, then executive vice president and president of Qualcomm's Wireless & Internet Group, in a statement. "Our acquisition of Iridigm will accelerate the time to market for the iMoD technology, which fits Qualcomm's overall strategy of rapidly increasing the capability of wireless devices while driving down cost, size and power consumption."

The company built a state-of-the-art R&D facility in San Jose, California and spent years perfecting the manufacturing technique. In 2009, it entered into a joint venture with Foxlink (Cheng Uei Precision Industry Co.) to manufacture the display. Development dragged on, and in 2011 the advertised first quarter launch of a Mirasol e-reader was postponed, and, that summer, cancelled. CEO Jacobs was not happy with the product they had, and said that they would "...focus on the next version of it." Mirasol was getting a reputation for being "perennial vaporware", and rumors of production problems were rampant.

In November of that same year the company announced its plans to build its own fabrication plant in Taiwan and planned to commit $975 million to the effort, with production scheduled for 2012. A limited run of 5.7 inch displays was made for the Kyobo e-Reader of South Korea. In all, four Asian companies ordered the display: Havon, Bambook, Kyobo, and Koobe. All of these readers or tablets were built on the Google Android OS platform.

By early 2012, Qualcomm had acquired yet another display startup and yet another technology. This time it was Pixtronix, Inc. of Andover, Massachusetts, for a reputed $175-$200 million. The company had developed a low-cost display technology prototype called PerfectLight. The display was activated by a MEMS-based digital micro shutter that modulated light from an RGB LED backlight.

This emissive technology was a marked contrast to the Mirasol reflective mechanism, and, at least on paper, had some qualities that Mirasol did not. A high switching speed made it applicable to full-speed video as well as e-reading. Pixtronix claimed that the display offered greater than 170 degree viewing angles, more than 3,000:1 contrast ratio and 24-bit color depth. Mirasol had compared unfavorably to LCD readers in color presentation, viewing angle, contrast and video refresh speed. Moreover, Pixtronix was claiming to use only one quarter of the power consumption of equivalent size and resolution liquid crystal displays.

In the summer of 2012, Jacobs made his announcement to the industry analysts. Qualcomm, despite having just built a $700 million fabrication plant and spent eight years in development, would cease production of the Mirasol display.

Qualcomm has continued to promote the Mirasol technology at recent tradeshows.

At the SID Display Week in June, 2012, for instance, the company showed three different prototype Mirasol displays: a tiny, 1.5-inch model, a smartphone-sized 4.3-inch model with a 720p resolution, and an updated version of the 5.7-inch, 1024 x 768 display. It has not, however, manufactured a commercial tablet-sized screen larger than 5.7 inches, or solved the significant drawbacks of low color, slow refresh rates, and by some reports, low quality assurance rates in the production line. It seems clear, with the recent announcement of production cancellation and the acquisition of another display technology, that the company has changed tacks in its quest for the mobile device market.

Some Possible Lessons

The iMoD technique of extracting color from white light without the use of much energy is still a very innovative and potentially useful device. Profitable applications for it, however, seem to lie outside of the current, mainstream mobile device market. There, bright color and speed seem to have trumped energy saving and sunlit viewing. User expectations and their study were perhaps underestimated by a company traditionally in the hardware business.

Although the market was driven by technological innovation and filled with hopeful contenders, there was still a significant entrenchment of interests. LCD's were more firmly established with the large players like Motorola, HTC, Samsung, and LG. While production uncertainties were to be expected with Mirasol, the manufacture of LCD's was well understood while still allowing for improvements. During the long development of Mirasol the entrenched LCD contenders had become more competitive by reducing semiconductor power consumption, making batteries lighter and switching their backlighting from cold cathode fluorescent lamps (CCFL) to LEDs. While the logic of the need for power saving was still sound, it seemed to become less critical and less of a counterbalance against some of the shortcomings of the Qualcomm product.

Similarly, over this development timespan, the requirements for devices had changed. Converging capabilities, although foreseen by Qualcomm, created a wider range of performance criteria and raised the bar on metrics like video refresh speed. Each technology contender had to optimize its overall performance, and no one technology seemed to do it all. Performance below adequacy in any one of the criteria could mean the end of contention. Mirasol, reputedly, could only run 60 Hz video, and this refresh rate drained the battery that the technique was supposed to be conserving.

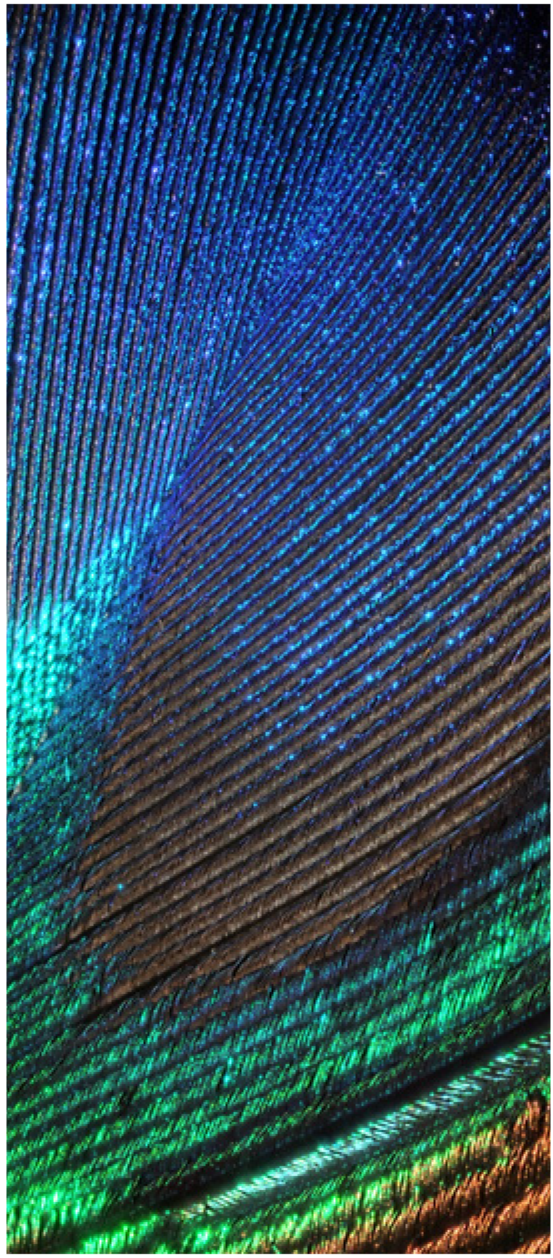
Cost of production was critical to success and would ultimately be weighed against value gained by any potential clients for a display screen. For example, the EPD technology, described above, rules the black and white world of e-readers with 95% of the non-tablet market. Although likely to be replaced by multi-functional devices like tablets, e-readers have been successful because they appeal to the user with a clear image, wide viewing angle, reflective character, and longer battery life. They are also very affordable. The main reason is that they can be manufactured using a roll-to-roll printing technique, in which a substrate can be spray-coated, micro-embossed, filled and sealed and then cut to shape; all in one continuous production sequence. The production of Mirasol by contrast, has apparently required much more precise tolerances in the laying of the glass substrate, sandwich pillars and wavelength gaps, evidenced by the need to build a $700 million dedicated fabrication plant.

The Mirasol iMoD technology as an idea continues to hold lessons for bio-inspired designers and problem-solvers. It is a great example of "surfing for free", taking advantage of natural environmental phenomena to save energy by harvesting free, ubiquitous light for its color through precise manipulation of form and space. It is an excellent translation of this example from the Morpho butterfly because it mimics the principle of light diffraction without trying to slavishly replicate the means. Finally, the development of the technique required the combining of several disparate ideas and processes into a totally new combination: innovation at its best.

Perhaps that same innovative thinking might be brought to bear on a re-purposing of the technology for a different market. iMoD might be described as “a bistable, low-energy signaling device that yields colors in broad daylight when other technologies fail”. The potential applications appear to be many, from navigation aids to billboards to the walls of your home.

The application targeted by Qualcomm does not define the possibilities for this method, although it has shaped its history within one market. The mobile display market will continue to change and with that change will come a new set of parameters for success. Observing the processes of this technology market and how bio-inspired innovations might fit within its dynamics will also continue to be a fascinating subject.

More interesting, however, will be to see to what use someone puts this disruptive technology that bends natural light into a patterned choice of colors. ×



Peacock feather

Photo : Thomas Bresson, 2011 | Wikimedia Commons

Young chestnut leaves nestled in pine tree

Photo: christiane wilke, 2012 | Flickr cc

Opinion

Why Don't Solar Panels Look Like Trees?

Steven Vogel

spring 2013 | Opinion

Author:
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Why Don't Solar Panels Look Like Trees?

Steven Vogel is James B. Duke, Professor Emeritus in the Department of Biology at Duke University, Durham, North Carolina, USA. He is the author of several books on biomechanics including *Cats Paws and Catapults*, *Comparative Biomechanics*, *Life in Moving Fluids*, *Prime Mover: A Natural History of Muscle*, and *The Life of a Leaf*.

"I think that I shall never see, a poem lovely as a tree." Even the non-bucolic and non-pastoral among us have shared the century-old sentiment behind Joyce Kilmer's words. For that matter, nature shares the sentiment, too. Tree-like plants of wood have evolved repeatedly, and include the largest organisms that have ever existed. A tree provides wood, long our most versatile structural material, seeds and fruits we find nourishing, cover against excessive solar exposure, and shelter against erosive and chilling winds. A tree, then, must obviously be a good design, one suitable for large-scale structures—such as we humans construct.

Or should we regard their design as terribly flawed? A hundred feet of trunk gets the photosynthetic machinery no nearer the sun, reflecting simply the inability of trees to collectively negotiate a trunk-limitation treaty. That height requires an enormous and ultimately non-productive investment in wood. It also means giving the drag-prone crown a long lever arm to facilitate breaking the trunk or wrenching the tree from the ground.

Leaves are typically divided, thin, and flexible, since they deal with the problems of weight aloft and, for many, the cost of annual replacement. They are arrayed in layers because they appear unable to form a continuous absorptive surface. Moreover, they are held out on expensive branches protruding from a single trunk because almost no trees form efficient, braced frameworks.

Trees lift prodigious quantities of water, quantities far beyond what photosynthesis requires (for some reason water must diffuse outward if carbon dioxide is to move inward), even if the rates involved vary widely. They do this peculiar task with a unique, solar-powered pump having no moving parts. One can easily cite many more examples of their oddly problematic features.

Sequoia

Photo: David Glover, 2008 | Flickr cc

Spirals

Photo: Jiggs Images, 2007 | Flickr cc

These features, however, while arguably dysfunctional in the abstract, "make sense". Indeed, they must make sense as the ipso facto products of natural selection. An organism has little functional reality out of its evolutionary and environmental context; concomitantly there's little sense looking for functional devices without taking the context into immediate account. No amount of antiquity or ubiquity can make the design of a tree attractive for our solar panels, whether for generating heat, power, or photosynthesized chemicals. By contrast, the details of the design may hold more lessons for us than the overall scheme.

Consider that trunk. In comparison to our structural columns, trunks, especially young ones, flex easily. Most are solid, not hollow, thus avoiding the problems of ovalization and local buckling of our hollow tubes. Hollow bamboos culms, by the way, minimize the problem with the stiffest (highest Young's modulus) of woods, as well as preventing ovalization with periodic diaphragms.

Typical tree trunk design offers multiple instructive details. As structures of anisotropic material with lengthwise fibers (as in our fiberglass), they withstand tension better than compression. Compensating for that is prestressing in tension: when saw bites trunk, the kerf opens rather than binds. As non-hollow columns, they are minimally sensitive to surface abuse or crack initiation, covering themselves with stretchy skins, divided soft bark that absorbs blows and provides a fire barrier, or overlapping scale-like coatings. As flexible structural columns, they are not only prestressed but often surrounded with a thick and continuous bark whose Poisson's ratio is close to zero, not the 0.3 typical of ferrous metals or the isovolumetric 0.5. Thus bending the columns does not cause buckling on the concave side. We take advantage of cork's peculiarity when we make cylindrical stoppers from it, ones that can be pushed inward without causing temporary girth increase. If we do want to build columns that are flexible or that might have vulnerable surfaces, then some of these devices might hold attraction.

Wood itself would be considered strange and wonderful were it not so familiar. Even dried and sliced it retains peculiar mechanical properties, often a nuisance for carpentry and cabinetry. For instance, an elongate piece of wood typically twists more easily than it bends, with a twistiness-to-bendiness ratio about four times higher than that of our ordinary metals and plastics. In nature that probably makes a tree less vulnerable to the torsional loading that will occur in irregular winds or on trees with asymmetrical crowns from breakage or bad pruning. By instructive contrast, the woods of roots and vines twist and bend in more familiar ways. We ought to find lessons of particu-

Tree Bark

Photo: Leonard John Matthews, 2009 | Flickr cc lar value here: in the way in which the structural anisotropy of a trunk contributes to this unusual behavior and as anisotropic composites become ever more efficiently manufactured.

Consider those leaves, in particular the familiar deciduous ones. To intercept the most sunlight with the least material, they must minimize thickness. If they are to be shed annually, their investment in material should similarly be kept low. Both considerations suggest flexible rather than rigid structures.

Thin, flexible structures of great surface area exposed to wind might impose high drag on their supports, as do flags. Leaves minimize this by reconfiguring into low-drag shapes during periods of high wind. They are also likely to be prone to tearing, fraying, and shredding. Besides keeping down drag, anisotropic fiber reinforcement helps minimize these disabilities. What leaf can readily be torn across? Moreover, the edges, especially of indented parts of leaves, have an extra edge, giving some three-dimensionality to their flatness and increasing the difficulty of starting a crack, whether from wind or herbivory. If we want to make thin, cheap, structures for whatever purpose, some of leaves' devices suggest themselves—flexibility, extra edge, anisotropic fiber reinforcement, specific stress and turbulence-minimizing shape reconfiguration.

Less widely appreciated than the mechanical problems of leaves are their thermal challenges. Both sides of the energy balance sheet test their designs. Structures that must expose themselves to sunlight to function at less than perfect efficiency cannot avoid some thermal load. Even modestly elevated temperatures disable structures whose functional components—enzymes in particular—consist of thermolabile proteins. Yes, they do some evaporative cooling, but all too often the enormous expenditure of water is no option. Leaves avoid about half their potential heat load simply by not absorbing sunlight arriving at wavelengths too long for photosynthetic use; the near infrared, specifically. Convective cooling plays a major role, but it becomes problematic during lulls in the local air movement, especially since these thin structures have short response times, often heating by a degree every few seconds.

A suite of tricks in a variety of combinations almost always suffices to prevent thermal death. Many leaves have shapes, often lobed or elongate, that couple them to what air movement does occur and to their own upward free convective flows. In water-deprived places leaves are commonly small, which improves convective coupling, and thick, which increases their response times and thus lowers peak temperatures during brief lulls. Thin, non-lobed leaves commonly

Wet Leaf

Photo: Faustas L., 2006 | Wikimedia Commons

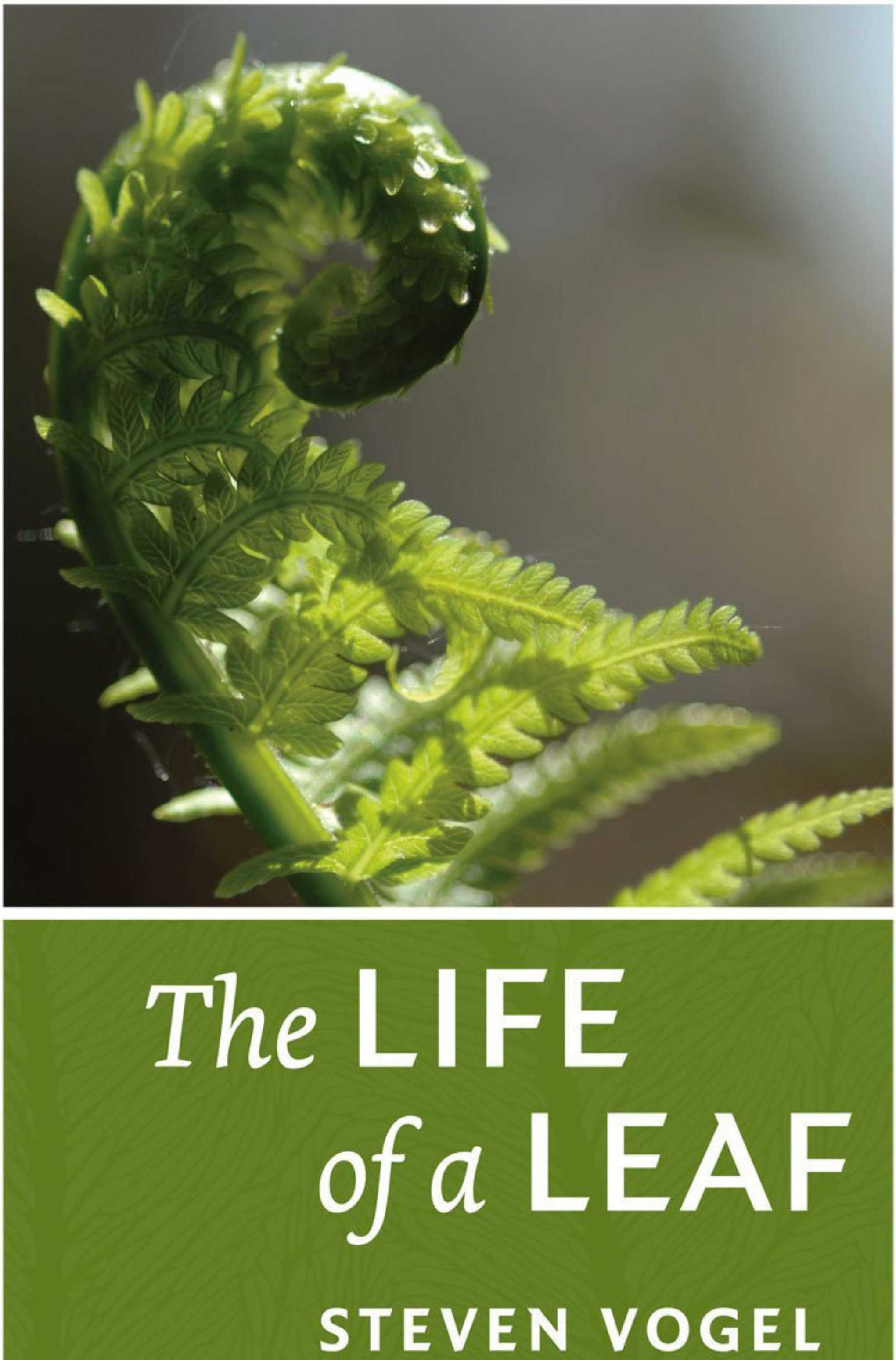
droop downward when hot and water-deprived, thus both reducing exposure to sunlight and improving convective coupling.

Still more subtle tricks deserve mention. Prolonged retention of water on the surfaces of leaves appears to be something they prefer to avoid, perhaps for its weight, perhaps for the growth of microorganisms it encourages. The hydrophobicity of leaf surfaces has received great attention recently, in particular because many are “superhydrophobic” — better than ordinary waxy surfaces, achieving this by combining chemical coatings with physical texturing. A feature recognized long ago was the shape of leaf tips, elongate and pointed, to shed the collected drop. A leaf with such a tip cut off retains more water. The long leaf tip is most common among leaves in tropical forests, where wetting may be at its worst; it is uncommon among higher latitude leaves, perhaps because the very tips that promote shedding of liquid water would promote formation of heavier icicles. We might well use such devices for structures that we prefer to shed water or to air-dry quickly.

For that matter, trees manage admirable control of local hydrophobicity. The mechanism by which sap is pulled up works only if the inner walls of the conduits, the xylem, are highly hydrophilic; otherwise those walls would provide nucleation sites and lead to rupture of the continuous liquid columns with their extreme negative pressures. The walls of the cells that line the air spaces within leaves must be similarly hydrophilic so that surface tension at their air-water interfaces can prevent air from entering the system and similarly disrupt the liquid columns. At the same time, the outer leaf surfaces, as already noted, work best if highly hydrophobic. Thus only a few micrometers separates surfaces of extremely different properties. Yes, we do worry about surface tension, but we do not often (if ever) build devices making use of both extremes in such close proximity, never mind devices that subject liquids to negative pressures of many atmospheres.

No, solar collectors should not look like trees. Starting with their terribly expensive height, too much of a tree’s design solves problems of no concern to us. Trees are “a triumph of engineering over design”, as put by biologist Martin Wells (of a family of facile phrase-makers) in an analogous context. They are, in so many respects, making the best of a bad deal. In that best effort, however, lie all manner of technologically attractive details. ×

The material for this piece comes from *The Life of a Leaf* (University of Chicago Press, 2013).


The LIFE
of a LEAF
STEVEN VOGEL

The Wake

Photo: Malene Thyssen, 2004 | Wikimedia Commons

Book
The Shark's Paintbrush by Jay Harman

Reviewed by Janet E. Kübler, Kamelia Miteva and Curt McNamara

spring 2013 **Book review**

Author:
Janet E. Kübler, Kamelia Miteva, and Curt McNamara

The Shark's Paintbrush

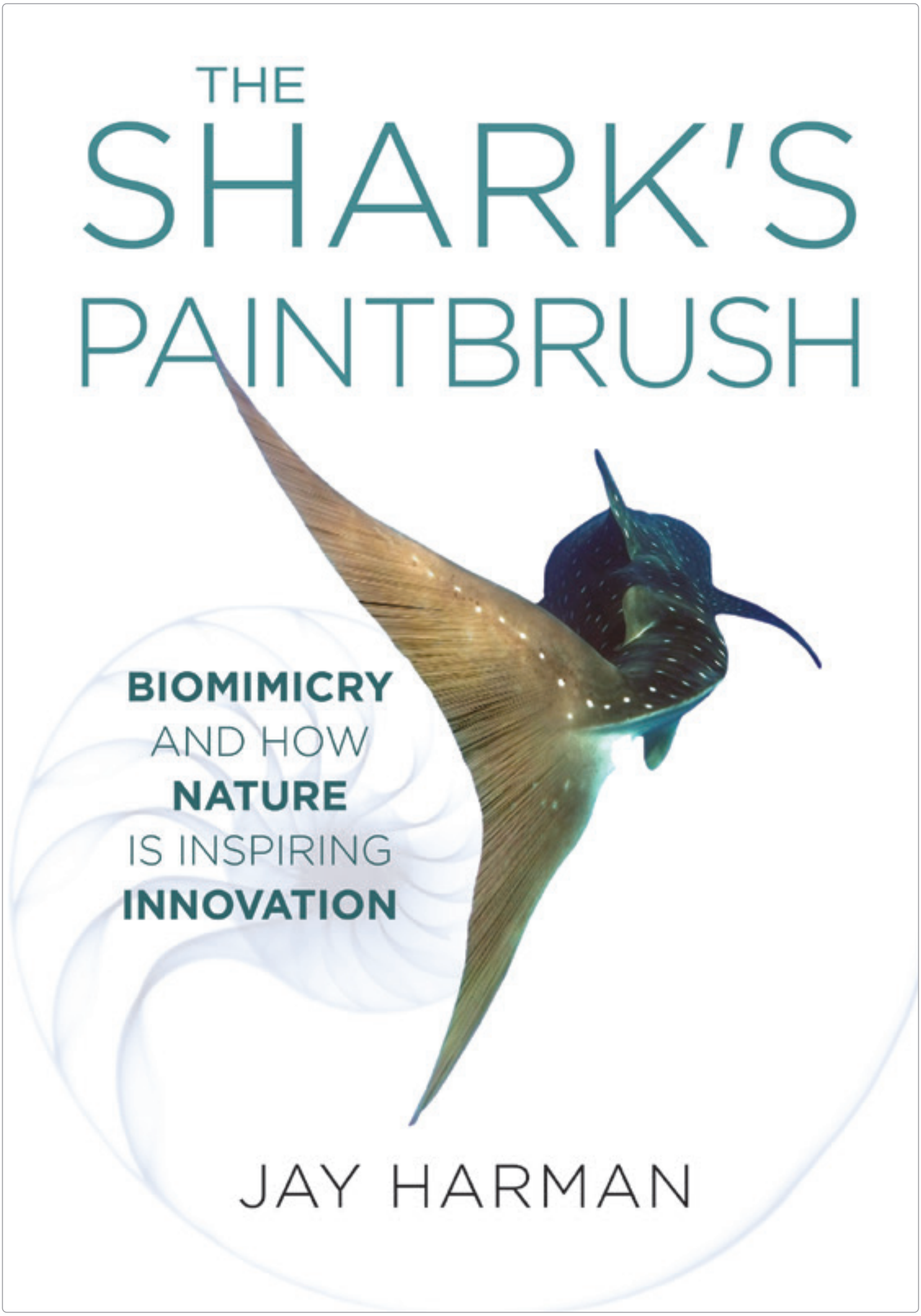
Biomimicry has been the darling of visionaries and dreamers who grasp its implications and who have been impatient for its innovative products to start rolling into everyday use. Harman, one of those visionaries and also the CEO of a groundbreaking biomimetic company, provides a pragmatic update of the vision in his new book, *The Shark's Paintbrush*.

This is a new kind of biomimicry book: equal parts memoir, explanation of biomimicry principles, and business advice. Harman tells the story of his life in business along with his passion to make a difference and his inspiration from nature. He relates the evolution of his biomimetic design in a market which values the tried and true. He also advises on the personal, business, and naturalist strategies for realizing great biomimetic ideas. With quotations and case studies from many of the early industrial success stories, Harman brings us into the small circle of businessmen and women who have paved a way for biomimicry in business.

Harman is motivated by his hope that we can produce technology in a sustainable way, despite our current environmental crisis. He holds the opinion that nature is the foundation from which humans thrive as species and, once we realize its full potential, we can survive for a very long time. He blends the personal, pragmatic and conceptual in a growing spiral of vision, implementation and scope. He hands the reader his personal evolution, evolution of the business of biomimetics and an analytical vision of where the study of natural flow and fluid dynamics has the most potential for the future.

His perspective should be invaluable to the new practitioner of bio-inspired design. Biomimicry is inherently interdisciplinary and we cannot expect any one person to embody all the knowledge and skills needed. Harman emphasizes the importance of translation between fields and sectors, building a strong team, and the ways that effective teams can use the Biomimicry 3.8's "Life's Principles" in their operation.

The middle section of the book gives an impressive tour of biomimetic success stories. The examples related to fluid and aero dynamics, in particular, show the author's understanding of his subject. We also get advice from others. For example, in Chapter Four Stephan Dewar of WhalePower advises on ways to secure funding for R&D, and survive economic trends, while Harman analyzes what makes the most sense in the WhalePower business plan. Chapters Five and Six contain a lighter treatment of more case studies of biomimetic technologies at several different levels of development (mostly at the research stage). These are interspersed with charming anecdotes of adventures in and around wilder nature. Chapter Seven covers fungi and bio-remediation, biofilms, the Lotus Effect®, photosynthesis, inspiration from seeds,


THE
SHARK'S
PAINTBRUSH
BIOMIMICRY
AND HOW
NATURE
IS INSPIRING
INNOVATION
JAY HARMAN

and patterns in limbs, veins, structures, and fibers. Chapter Eight includes a discussion of eggs, shells, bones, and coral. Harman writes that "even a common garden snail can teach us about nanotechnology, optimized balance, minimization of materials, streamlining, defense, camouflage, and aesthetics."

There are places in the book where the text could have been improved by a critical review from a biologist. Overall, however, we are inspired to a sense of awe of both natural diversity and of the myriad ways that humans are interpreting nature in technology.

The author is on firmer ground when he discusses his company and its business evolution. PAX Scientific is an intellectual property-creating research and development company. The company relied initially on angel investors, and Harman wanted to licence the technology to industry leaders who would deploy it through their own companies. He soon realized, however, that PAX needed to produce real products to compare to traditional ones.

Harman created the PAX pumps and propellers via experimentation with whirlpools, and they exhibit the uncanny beauty of mollusc shells and plants. Indeed, his business journey is entwined with his study of spiral shapes found in nature, with examples ranging from spirals in the human heart, to the DNA double-helix/spiral, and in the drawings of different tribes spread throughout the world. He believes that everything in the universe travels in spirals, and never in straight lines, and that studying spirals is important as fluid dynamics is widely used in our transportation systems and many industrial processes.

Harman states that there are three key differences between traditional and biomimetic businesses: (1) the inter-disciplinary nature of the work, (2) that biomimics often want to change a well established way of doing business, and (3) biomimetic business is more like planting an orchard than a crop of tomatoes. He has tried a variety of business models including licensing, grants, working with established companies (and the military), and production. His advice includes planning for patience, teaming with highly respected established professionals, and starting an engagement with the legal department of a company first. He recommends choosing a business model that gives access to end users, notes that sales to end users are more effective than licensing, and that designs should be patented. Finally he reminds the reader to keep it simple, and that the path to business success is like a sailboat on an ocean crossing. He discusses angel investors, venture capitalists, and government grants, each of which has its own benefits and drawbacks. Readers will benefit from the fact that he relates stories of failures as well as successes. Harman concludes the book by showing how the Biomimicry 3.8's Life's Principles can be applicable to the creation and operation of a business. The book includes an extensive list of references.

Overall, this is a tour-de-force combination that includes memoir, a broad overview of biomimicry, a detailed review of spiral geometry and its applications, views on creating and running a transformative business, and practical advice on using biology to build an effective organization. Our review team recommends this book to anyone interested in biomimicry.

snail

Photo : tmankartz, 2012 | flickr cc

Janet E. Kübler, Ph.D., marine biologist and coauthor of *The Algorithmic Beauty of Seaweeds, Sponges and Corals*, has been involved in biomimicry since training as a Biologist at the Design Table in 2004. Currently a research scientist at California State University at Northridge, she divides her time between California and Maine.

Kamelia Miteva (http://www.linkedin.com/profile/view?id=92463423) is a creativity consultant who trained as a biologist, is passionate about biomimicry and teaches biology to children. She founded Bulgaria-based Bio Games (http://www.f6s.com/biogames) that offers interdisciplinary education in biology and ecology with elements of biomimicry in the form of workshops for kids, laboratories in biomimicry for adults and adolescents, and design of educational programs in the sciences.

Curt McNamara, P.E. (BSc/University of Minnesota, MEng./Portland State University) is a practicing designer with 30 years experience in medical, commercial, and industrial markets. He is a scholar of R. Buckminster Fuller and authored the entry on Fuller in the UNESCO Encyclopedia of Life Support Systems. Curt created and teaches the Systems course for the Minneapolis College of Art and Design Sustainable Design certificate.

Publication Details

The Shark's Paintbrush: Biomimicry and How Nature is Inspiring Innovation by Jay Harman

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Beach_Bokeh

Photo : @Doug88888, 2008 | flickr cc

Dragonfly eyes

Photo: sunxez, 2010 | Flickr cc

People

Interviews with

Dayna Baumeister, Larry Stambaugh & Laura M. Ferguson

Flower

Photo: asperic.lens, 2009 | Flickr cc

Interview
Dr. Dayna Baumeister

Interview with Dr. Dayna Baumeister

With a background in biology, a devotion to applied natural history, and a passion for sharing the wonders of nature with others, Dayna has worked in the field of biomimicry with Janine Benyus, author of *Biomimicry: Innovation Inspired by Nature*, since 1998 as a business catalyst, educator, researcher, and design consultant. Together they founded the Biomimicry Guild, The Biomimicry Institute, and Biomimicry 3.8, collectively fertilizing the movement of biomimicry as an innovative practice and philosophy to meet the world's sustainability challenges. Dayna designed and teaches the world's first Biomimicry Professional Certification Program and has compiled over a decade of experience in biomimicry into the *Biomimicry Resource Handbook: A Seed Bank of Best Practices* (2013). Dayna received a BS in marine biology from New College in Sarasota, Florida and earned an MS in resource conservation and a PhD in organismic biology and ecology from The University of Montana.

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

Over the last 15 years of working in biomimicry, I have watched this field grow faster worldwide than is possible to track. When Janine [Benyus] first captured in the '90s the stories of the practitioners that she shared in her book, the practice didn't even have a commonly understood name assigned to it. By naming it and promoting the practice through our efforts at the Biomimicry Guild, The Biomimicry Institute, and now through Biomimicry 3.8, as well as the efforts of others via various different avenues around the world, we now see a wide array of activities in the field ranging from the National Science Foundation in the US specifically funding proposals focusing on biomimicry, scientific journals devoted to the field, popular magazines like *Zygote Quarterly* (of course!) that seek to deepen our understanding of biomimicry and bio-inspired design, special sections of conferences in academics, industry, and for the general public, and even more recently entire conferences devoted to biomimicry. Our biomimicry case studies database has over 800 examples ranging from early research to on the market.

What's particularly interesting is for those who are heavily involved in the field, what we call the practice and what we mean by it, actually varies quite widely. While some media state that bio-inspired, biomimicry, biomimetics, bionics, bionik, and all the non-English translations mean the same and are the same practice, and indeed some do use the terms loosely and interchangeably, I've noticed that there are some significant differences, and these differences may ultimately frame the long-term outcome of the practice. Where we focus our design energies and to what end certainly will influence the future of the field.

Of course, what the practices in common (no matter how they are named) hold is learning from nature. What I'm personally passionate about, and actually quite relieved to see is that more and more of the efforts in this realm are fo-

dragonfly#4 | Photo: join the dots, 2010 | Flickr cc cusing their time and energy on using the practice of biomimicry or bio-inspired design to both solve some of the worlds most pressing environmental challenges, and are doing so in a way that is also sustainable. In other words, we have to ask ourselves, what's worth doing? And if we learn from nature to build another robot that while innovative and sexy, actually causes harm either from its toxic manufacturing processes, or consumes far too many non-renewable resources, or makes us better warriors, what have we actually learned from nature about creating conditions conducive to life?

When we teach biomimicry at Biomimicry 3.8, we share three critical essential elements of biomimicry: ethos, reconnect, and emulate. The ethos component is the sustainability focus, both social and environmental. We can't imagine asking nature for advice and not using to help humans become better adapted for the long haul. Reconnect recognizes that humans are nature, but we've managed to create a divide that may ultimately do us in as a species. Reconnect seeks to literally mend that rift by embedding in the practice of biomimicry both a quieting of our cleverness and learning and practicing deep observation of nature. Outside. By leveraging our desire and need to reconnect with the natural world, we can simultaneously foster the emergence of a world empowered by nature's genius and heal ourselves. Getting out of the labs, the design studios, and away from the computer, and spending time in the natural world observing and learning from the amazing strategies that have been evolving over the last 3.8 billion years, then and only then are we really practicing biomimicry. Lastly, emulate recognizes that it's not a direct copying of nature, but rather the abstracted design principles that ultimately hold the most promise. Recognizing context (of the original biological strategy) and what I call "evolutionary baggage", our job as biomimics is to apply those design principles in a finessed way that is still true to the science, but uses our technical expertise to test out the best applications of those strategies.

So where is the field evolving? Not surprisingly, the field as a meme seems subject to the laws of natural selection. I see local adaptation, niche differentiation, naturalization, mutations and cross-pollination. I see incredible opportunities for deepening the practice and taking its full potential into all aspects of human design. By asking not just what nature can teach us with regards to forms and structures, but also asking how we can learn from processes, systems, and time-tested universal principles (Life's Principles), we have the opportunity to reconfigure how we as a species exist on this planet. But this requires that we start by listening, building on what works, use our best innovative thinking and interdisciplinary problem solving, and recognize the larger system dynamics in which our strategies must thrive. I believe this is one of the most exciting times we as a species have ever experienced on this planet. I also believe biomimicry can play a significant role in how the next century unfolds.

What do you see as the biggest challenges?

I touched on some of these above, focusing more on those currently engaged in the field. However, as a whole, I do see that some of the biggest impediments (but certainly not the only ones) to

Aspens | Photo: Andy Atzert, 2009 | Flickr cc biomimicry have less to do with biomimicry per se and more to do with externalities and human tendencies like:

1) the current political and economic climate globally causing many to rely on old paradigms ("but they worked before…"),

2) the tendency of humans to focus on short-term feedback loops (which evolutionarily makes sense, and worked well for us when our ability to impact the world was limited),

3) the growing divide between the amount of time we spend in nature and time we spend with technology, and

4) our current focus on certain leverage points in humans systems that while more "manageable" have relatively limited impact (e.g. the focus on metrics) as compared to those that are more challenging (e.g. paradigm shifts) but far more impactful.

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

To advance the discipline of biomimicry beyond the exponential growth we've seen thus far, and past the early adopters and innovators, we need:

1) More interdisciplinary training. We need biologists, designers, engineers, business people, policy makers, and any one else involved in the practice to be able to communicate and work with each other. This entails not just translating language, but understanding how each of these disciplines works, how each can contribute to the practice of biomimicry, and how biomimicry can be integrated into each discipline. I believe without this the field will not succeed.

2) Great access to biological information. Our website, AskNature.org, has over 1800 biologically-based strategies listed, but it currently contains a small fraction of what Life has to teach us. We are currently engaged in creating AskNature 2.0, both increasing the strategies and making the biological information more accessible, but to really do it right, it's a project as big as the Human Genome Project, built not by one entity but hundreds of universities and research labs and field stations worldwide collecting data and contributing to the global database. What would happen if we had as much interest about other species as we have in our own DNA? And it goes far beyond just gathering and translating the information currently available in the biological literature, but it also means directing our research efforts to understanding more about the strategies and mechanisms of Life's genius. Imagine how many biologists would be elated if they were told we now value your field observations more than your genetic assays. Get out of the lab and become a naturalist again!

3) Time to deepen the practice. If you've been practicing biomimicry for any length of time, you've probably come to realize that this work takes time. The stories shared in the media can create a sense that one walk in the woods led to an ah-ha, and a new biomimetic design was born. The reality is far different. Dr. Frank Fish's tubercle-inspired turbine blades for Whale Power actually took ten years from his first observation of the humpback (a sculpture at that) and the first business-viable prototypes. Creating mental space in our days to quiet our cleverness, choosing to engage cross-disciplines, really

Fungus | Photo: aspheric.lens, 2009 | Flickr cc working cooperatively, and lots of trial and error in this out-of-the-box thinking space takes time. We have to choose to take it.

4) Better storytelling. Not surprisingly, the media takes great interest in the sexy stories that are quick and easy to tell and come with beautiful pictures, especially in the United States. But the true potential of biomimicry and some of the most compelling case studies can't be captured in a "Top 10" list, or even a keynote presentation. Yet, it is these stories that offer the greatest potential for biomimicry to spread into all aspects of our lives, because we can then empower everyone in some form or shape to ask nature what she might do, because they can see the value and the relevance to their every day decisions. Part of this lies on those of us who practice biomimicry. What we convey, how we tell the stories, and what information we focus on has great power over the message delivered.

What is your best definition of what we do?

Anyone passionate about biomimicry, whether an inspired proponent, a life-long learner, or an engaged practitioner (or likely all three), I believe biomimicry is reconnecting humans not just with nature, but with our humanity. We are entering an incredibly important era of our evolutionary history on this planet where we have to ask ourselves, will it be our cleverness, or our humility that allows us as a species to survive on Earth. Our short 23 minutes of the year of Earth (200,000 years of a 4.5 billion year planet) is a blink in time. Will natural selection yield us a few more minutes?

By what criteria should we judge the work?

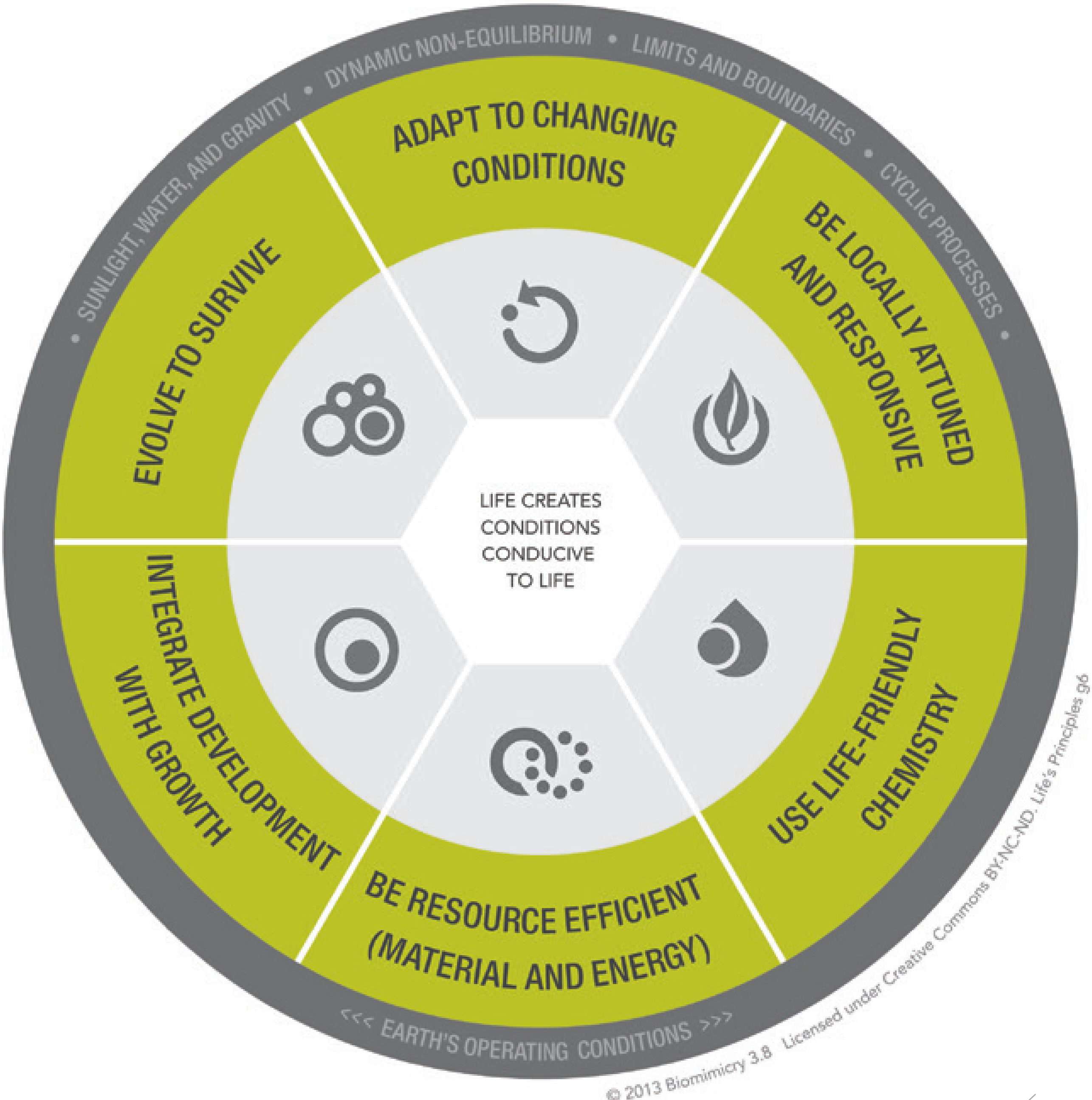
I think the attributes of a good biomimic are humility, honesty, gratitude (for nature), and (scientific) integrity. The biomimicry stories I choose to tell must be a context appropriate emulation of a biologically accurate abstracted design principle, must have some environmental or social sustainability win, do not use genetic engineering, do not cause more harm than good, and aren't just green-washing play. The good news is that there are many examples that fit thes criteria. One day, I hope to be able to tell the story of a biomimicry case study that does all of the above AND meets all of Biomimicry 3.8's Life's Principles.

What are you working on right now?

I'm actually working on a number of different projects, but what I am most passionate about is starting the third cohort of our Certified Biomimicry Professional program this fall. Designed for 20 working professionals from biology, design, engineering, and business, the course is a two-year journey that includes six visits to biologically spectacular habitats around the world complemented by a collection of on-line courses taught by a faculty of seven. This leverage point is one of the most inspiring directions for me to put my energy in right now. Applications for this program are due April 26th.

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

I started in the field of biomimicry 15 years ago this spring. It's been an amazing journey



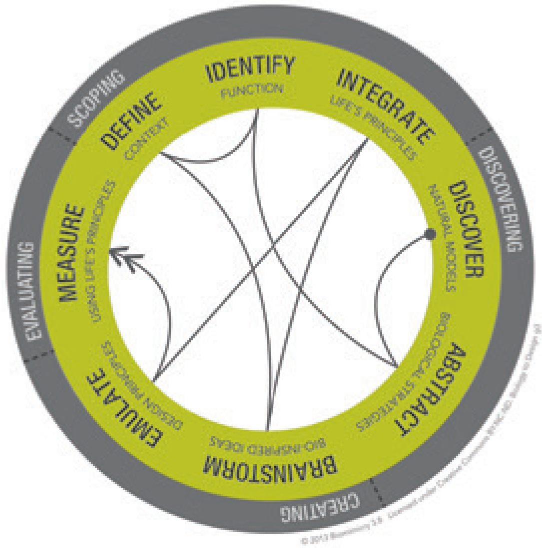
Life's Principles

Image : Biomimicry 3.8, 2013 | CC BY-NC-ND to watch the field of biomimicry and bio-inspired design grow and captivate so many different disciplines and audiences around the world. In January 1998, when I was in graduate school working on my doctorate in biology, I heard about a book that had just been published called *Biomimicry: Innovation Inspired by Nature* by Janine Benyus. I actually walked out in the middle of the class in which the book was mentioned and went straight to the bookstore. I sat down and read the book in one setting and felt like I had found my way home. With a background and degrees in pure biology, applied biology, design and arts, and a commitment to environmental sustainability, biomimicry was the intersection of all of my passions. Soon after I read the book, I discovered that Janine serendipitously lived just 30 minutes down the road. Timidly I gave her a call, knowing that it was probably the most important call of my life.

Her invitation to visit resulted in a marathon 14 hour first conversation. You might say we'd found a kindred spirit in each other! At the time, Janine was working on her next book and didn't imagine her life fully engaged in biomimicry. Of course, the world had other plans.

Janine and I worked collaboratively for many years and started the Biomimicry Guild in 2000 with the help of Catherine (Bragdon) Creamer, a business mind, as our first official entity. During that time we met amazing passionate scientists, designers, entrepreneurs, proponents, and friends. We held several biomimicry "gatherings", each helping shape the path forward. Many of our closest colleagues from those gatherings are still in the biomimicry circles today. We held our first Biomimicry and Design multi-day workshop in 2003 (with my three-week old daughter strapped to my chest!) and taught our first Biologist at the Design Table training in 2004. In 2004, we hired our first part-time employee, Sherry Ritter, who is still with us today. Her job was to populate the case studies database, a job that we could no longer keep up with.

In 2005, recognizing that many of our activities were in the non-profit realm, we created, with Bryony Schwan, The Biomimicry Institute, a 501(c)3 organization. Soon after we began hiring educators and researchers growing both our education efforts and the background research that was to ultimately seed AskNature.org. Fast forward another seven years, and now Biomimicry 3.8, the umbrella organization for all our social enterprises, including AskNature.org, now has a staff of 26. Our Biomimicry Specialist (8-month) and Biomimicry Professional (2-year)



Biology to Design | Biomimicry Thinking

Image : Biomimicry 3.8, 2013 | CC BY-SA

certification programs have almost 100 graduates with another 45 enrolling this year. We work with dozens of individuals around the world to fulfill our mission of training, connecting, and equipping a global network of biomimicry leaders who will transform the world by emulating nature's designs and core principles. Every day is a brand new adventure.

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

I'm fascinated by enabling technologies for biomimicry and their potential to change the conversation about how we as a species live on this planet. One that comes immediately to mind includes the rapid rise of the maker community and the concurrent accessibility to 3-D printing. As long as the conversation isn't limited to the technology itself, but includes what exactly our feedstock will be for the printer, as well as what we are printing (nature's models?), the potential for this enabling technology (and the community behind it) to redefine the "story of stuff" is profound.

Two others that crossed my viewfield in the last year are Zelfo Technologies, another "building block" technology that allows for the conversion of "waste" cellulose to structural forms using minimal energy and no added ingredients, and an absolutely brilliant joint technology for the built environment invented by a young Turkish architect who was inspired by nature. Until she gets her patent though, I promised I wouldn't talk about it!

What is your favorite biomimetic work of all time?

You can't ask a biomimic their favorite case study, and you can't ask a biologist their favorite organism. If I were to dare select one, I'd immediately feel bad about the ones who didn't make the list, each that has their own fascinating and redeeming qualities. So, sorry, I decline to answer the question. [I also can't answer most of the password recall questions: favorite teacher, film, food, city, etc...!]

What is the last book you enjoyed?

Right now, I'm reading *Quiet: The Power of Introverts in a World That Can't Stop Talking*, by Susan Cain. I find incredibly fascinating the linkage between introversion and the types and amount of stimulation that introverts need versus extroverts. This has significant implications for nature as "stimulant" and how we connect with nature. On one hand, nature experiences can be highly stimulating observing organisms and their strategies and the relationships of all the parts. The richness of habitats and the speed at which we navigate them can increase the level of stimulation. At the same time, quieting one's cleverness and spending time to deeply observe a particular strategy to discern what we might learn is an entirely different degree and type of stimulation.

Roughly 99% of our existence on the planet involved complete immersion in nature. Combining this recognition with the understanding that 40 to 50% of the inclination towards introversion or extroversion is explained by genetics, the fact that introversion is still part of our evolutionary history (despite cultural norms today that pro-

Dragonfly on Aloe | Photo: tonrulkens, 2011 | Flickr cc

mote otherwise) suggests that reflective time is incredibly important to our very survival. To really do biomimicry well, we will have to tap into the wisdom that comes from quiet. Fortunately, it's still part of our genetic heritage as a species. As an introvert myself, I appreciate the value that that in-depth time to the quiet experiences with the natural world can bring us.

Who do you admire? Why...

Honestly, I'm absolutely a huge fan of octopus, dragonflies, and aspen trees. I think they all move through the world with incredible grace. They are incredibly adaptive to their individual environments and seem to have the ability to withstand the test of time.

Octopuses are an incredibly nurturing species. They live out their last weeks, depleting their reserves while nurturing their young until they are ready for the world. They are creative and innovative about how they access resources and their habitat.

Dragonflies undergo metamorphosis, transforming from underwater larva to the flying lions of the insect world. Their amazing structural colors, highly optimized attachment mechanisms to keep their large heads attached to their bodies, and incredibly delicate wings that are capable of transporting them across thousands of miles of open water during their migrations.

Aspen are one of the most widespread tree species on the planet, found across the whole northern hemisphere. They've got a underground clonal network that connects each trunk with another, providing resilience to wind, fire, disease, and climate change. Some argue that a clonal stand could be a million years old. They can photosynthesize through their bark, protected by a natural SPF8 sunscreen. My favorite place during summer and fall is standing in an aspen stand. What's not to admire about all of that?

What's your favorite motto or quotation?

At the bottom of my email, I've had for the last 15 years, the following well-known quotation from Albert Einstein:

"The world will not evolve past its current state of crisis by using the same thinking that created it."

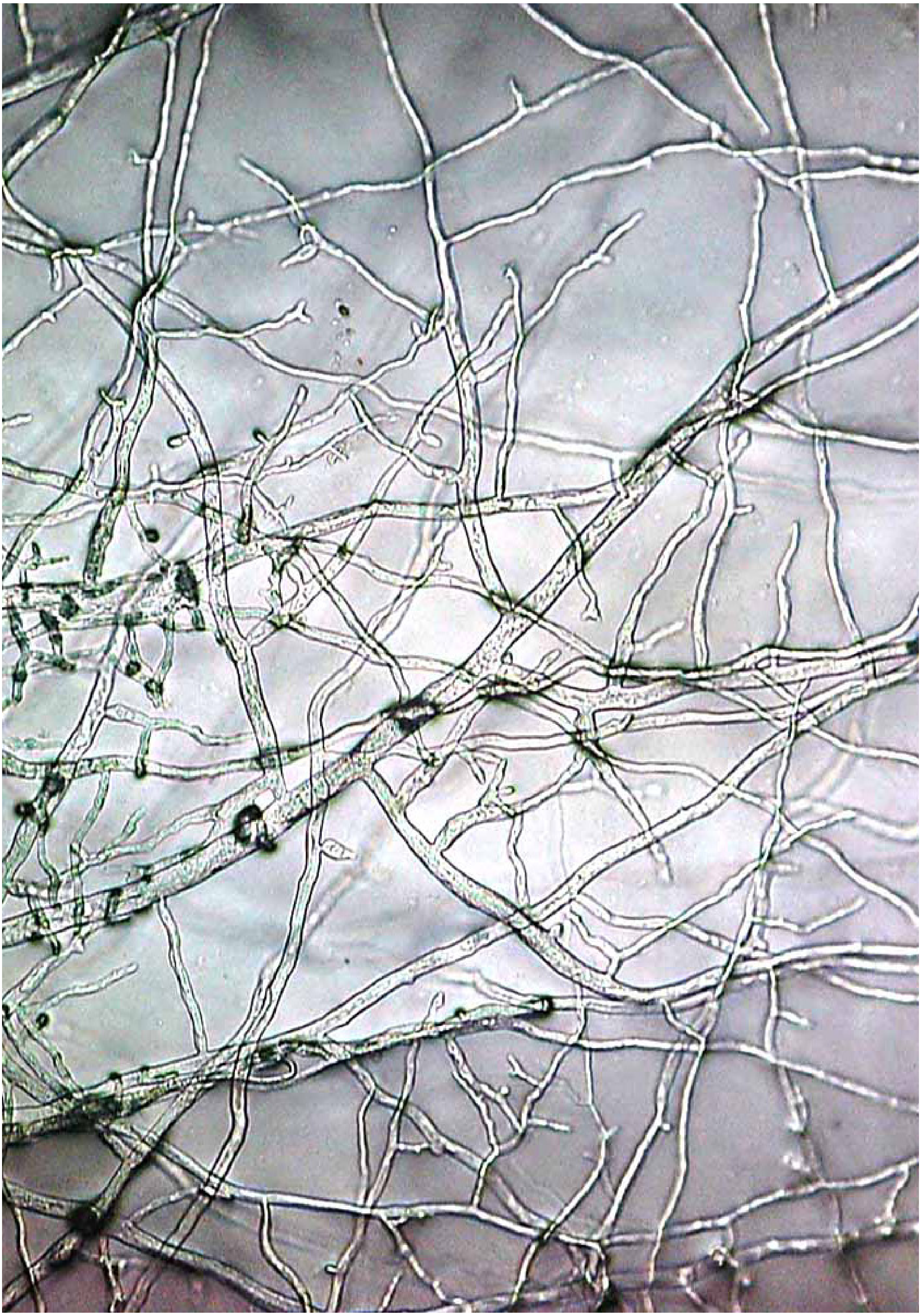
It is still as apropos as ever.

What is your idea of perfect happiness?

Unencumbered evolution. That and being in the presence of my daughter's laughter and my son's awe of nature's beauty.

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

Mycellia [the underground interconnected network of fungi]. Fungi are amazing adaptive; they been thriving here for at least six weeks of our planet's year. That way, I might be able to stick around long enough to see how things turn out for humans. ×



Mycelia | Photo: Bob Blaylock, 2010 | Wikimedia Commons

Photo courtesy of San Diego Zoo Global

Interview
Larry Stambaugh

Larry Stambaugh is the Managing Director at the San Diego Zoo Global Centre for Bioinspiration. He joined the Zoo to establish the Centre to develop a model for nature-inspired innovation and technology transfer. The Centre brings together private, public and academic organizations to develop innovative products and processes. Stambaugh brings extensive experience as the CEO, Director, and Chairman of the Board of several global public and private companies. During his 40-year career, Stambaugh has served as a top executive building successful management teams around his ability to awaken the leader within his associates to have them achieve extraordinary results.

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

The field of nature-inspired design is emerging as a recognized field for innovation. Education, research, and collaboration activities are growing within organizations and early product and process successes are being achieved. We will see the field go through normal early-stage ups and downs as it advances and becomes more mature.

What do you see as the biggest challenges?

Bioinspiration needs more financial and infrastructure resources to accelerate the development of ideas into applied uses. In addition, the field needs more case studies of commercial success to establish the credibility and understanding of its full potential.

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

Bringing research, capital for project development and entrepreneurs together to translate inspiration to real applications is the next important step for bioinspiration. Broader technology transfer is just beginning to emerge in this field.

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

Growing up in Kansas, I've always felt a deep connection to nature. Now after 40 years of watching incremental innovation as a CEO in life sciences, environmental and other companies, I saw the potential of bio-inspired design to provide a new bold source of innovation. In addition, I recognized the need to develop effective technology transfer models for the field. Where better to do that than the world famous San Diego Zoo Global where they had already established themselves as a leader in this filed and have the largest and most diverse collection of plants and animals in North America.

What is your best definition of what we do?

We are building a model for effective technology transfer of nature-inspired ideas into applications that can be used in the world. Our model will be used at the San Diego Zoo Global and openly shared with other zoos, botanical gardens, aquaria, natural history museums or others that have knowledge of nature that deserves to be investigated and developed.

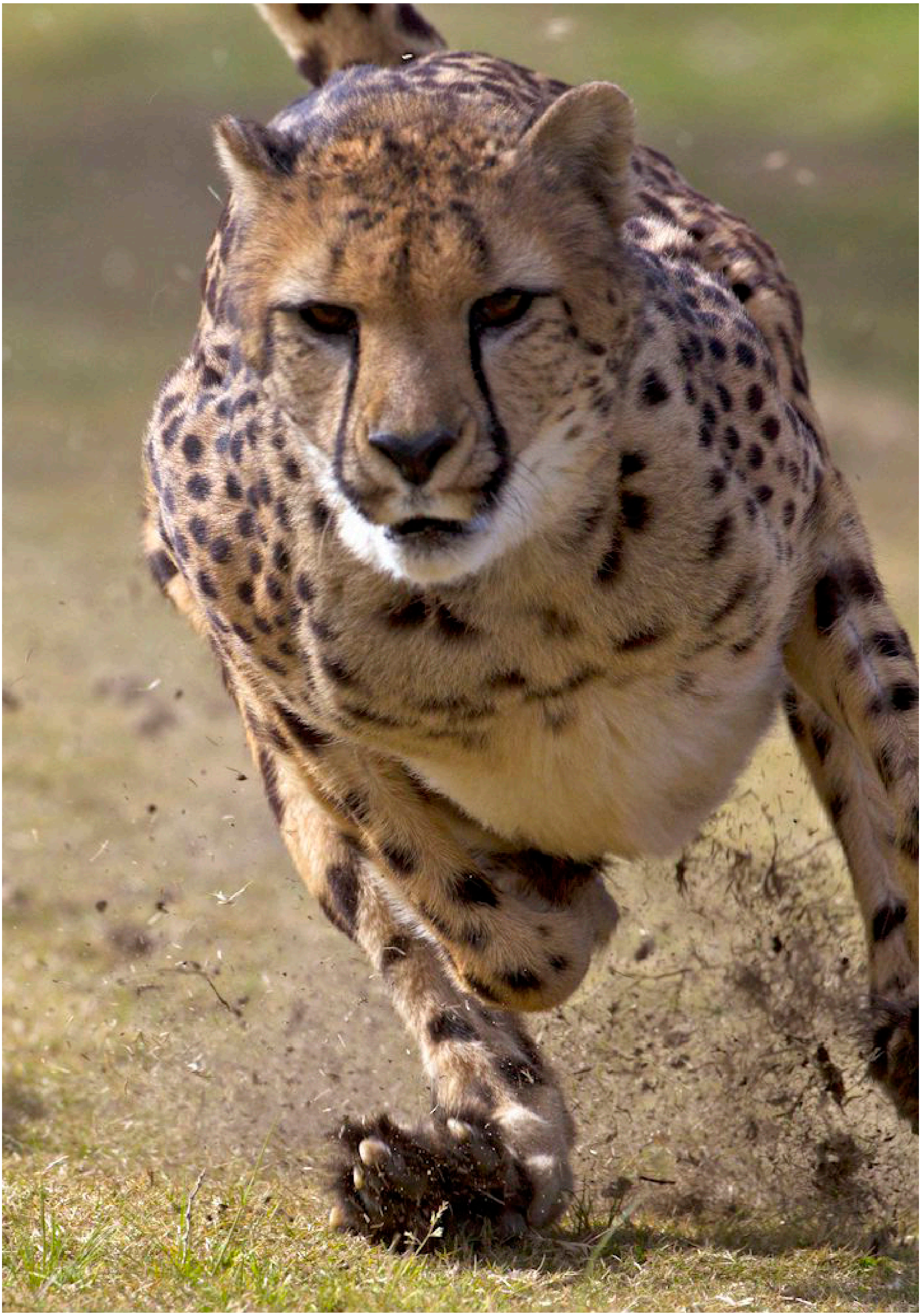


Photo courtesy of San Diego Zoo Global

By what criteria should we judge the work?

We will be judged by our success in achieving effective solutions inspired by nature and through the use of our model shared with other organizations.

What are you working on right now?

We are working with a number of large corporate clients to address their industrial challenges. Additionally, we have begun to identify novel discoveries within San Diego Zoo Global that have commercial potential.

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

I was first made aware of this field by an attorney with whom I was working that saw the potential of the field and then through Janine Benyus who shared her vision of the potential for biomimicry.

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

Each day, we witness the breadth and depth of nature's solutions here at the Zoo by interacting with our expert staff and the species they steward. They continually excite me about the potential to observe and learn from nature.

What is your favorite biomimetic work of all time?

It is hard to answer this since there are several great emerging examples. Interface carpets, gecko-inspired adhesives, and Lotus Effect® materials come to mind.

What is the last book you enjoyed?

The Order of Things by Michael Foucault

Who do you admire? Why...

Einstein for his daring, his curiosity, his passion and understanding of nature and humanitarian outlook.

What's your favorite motto or quotation?

Imagination is more important than knowledge - Albert Einstein

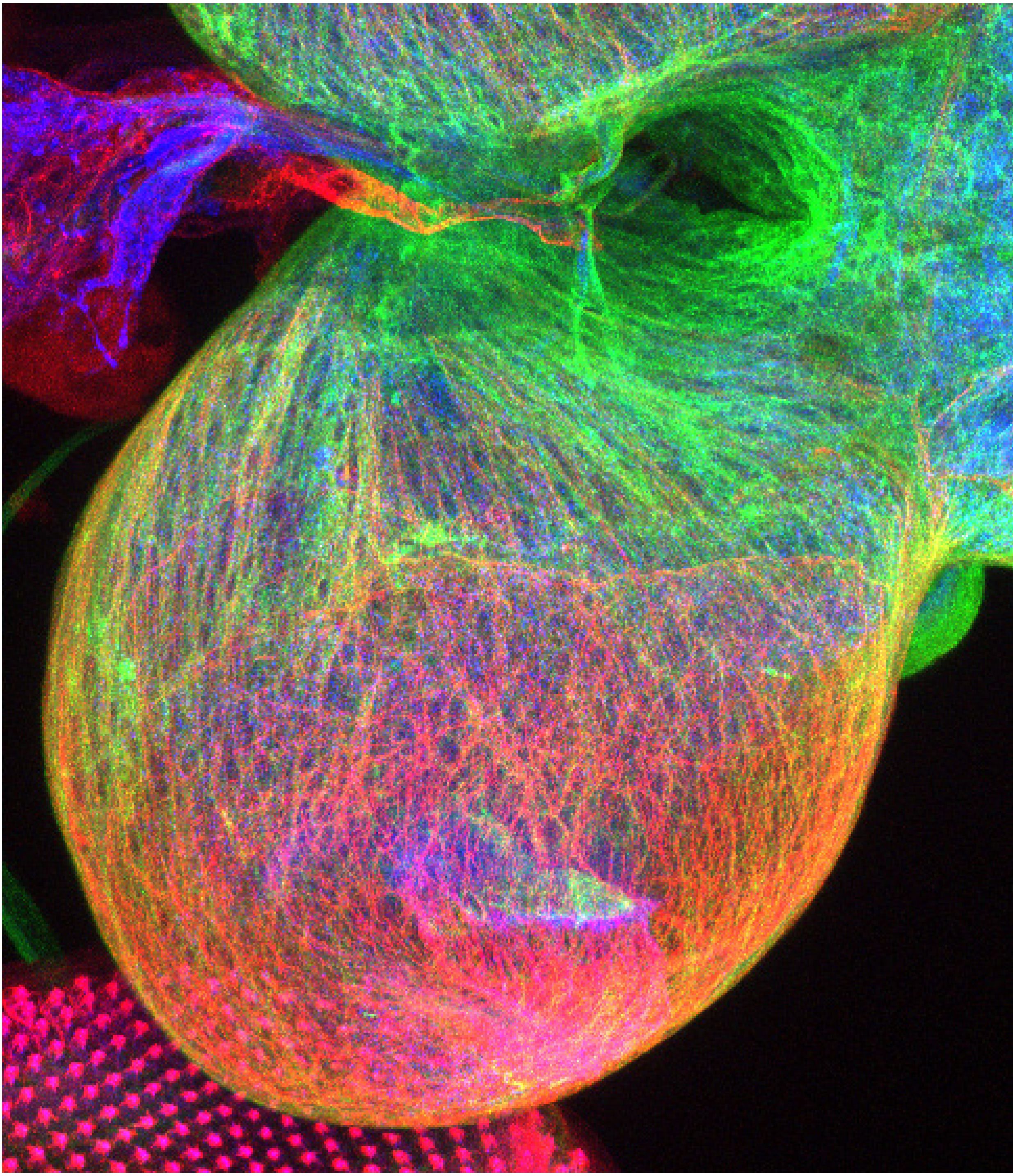
What is your idea of perfect happiness?

When what you are doing each day is your passion and not work.

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

I am doing what I love, making a difference in the world through the Centre for Bioinspiration at San Diego Zoo Global. ×

Photos courtesy of San Diego Zoo Global



Drosophila third instar larval brain [detail]
Christian Klämbt and Imke Schmidt | 2012

Interview

Laura M. Ferguson

Bioscapes 2012

Interview with Laura M. Ferguson

Laura M. Ferguson, Ph.D. | Planning and Business Strategy, Scientific Equipment Group, Olympus Corporation of the Americas.

What were the criteria by which you judged the work?

Each year, Olympus selects a panel of four independent expert microscopists who judge the more than 2000 still and video entries to the competition. While Olympus observes the judging, we only contribute when a clarification of the rules is needed or a historical perspective citing previous panels' decisions would be helpful. To qualify, images and movies must be captured with a compound optical microscope and must be of a life science sample. Any brand of microscope and any magnification is acceptable, and participants can submit up to five images, image series or movies for judging.

The judges evaluate each entry based on three criteria: science, aesthetics, and technical merit. The science represented in an image or video may be revealed in the choice of specimen, the details revealed (either anatomical or functional), or the context of the whole such as the story behind the observed details. The aesthetics of an entry is, by the very nature of an imaging competition, the first feature that catches the judges' attention. The image must be striking in some way – not necessarily traditionally beautiful, but certainly at least arresting and interesting. Technical merit relates to the difficulty of capturing the image or video and the skill necessary to prepare the specimen or otherwise obtain the high quality of the finished submission.

After a long day of viewing and reviewing, the judges will have created a collection of some 70 or so images and videos that will receive awards. The panel then selects and ranks the Top 10 awards from the collection, and the other award winners are given Honorable Mentions. For instance, some judging panels have taken images that have a specimen or technique in common, selected the best image among them for one of the numbered prizes, and given the others in the group Honorable Mention awards. Each panel of judges finds its own way of negotiating to agree upon the ordering of the Top 10. It's quite entertaining to observe this final stage of decision making with its spirited discussion of the images and sometimes a bit of bargaining. When the assignment of the Top 10 prizes is finished, there are smiles all around.

There are times when the judges choose to single out an entry for a special award recognizing technical or historical merit. These special award-winning images are often captured using new techniques or are especially striking examples of traditional techniques.

What - to date - is the most unusual creature?

What a difficult question! I can't choose a 'most' unusual specimen but I can share a few that would be in the running. In 2008, Mr. Solvin Zankl of Kiel, Schleswig-Holstein, Germany won an Honorable Mention award for a chironomidae fly captured with darkfield stereomicroscopy. The insect is transparent with a red undertone and has bright white "hair" on its head. The image reminds me of Billy Idol on the cover of the album Rebel Yell. In 2011, Mr. Haris Antonopoulos of Athens, Greece won 6th Prize with a stunning brightfield image of insect eggs, stink bug eggs to be exact. It is amusing to observe the attention of visitors to the museum exhibit as they shift from appreciation of the image to shock at the nature of the subject. Inevitably, a grimace crosses their faces.

Last, I'll mention unusual specimen constructions. Diatoms are actually a favorite subject of many microscopy hobbyists and sometimes they are captured in purely whimsical arrangements. In 2011, Dr. Steve Lowry of Portstewart, United Kingdom, received an honorable mention award for his "diatoms arranged in a familiar shape". He collected four types of diatoms and made a bicycle out of them. (By the way, some judges are amused by contestants' efforts to create an in-

Chironomidae Fly

Solvin Zankl | 2008 | Kiel, Schleswig-Holstein, Germany

Technique: Darkfield Stereomicroscopy

teresting picture while others reject "unnatural" images.) In 2009, Dr. Ma. Ivy Clemente of Pulilan, Philippines, collected, photographed and assembled image fragments of glandular structures in clinical tissue that seemed to depict the letters of the alphabet in order.

What - to date - is the most unusual technique?

Each year the competition receives entries that are early examples of the promise of new microscopy techniques. Some of these represent innovations in sample preparation, illumination sources or angles, image capture, or image data processing. Also, some contestants will use a relatively common technique with a few tweaks. In the first category for most important and unusual innovations, I would choose Brainbow imaging. This technique, developed by a team of researchers at Harvard in 2007, involves genetic tagging of individual cells, usually neurons, with genes encoding fluorescent proteins in dozens of different hues. Individual cells and neural pathways can then be traced through tissue, allowing mapping of neuronal networks. Dr. Jean Livet of Harvard University entered an extraordinary early image using this technique

Stink bug eggs

Haris Antonopoulos | 2011 | Athens, Greece

Technique: Brightfield illumination

in 2007 and it was awarded First Prize. In that year and subsequent years, we've given awards to many beautiful and significant Brainbow images and videos captured by others as well.

What is the most "doable" technique for the layman (cheapest and easiest with the best results)?

Stereomicroscopy is the most accessible technique for the novice microscopist to use to create a great image or video. Kathryn Markey of Roger Williams University in Rhode Island, USA, won Honorable Mention awards two years in a row for the same subject, a bay scallop. In 2011, she won for a still image and in 2012, a video was recognized. Her work only requires her to use microscopes to check the health of scallop samples taken for the scallop population recovery program her lab is involved with but she has been able to capture fascinating, award-winning microscope images without expensive equipment, extensive training or years of experience.

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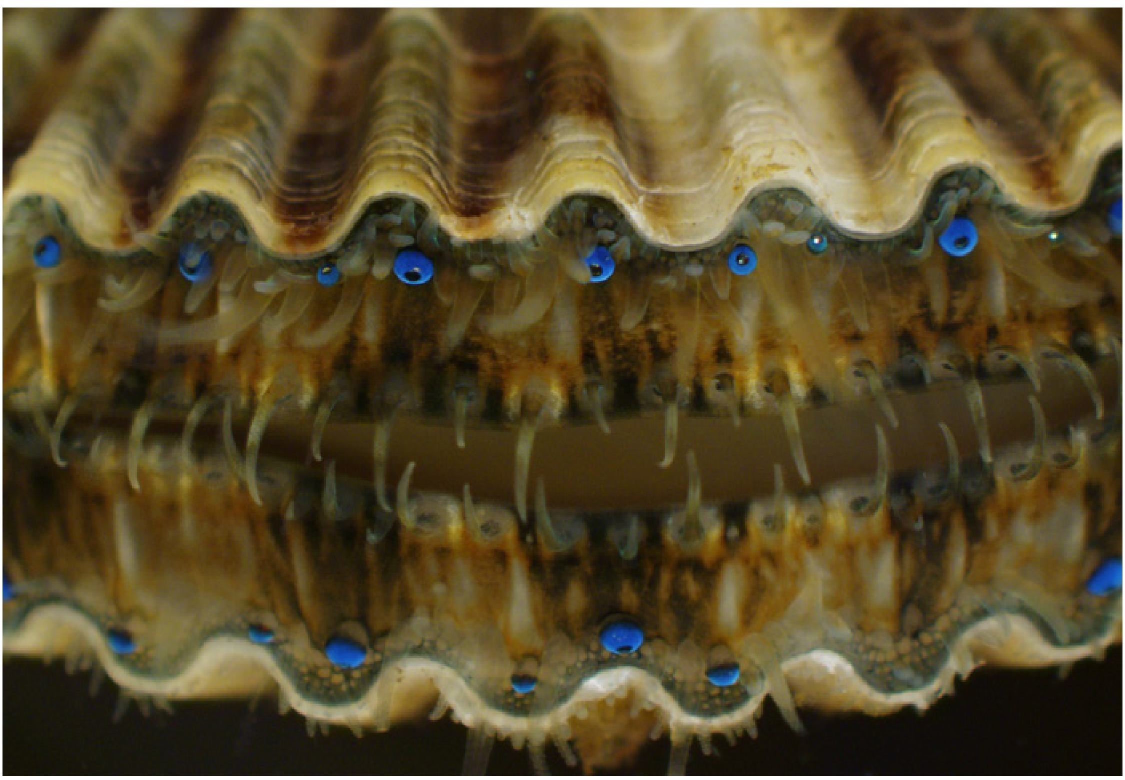
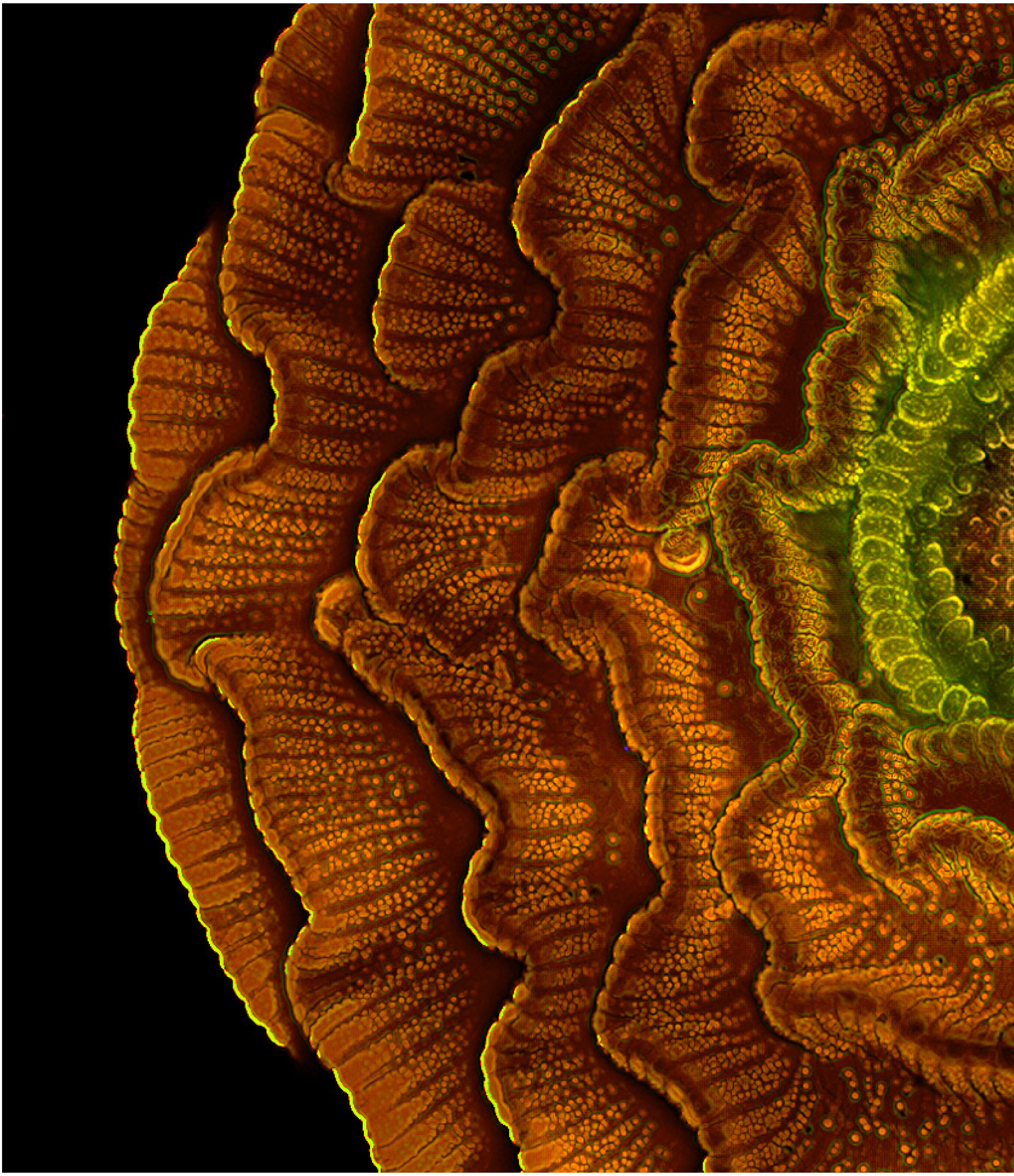


Juvenile live bay scallop Argopecten irradians

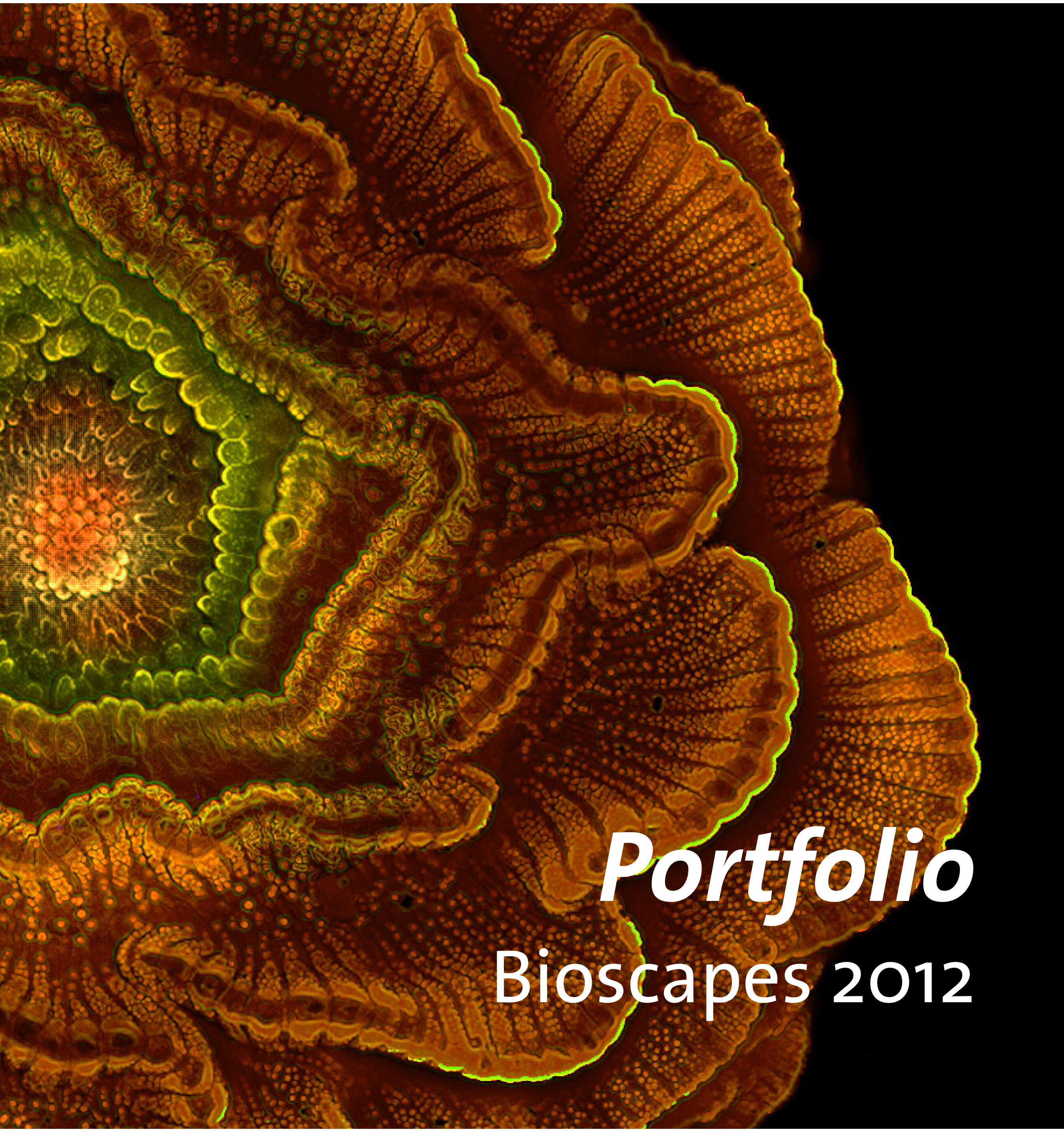
Kathryn Markey | 2011 | Aquatic Diagnostic Laboratory | Roger Williams University | Bristol, Rhode Island, USA

Technique: Stereomicroscopy



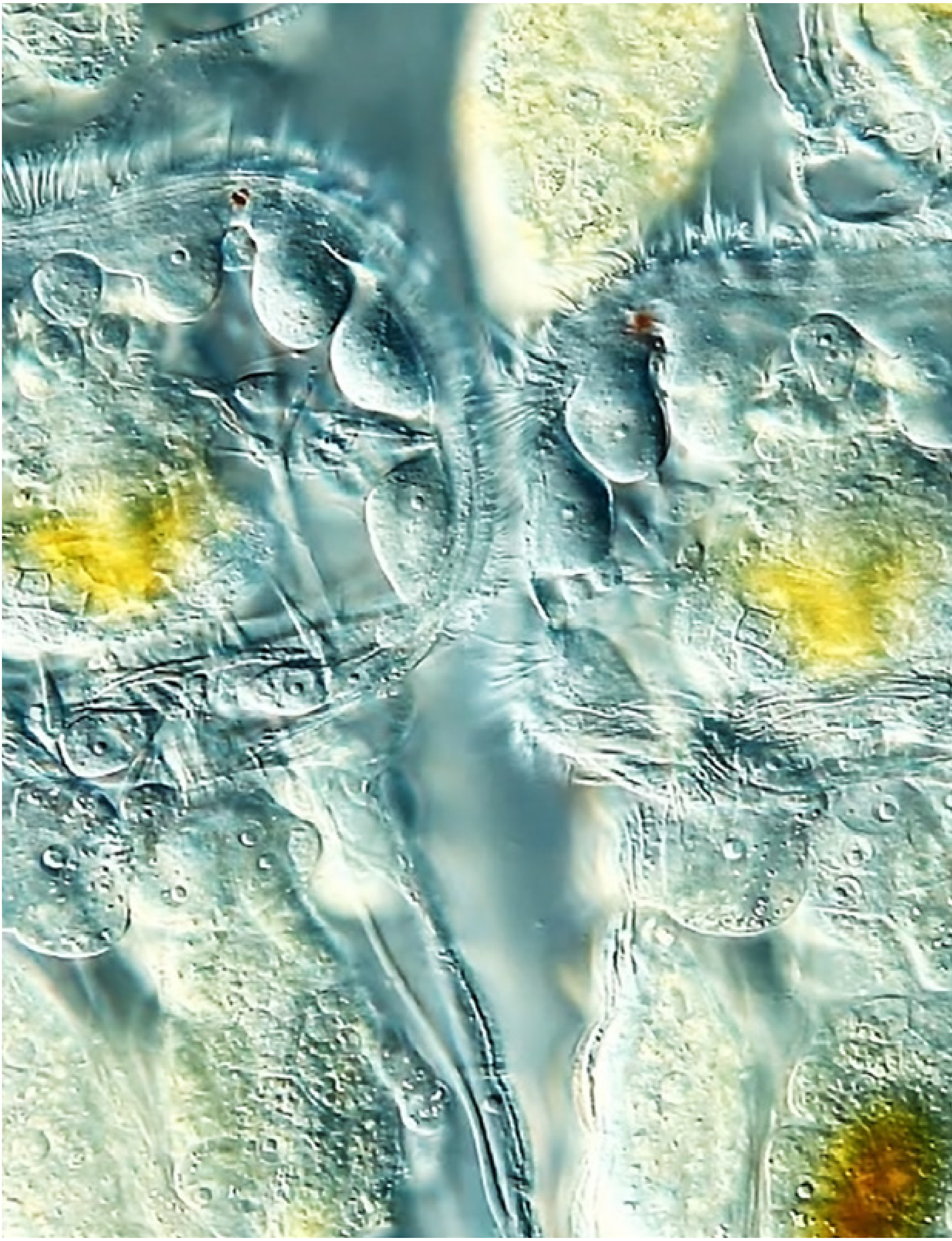
Seed of Delphinium [detail]

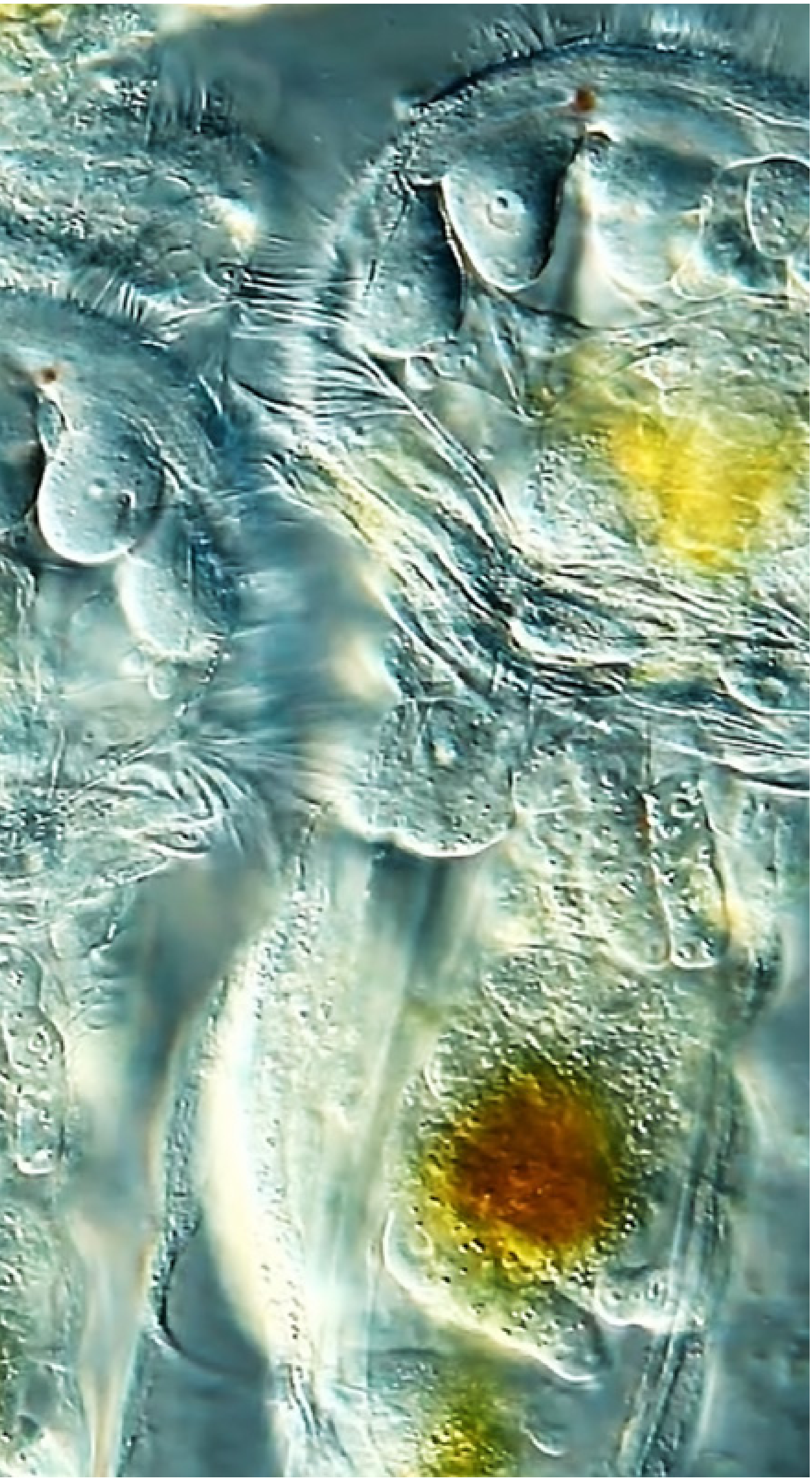
Sahar Khodaverdi | 2012



Portfolio

Bioscapes 2012





Still from movie: Colonial rotifers showing eyespots and corona, magnification 200x - 500x. Differential interference contrast microscopy.

Ralph Grimm, Jimboomba, Queensland, Australia.

First Prize | 2012

Olympus BioScapes Digital Imaging Competition®

www.OlympusBioScapes.com

Red algae Scagelia, showing reproductive tetraspores and golden diatoms. Darkfield.

Arlene Wechezak, Anacortes, Washington, USA.

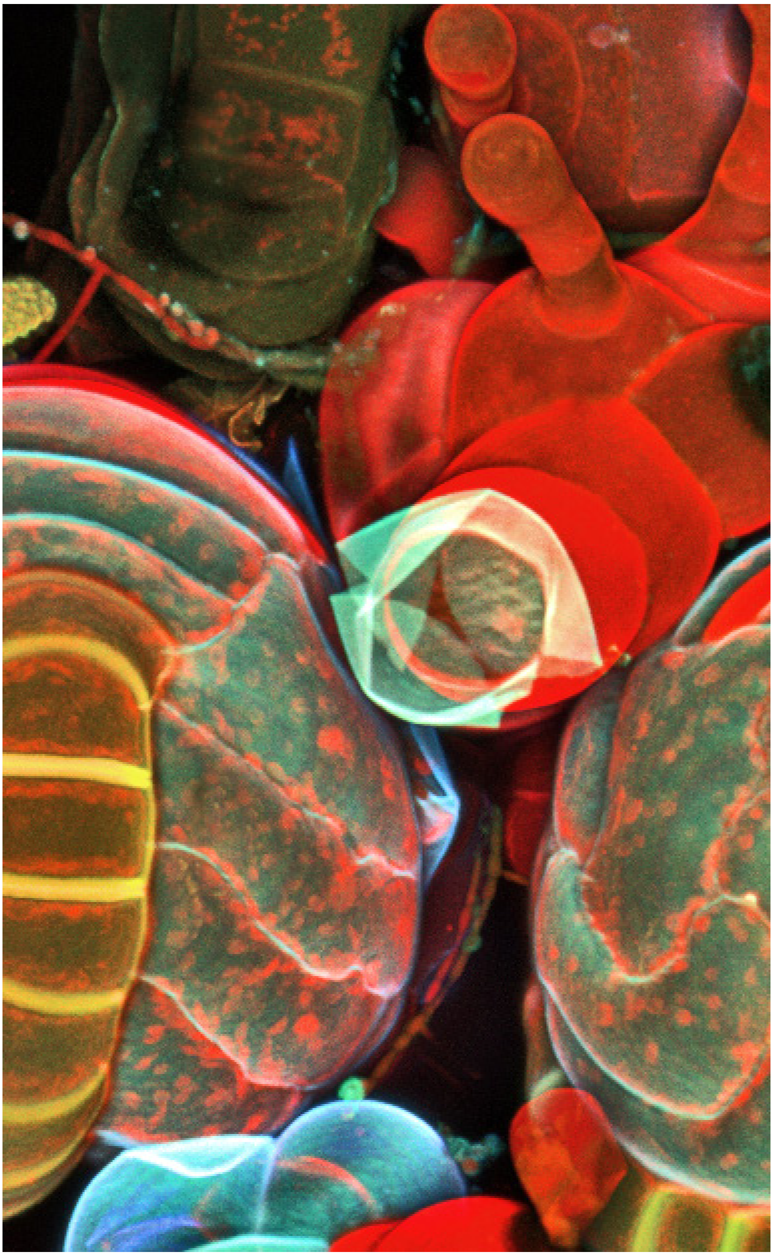
Second Prize | 2012

Olympus BioScapes Digital Imaging Competition®

www.OlympusBioScapes.com

Portfolio

Bioscapes 2012



A common East-coast US fern, Polypodium virginianum, showing a cluster of spore-filled sporangia and specialized protective hairs called paraphyses. Confocal microscopy.

Igor Siwanowicz, HHMI
Janelia Farm Research Campus, Ashburn, Virginia, USA.

Third Prize | 2012

Olympus BioScapes Digital Imaging Competition®

www.OlympusBioScapes.com

Also see pp. 110-149

Claw of the crustacean amphipode Phronima sp. Muscles and rows of pigment cells (melanocytes) are visible.

Christian Sardet and Sharif Mirshak, The Plankton Chronicles Project, Villefranchesur-Mer, France, and Montreal, Quebec, Canada.

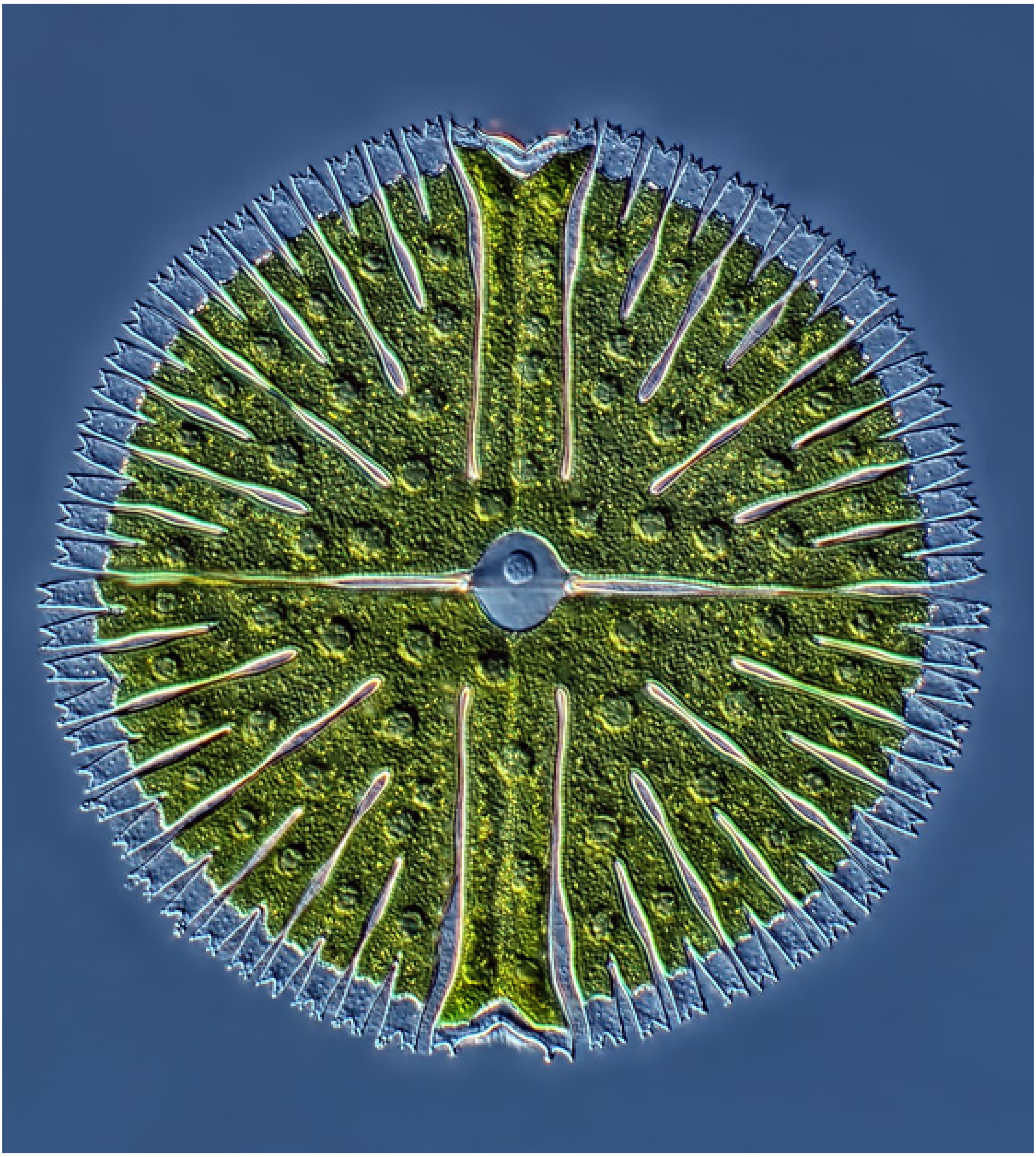
Fourth Prize | 2012

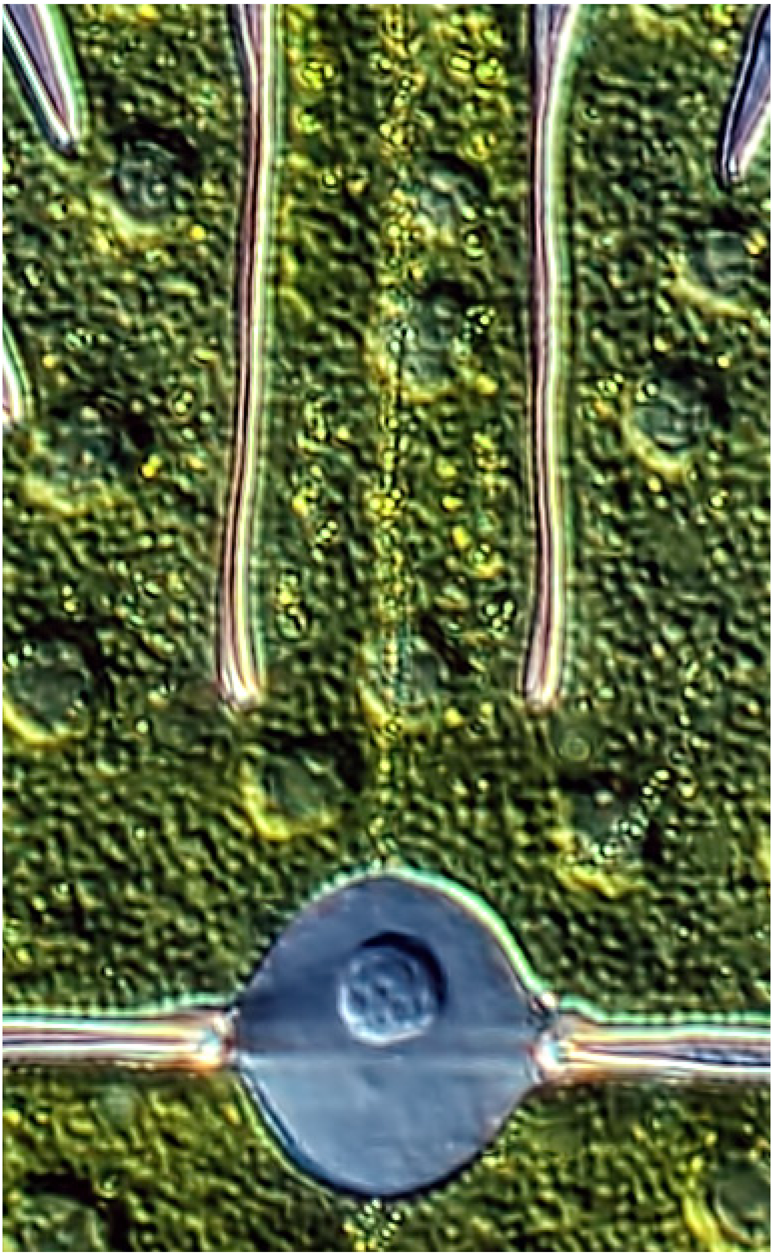
Olympus BioScapes Digital Imaging Competition®

www.OlympusBioScapes.com

Portfolio

Bioscapes 2012





Unicellular green alga Micrasterias from lake sample. Twenty-two stacked images, captured using differential interference contrast.

Rogelio Moreno Gill, Panama City, Panama.

Fifth Prize | 2012

Olympus BioScapes Digital Imaging Competition®

www.OlympusBioScapes.com

Live mushroom coral Fungia sp. Close-up of mouth during expansion. Captured using tungsten illumination; the green color is bright autofluorescence.

James Nicholson, NOAA/NOS/NCCOS Center for Coastal Environmental Health & Biomolecular Research, Fort Johnson Marine Lab, Charleston, South Carolina, USA.

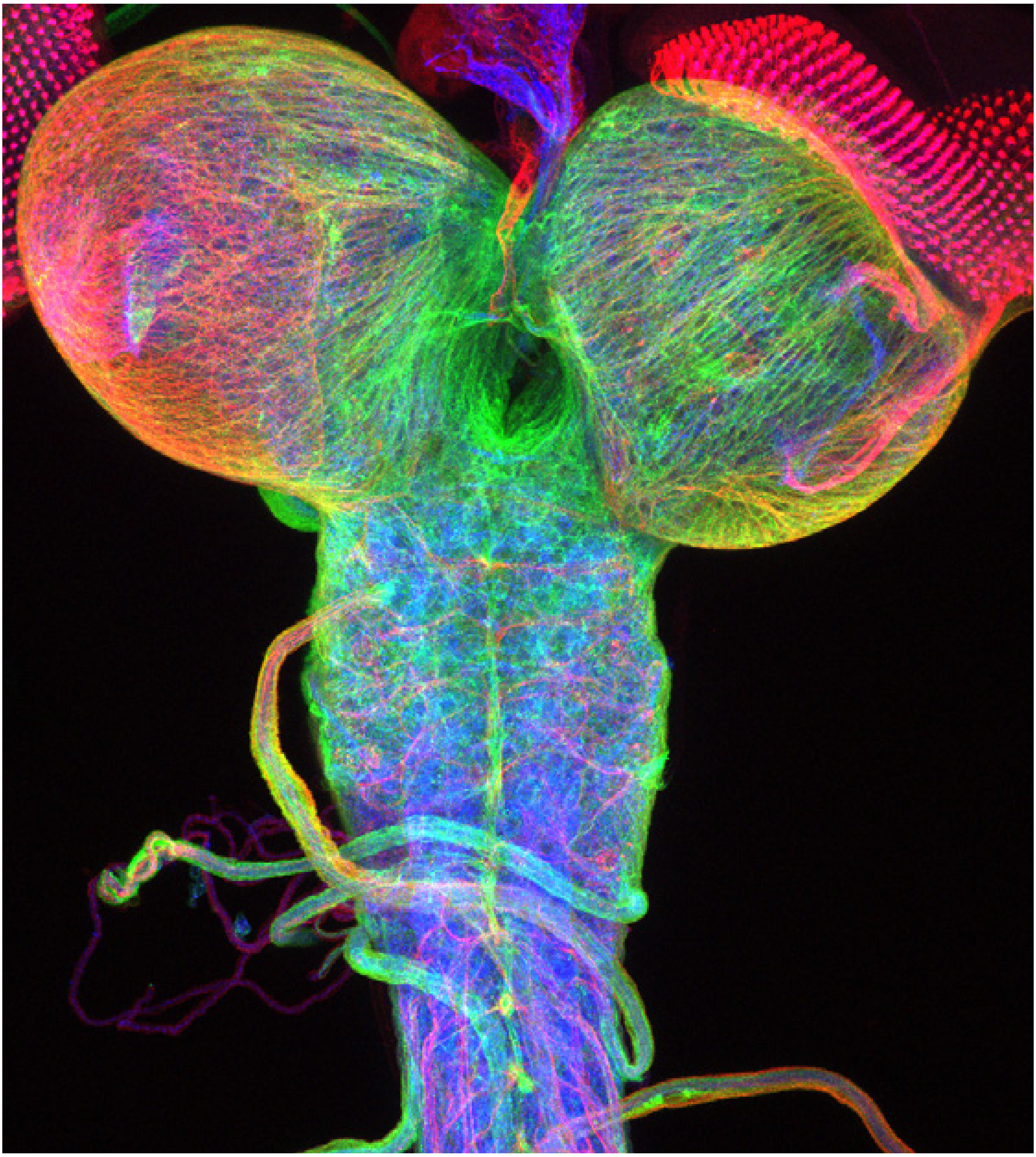
Sixth Prize | 2012

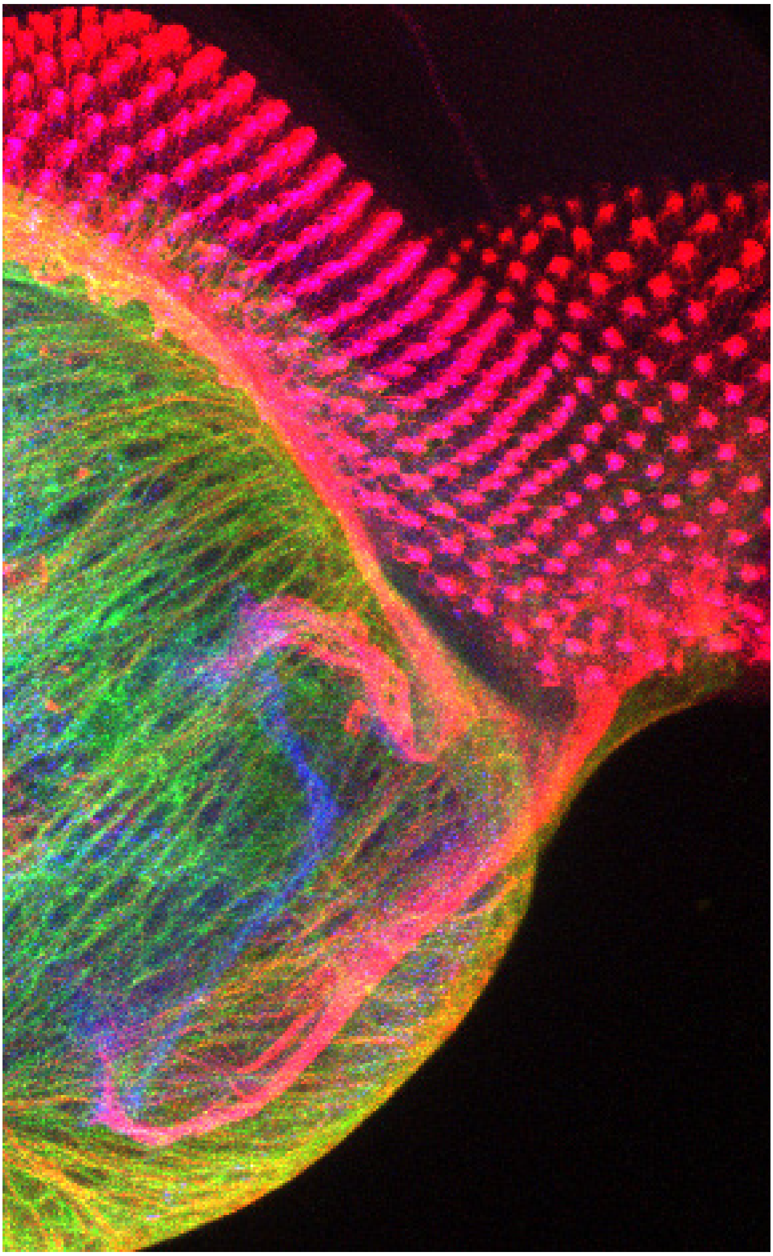
Olympus BioScapes Digital Imaging Competition®

www.OlympusBioScapes.com

Portfolio

Bioscapes 2012





Beta-tubulin expression of a Drosophila third instar larval brain, with attached eye imaginal discs. Image captured using confocal microscopy.

Christian Klämbt and Imke Schmidt, University of Münster, Münster, Germany.

Seventh Prize | 2012

Olympus BioScapes Digital Imaging Competition®

www.OlympusBioScapes.com

Henbit (Lamium amplexicaule) stamens anthers and filaments. Henbit is an annual plant that is sometimes regarded as a weed. The stamen is the male reproductive part of the flower. During pollination, pollen from the anthers is carried by wind or insects to the stigma of the pistil of another flower, where fertilization takes place. Phase contrast illumination, 100x.

Edwin Lee, Carrollton, Texas, USA.

Eighth Prize | 2012

Olympus BioScapes Digital Imaging Competition®

www.OlympusBioScapes.com

Portfolio

Bioscapes 2012

Seed of Delphinium. The image was acquired from multiple Z-stacked images using epi-fluorescence.

Sahar Khodaverdi, University of Tabriz, Tabriz, East Azerbaijan, Iran.

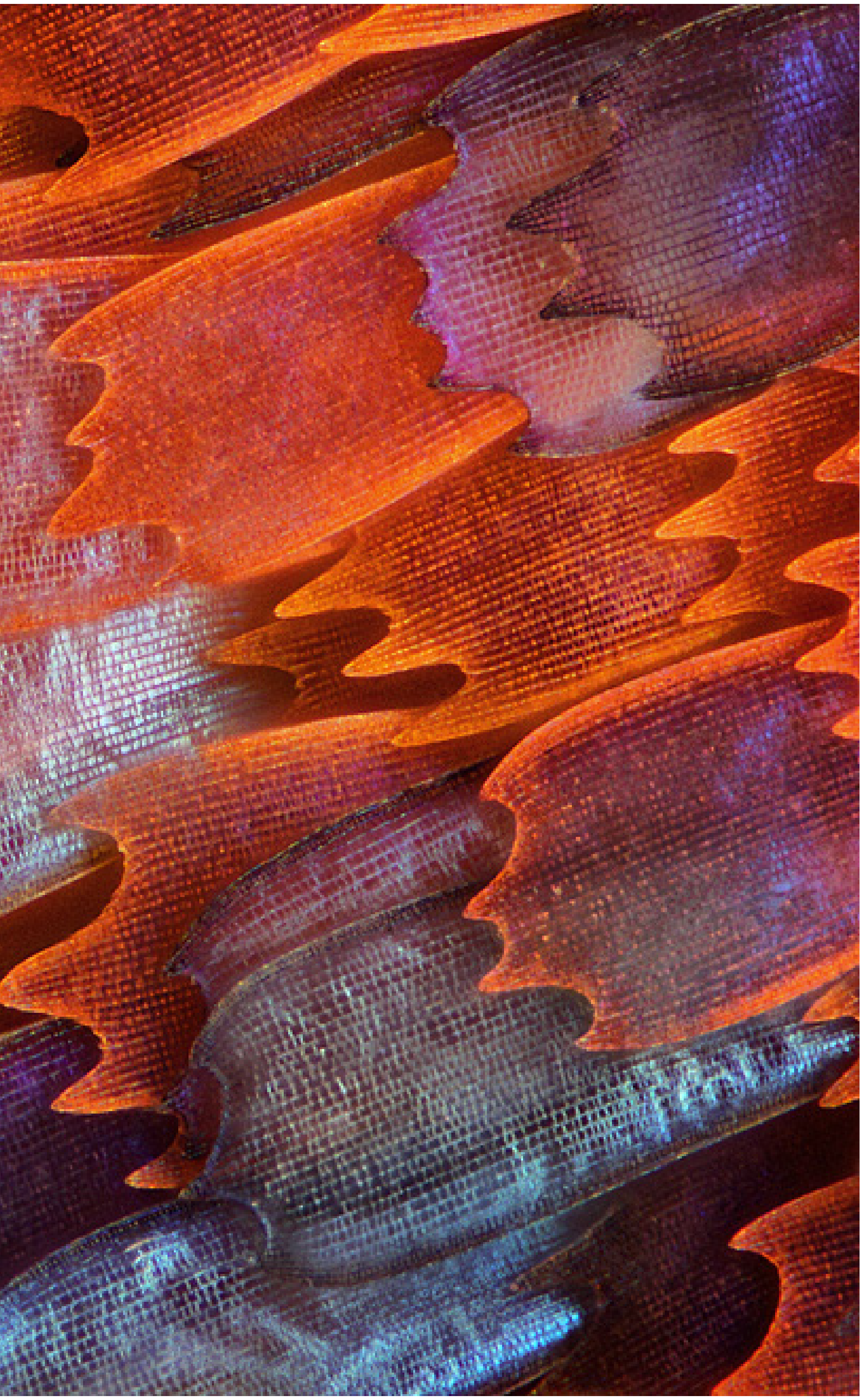
Ninth Prize | 2012

Olympus BioScapes Digital Imaging Competition®

www.OlympusBioScapes.com

Portfolio

Bioscapes 2012



Butterfly “Prola Beauty” (Panacea prola) wing scales, 200x. Image captured using diffused reflected illumination.

Charles Krebs, Issaquah, Washington, USA.

Tenth Prize | 2012

Olympus BioScapes Digital Imaging Competition®

www.OlympusBioScapes.com

Heliconius

Photo: e³°°°, 2007 | Flickr cc

Opinion

Tilting in the Lists over Lists: Database vs. Ontology

Julian Vincent

spring 2013 **Opinion**

Author:
Julian Vincent

Tilting in the Lists over Lists: Database vs. Ontology

Julian Vincent has always been intrigued by the exposed mechanics of insects. Largely in response to broken promises of promotion, he became a semi-professional musician and branched out into areas of science and technology bounded by biology and materials science. Since retiring he has had no laboratory and has had to resort to thinking.

I read somewhere that one of the hallmarks of creative people is their continual desire to make lists of everything. Sigmund Freud would say something rather less complimentary, I suspect, but lists are very useful, especially when you go shopping - whether it's for chips or new ideas. Like all tools, however, lists can be as limiting as they can be enlightening. The interface between biology and technology is ripe for lists, because few people know a lot about both these topics, but there are lists . . . and then there are lists . . .

In this short article I compare database (the most commonly found type of list) with ontology (a tool for describing the relationships between things). Ontologies are widely used in biology and medicine - the largest one is the gene ontology, the product of an international research community that has had an enormous influence on bioinformatics and molecular genetics. This has led to the Human Phenotype Ontology that is used in medical diagnostics and computational analyses of phenotypes. Ultimately, an ontology can be used for sophisticated numerical analysis using Bayesian statistics and semantic similarity. I am using the ontological approach to develop a computational reasoning tool for biomimetics which can be developed into a diagnostic tool and, possibly, an AI (artificial intelligence) kernel for biomimetic robotics . . . eventually.

In essence, creativity relies largely upon finding new relationships between bits of knowledge that you already have. The preference, then, would be for a list that makes connections between items on the list, rather than just a list. A database can do this to a limited extent (recording relationships in a hierarchical manner; arranging the data into branching tree structures), but a database cannot deal very well with partial data. It relies on a 'closed world' logic. If something is not stated to exist then it is assumed not to exist, which, in turn, implies that a database assumes that the data available is complete. It also means that a database will not suggest relationships which might exist but for which it hasn't got complete information.

By contrast, an ontology uses an 'open world' logic which makes no assumptions about data which is not presented, and this, of course, makes it easier to add information. Probably more important is that an ontology is a tool for

Twig Wilter on Jatropha | Photo: tomrulkens, 2012 | Flickr cc

Author:
Julian Vincent

Black Potter Wasp (*Anterhynchium fallax*) on Jatropha gossypiifolia

Photo: oystercatcher, 2012 | Flickr cc

arranging and interrelating ideas and meanings in a network (rather than a tree), using formal semantics. These relationships can be applied to embedded data so that the instances which might appear in a database can be interrogated, arranged and rearranged in a variety of ways. This plasticity and openness to change is difficult to implement in a database, which requires the purpose and scope to be known and defined before it is populated with information. Thus, a database has always to be started from scratch and its structure is rarely re-usable. An ontology is inherently re-usable, and not only can the relationships between the ideas be refined easily, but the data can be stripped out and replaced.

This makes it easy to share ontological structures, many of which are available on the Internet (the Gene Ontology is the prime example), leading to widespread standardization of expression and the integration of ideas and data at a community level. It also makes joining such a community attractive since quite a lot of the basic effort of providing a framework for the integration of data will have already been done. The most useful aspect of an ontology is that it is possible, using a theory-proving reasoner, to derive new information from the implicit relationships which were embedded in the ontology during its construction. This is because an ontology has more semantic power and freedom of expression. Freedom can be dangerous, so it is necessary to check the integrity of the ontology, but tools are available to do this. Ultimately, it is easy to generate and use an ontology with relatively little experience in computing.

It would be very difficult to generate an ontology by writing the raw code, so an editor is used. There are several editors, but probably the easiest to use is Protégé. It is Java-based and free to download from Stanford University (http://protege.stanford.edu). There are two types of Protégé - Frames (Protégé 3.x) and OWL (Protégé 4.x). I prefer Protégé 4.x, which is largely the work of the University of Manchester in the UK. The embedded syntax is pretty strict, I always feel, but that, of course, means it is more difficult to make a mistake!

OWL, surprisingly, stands for “Web Ontology Language” from the World Wide Web Consortium. An OWL ontology consists of Individuals, Properties and Classes. Individuals are grouped into Classes, and both can be related by Properties. It has a rich set of operators - e.g. intersection, union and negation - which makes it possible for concepts to be defined as well as described. Complex concepts can thus be built up from definitions of simpler concepts. Furthermore, the logical model allows the use of a reasoner that can check the mutual consistence of the statements and can recognize which concepts fit under which definitions. The reasoner can, therefore, help to maintain the proper hierarchy. This is particularly useful when dealing with cases where classes can have more than one parent.

Why, then, do I want to use an ontology when nearly everyone else in biomimetics is using a database? The answer is crushingly simple: I tried using a database for what I was trying to do, and it didn’t work! Rather than, as most databases seem to do, produce a list of biological effects which might be, or can be, used in an engineering environment, I want to produce a system that can compare biology and engineering at a far more general level; one that can provide appropriate answers to problems in design or engineering comparable to the information from a biology textbook. This has to be done at a descriptive level, so I need an existing system which describes engineering, to which I can add biology at the same level of definition and thus achieve some sort of parity and equivalence, ultimately enabling the direct replacement of an engineering concept with one from biology wherever it is appropriate. I don't need just a method for innovation: I need integration as well.

My ontology is available for downloading at https://wiki.bath.ac.uk/display/OOB/. The site also explains how the ontology is arranged and how it can be used. Unfortunately, the ontology doesn't have a friendly opening screen so you are dropped straight into it. I prefer things that way for now, however, since I am more interested in developing something that works rather than making something pretty. Pretty can come later!

My ontology is based on the Russian system of solving problems inventively - TRIZ. You have may have seen TRIZ mentioned in these pages in the article by Nikolay Bogatyrev (http://issuu.com/eggermont/docs/zq_issue_02final/90). It was when he and his wife worked with me that we developed ideas for integrating TRIZ and biology, and invented BioTRIZ (http://rsif.royalsocietypublishing.org/content/3/9/471.full). My ontology has been developed in the years since I retired, and so is an offshoot of that period of development.

There are several ontologies that use TRIZ, and several studies that use an ontological approach to formalize aspects of TRIZ which are still undefined. I have stolen a part of TRIZ - the "Contradiction Matrix" and the associated Inventive Principles - to represent a codification of engineering practice. There is no guarantee that the engineering we do is best practice, of course, so bringing biology into the mix also acts as a test of the efficacy of engineering (it isn't always the best, as we know!). The underlying concept is simple and well known: just as TRIZ was initiated and developed by examining a large number of technical patents, so biology is providing many "patents of nature" for a similar base of understanding.

All the information is taken from published research papers that have been examined by experts in their own area before being published, and so can be said to have some authority. Even then, very few papers in biology state a problem and go on to say how biology solved that problem. Many of these simply report a new physiological or behavioral phenomenon, and give no indication of the advantage that that phenomenon might yield to the organism. As a consequence I have adopted the technique of looking for key words, the basic one being "optimization". This commonly gives me a study where there are two or more variables somewhat at odds with each other. This is in accord with the classical definition of a problem, first mooted by Heraclitus in Ancient Greece, and more recently by the philosopher Hegel. It was the teaching of Hegelian philosophy in Russian schools that led to the methods developed in TRIZ. I am, therefore, going down a well-worn path, albeit with new partners. With the two opposing characteristics requiring optimization I can then see what biology offered as the resolution. Moreover, I have codified some biological observations in the same way as TRIZ, and have achieved my comparison with engineering. Added in to this mix is a large amount of biology, physiology, taxonomy and morphology. Ultimately, I shall include more on the range of biological effects which bring about the changes I am documenting. ×

Perhaps you can help me? Go to my wiki page https://wiki.bath.ac.uk/display/OOB/ and begin!

Meanwhile, here is my admonition concerning lists (shopping and otherwise):

- Consider using an Ontology when the schema is large and/or complex and when it's not possible/reasonable to assume complete information

- Consider using a Database when the schema is small and/or simple and complete information is available

Some Suggested Reading

Bowers, S., Madin, J. S. and Schildhauer, M. P. (2010). Owlifier: Creating OWL-DL ontologies from simple spreadsheet-based knowledge descriptions. *Ecological Informatics* **5**, 19-25.

Cavallucci, D., Rousselot, F. and Zanni, C. (2011). An ontology for TRIZ. *Procedia Engineering* **9**, 251-260.

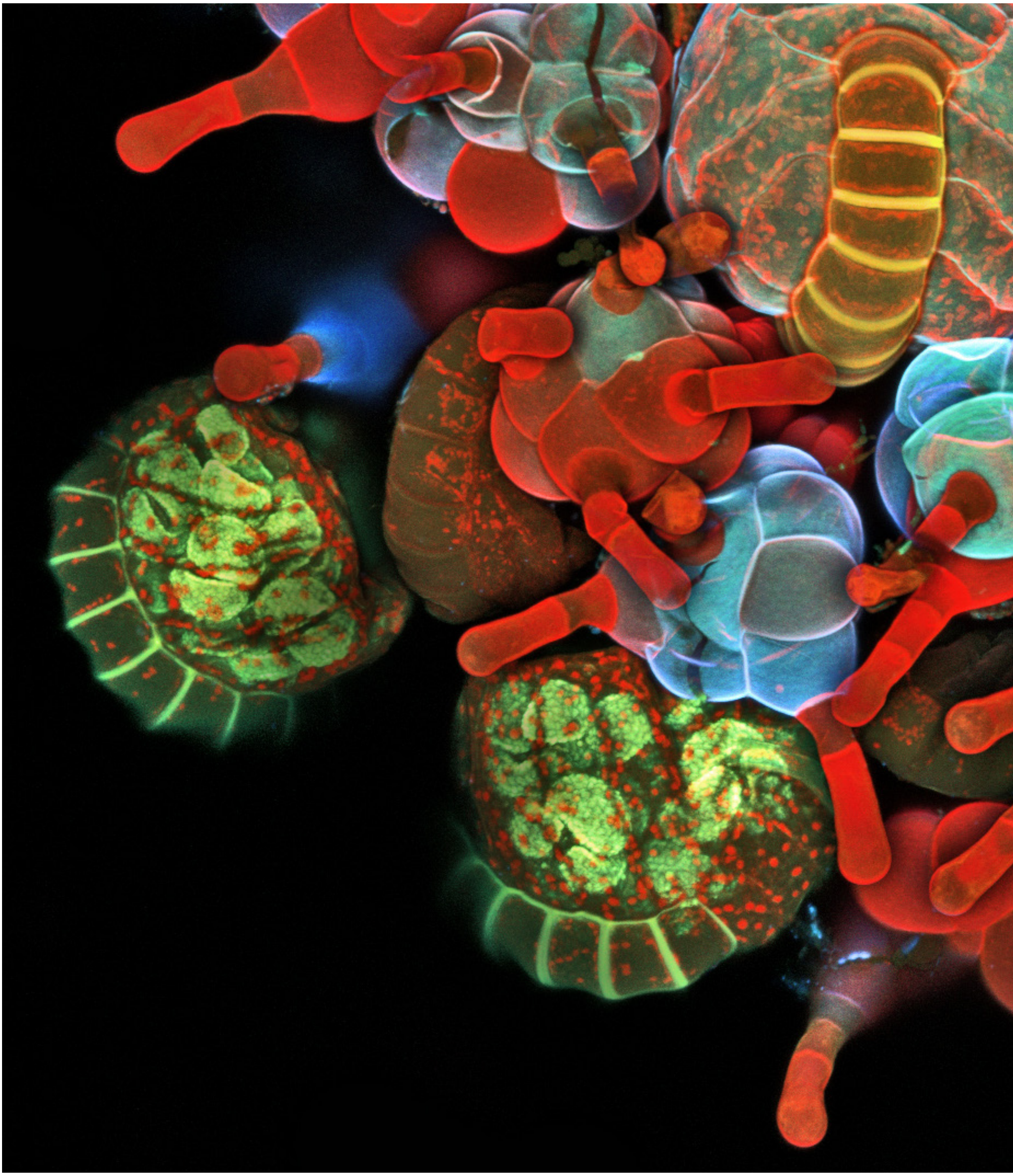
Jensen, L. J. and Bork, P. (2010). Ontologies in Quantitative Biology: A Basis for Comparison, Integration, and Discovery. *PLoS Biol* **8**, e1000374.

Robinson, P. N. and Bauer, S. (2011). *Introduction to bio-ontologies*. London: CRC Press, Taylor and Francis Group.

Editor's note: Despite his modesty and wit, Julian Vincent does have a background. He was Professor of Biomimetics in the Department of Mechanical Engineering at the University of Bath, UK, and has written over 300 papers, article and books, including the classic text, *Structural Biomaterials*. In 1990 he won the Prince of Wales Environmental Innovation Award.

Leaf beetle

Photo: tonrulkens, 2010 | Flickr cc



Sporangia paraphyses [detail]

Igor Siwanowicz | 2012

Portfolio

Igor Siwanowicz

Could you tell us about your background and how you got started in the field of art and photography?

I was fascinated with nature since before I remember; my parents are biologists and I grew up surrounded by biology textbooks. I enjoyed browsing through the illustrations and photographs long before I learned how to read. It wasn't until 10 years ago, at the age of 26, that I bought my first camera and found myself on the supply side of nature photography, with the special focus on macro technique. I quickly realized that microscopy would perfectly complement that activity and give me an even more intimate perspective of my "models." Five years ago - after abandoning protein biochemistry and moving to the field of neurobiology - I finally gained an access to a confocal microscope. Luckily, my former boss Dr. Hiromu Tanimoto was very supportive of that extracurricular activity, as is my present supervisor, Dr. Anthony Leonardo.

I am a biochemist by education, with a PhD in structural biochemistry and two years of postdoctoral experience in the field. At some point I found determining three-dimesional structures of bio molecules at atomic scales to be too reductionist for my personal taste; I felt that by focusing on a single interaction within a large biochemical pathway, one of thousands within a cell, I'm losing the bigger picture. I decided to change fields to make the best of my extracurricular expertise in invertebrate anatomy and macro photography. Neurobiology is much more in tune with my naturalist's interests, and as an added bonus it gives me an access to high-end microscopes. For a while I was involved in studies of neuronal mechanisms of memory formation, consolidation, and retrieval using the fruit fly as a model organism. I'm currently studying neuroanatomy of the dragonfly – specifically the neural circuits responsible for prey capture in dragonflies – but I find it irresistible to study other morphological adaptations that make those insects such formidable predators.

I'm fascinated with invertebrate morphology; the usual evolutionary restraints don't seem to apply within the realm of tiny animals, which is evident in the abundance and variety of often grotesque and utterly alien forms. Microscopy allows me to see beyond the cuticle, explore the baroque arrangement of muscle fibers or an intricate fractal-like network of neurons, and appreciate that beauty (probably in the most subjective sense possible) isn't only skin deep.

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

My tools of trade are a digital camera and a digital imaging microscope, and since both deliver digital files, the use of software is a given. To process the data sets produced by the laser scanning microscope (called "optical stacks" – more about how they are generated below) I'm using specialized programs running on a very powerful computer – a single high-resolution, three-color set can be more than six gigabytes, so one needs lots of RAM on board! I'm using Adobe Photoshop for final touch-ups such as contrast enhancement, clean-up from all sorts of specks etc. – the workflow varies from case to case. I should mention here that I don't alter the colors in my images to make "false color" photomicrographs, a type of digital alteration/processing

Colors represent varied affinity of the insect's exoskeleton to chitin-binding dyes reflecting different structural properties of chitin.

Insect's total length: 3 mm.

Piercing/sucking mouthparts and raptorial front legs are visible, as well as fragments of jagged pronotum.

Portrait of a beetle *Platystomos albinus*

Igor Siwanowicz | 2012

that is routinely used to make monochromatic images produced with scanning electron microscopes (a different type of microscope) “pop.”

Macro photography and photomicrography present very different challenges; the largest difference is that the insects I take photos of are always alive and healthy and always on the move; timing is crucial – depressing the shutter a fraction of a second too late and your “model” darts out of frame. The specimens for my microscopy images, on the other hand, are dead (in my work, that is – live cell imaging techniques are extensively used by many researchers), and I often work with fragments of organisms such as legs, mouthparts or sections. In most cases samples have to be made fluorescent by the use of dyes or conjugated antibodies specifically binding certain intra- or extracellular structures. Sometimes bleaching of dark-pigmented cuticle is necessary since pigment molecules will absorb most of excitatory or emitted light. Mounting the specimen on a microscopy slide requires very steady hands – the structures I'm interested in imaging are very fragile, and the mounting medium is a viscous liquid, so it has tendency to trap air bubbles, something one has to be extra careful to avoid.

How has your style changed since you first started?

When I got my first camera, I already had pretty clearly defined goals; like most photographers, I wanted to capture beauty and communicate feelings and emotions, while focusing on creatures commonly considered disgusting or frightening. I wanted to instill in the viewers a sense of wonder, admiration and respect for life in all its manifestations, to encourage them to honor every life form's right to exist. Ten years later, I'm still striving to achieve the level of excellence that would give justice to the beauty of nature's creations. It's an ongoing process, but I think I actually made a leap two years ago, when I met my wife Lisa (the Olympus BioScapes Competition actually was instrumental in us getting together; it's a long story!). I changed my illumination technique and started to compose the shots to bring brighter hues into the frame. This little tweak in my style met with a very encouraging reception – someone actually commented that my photographs “became happier.”

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

I don't think it has changed the way I see the world, but with my attention constantly focused on finding new subjects I'm definitely noticing more. My hikes, previously rather aimless walks in nature, became more goal oriented, and, as a result of my compulsion to flip every rotting log and frequent peeking under leafs, slower and non-linear...

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

Browsing through artwork of Hieronymus Bosch, M.C. Escher, Salvador Dali and HR Giger often help me break through the photographer's block and get into the creative zone. Ernst Haeckel is a continuous source of inspiration; his *Artforms from Nature* is a perfect exemplification of a very successful marriage between scientific approach and artistic talent. But there is nothing that inspires me more than finding some bizarre-looking little creature – and having a new “model” in front of me.

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

Winter keeps me focused on my actual research project in the laboratory, so I'm making a good progress describing all sorts of anatomical details of the dragonfly, a process that is, in fact, very exciting. My extracurricular activities are on hold till Spring. I'm looking forward to the change of season that should bring all sorts of crawling and buzzing critters to my studio and under the dissecting microscope. New photos will surely follow shortly after, so stay tuned!

I believe I have enough material for another book or two (my first one, published in 2007 by Dorling Kindersley and entitled *Animals up Close*, is available on Amazon!). We are seriously considering putting together a lush coffee table album featuring both photos and microscopy images (also in 3D – the red-cyan filter glasses included!) in the near future.

Can you detail the technique you used to capture the winning shot and what challenges you faced in getting it?

The fragment of the fern leaf with the cluster of sporangia was the very first plant specimen I had imaged. I'm usually on the lookout for the more bizarre looking arthropods; macro photography of insects – of which photomicrography is for me a logical extension – is my greatest extracurricular passion. Not such a long time ago I decided that my specialization was way too narrow and that by neglecting a whole kingdom of life, I'm losing the opportunity to take interesting, if more abstract, images. I took a walk on the grounds of my Institute and brought back several leaves taken from local ferns; I recalled vaguely that spore clusters have an interesting morphology, but didn't quite expect what I saw under the microscope. All those swollen bottle-like structures looked weirdly out of place there. To be perfectly honest, I had to educate myself to fully comprehend what I was seeing in the image I took. I faintly remembered morphology of sporangia from my high school botany classes, but the bulbous red structures dominating the image puzzled me. Upon conducting an extensive online research (thank you Google!) I came to the conclusion that the structures are in fact specialized hairs called paraphyses. *P. virginianum* is an evergreen species; the hairs probably protect the spores from the elements – freezing and dehydration.

To produce the image I used a laser scanning confocal microscope, a device that collects images in a very different way than a brightfield microscope (your standard biology class microscope).

The confocal microscope is a fluorescent microscope; it means that the imaged specimen is illuminated (excited) with light of certain wavelength and emits light of a different, longer wavelength. The source of the excitatory light is a laser; a confocal microscope can be equipped with several lasers producing light of different frequencies (wavelength, or simply color), since fluorescent molecules (pigments that emit light) used in research interact with light to absorb only certain wavelengths. The specimen is illuminated, point by point, by a focused laser beam that moves somewhat like an electron beam producing the familiar scanned image on the phosphorescent surface of a cathode-tube TV or computer monitor. The light emitted from the specimen is collected by the objective and passes through a pinhole aperture that cuts off stray rays of light arriving from fragments of the sample that are not in focus – only light that is emitted from the very thin area (optical slice) within the focal plane can pass. Emitted light is then detected by the microscope's photodetector (photomultiplier), and the image is reconstructed – point by point – on the computer screen. Because most specimens are much thicker than the focal plane, a series of images - called a "stack" - is collected by moving the focal plane up or down. From those images, a three-dimensional image of the sample can be reconstructed.

A researcher has control of a number of parameters, including the number and size of the illuminated points in both X and Y axes that define the resolution (grain) and magnification. The distance between and the number of optical slices can be also set, determining the resolution in the Z-direction and total depth of imaging.

In most cases samples have to be made fluorescent by the use of dyes or conjugated antibodies specifically binding certain intra- or extracellular structures. To be able to image cellulose (building material of plant's cell walls) or chitin (exoskeletons of various arthropods) I usually use two substances: Congo Red and Calcofluor White. Both were first used in the textile industry for their propensity for binding cellulose fibers (cellulose has very similar composition and structure to chitin). Both were abandoned because of their toxicity; Calcofluor still finds use in medicine for identification of fungal pathogens in animal tissues.

A confocal microscope "sees" the sample very differently than we do - to our eyes the specimens appear very different than the final image. The amount of ultraviolet in sunlight is – fortunately! – too low to appreciably excite Calcofluor, and all we see is a reddish hue from Congo Red (and in the particular case of the fern sporangia, green from the natural pigment chlorophyll).

To produce the image, I used three excitatory wavelengths and recorded emission in three channels simultaneously. Assignment of the color in the captured image to any given channel is purely arbitrary; however, I do assign blue to the channel recording light of the shortest wavelength, green and red in similar fashion, in the "natural" order. 'Combining the three channels or prime color images into one produces the whole palette of colors – in effect, it is like the microscope had trichromatic "vision," just as we do.

What are your favorite 3 websites, and why?

http://boingboing.net/ The blog Boing Boing covers topics from tech culture to cyber- and steampunk, from intellectual property to science fiction, and it totally satisfies my needs for information on current events in the outside world.

http://www.ted.com/talks TED talks address a broad spectrum of subjects within science, research, design, culture etc. The ideas presented are almost always illuminating, sometimes mind-boggling, and once in a while illuminating to the point of shifting one's paradigm. The 18-minute format is perfect for someone with a short attention span.

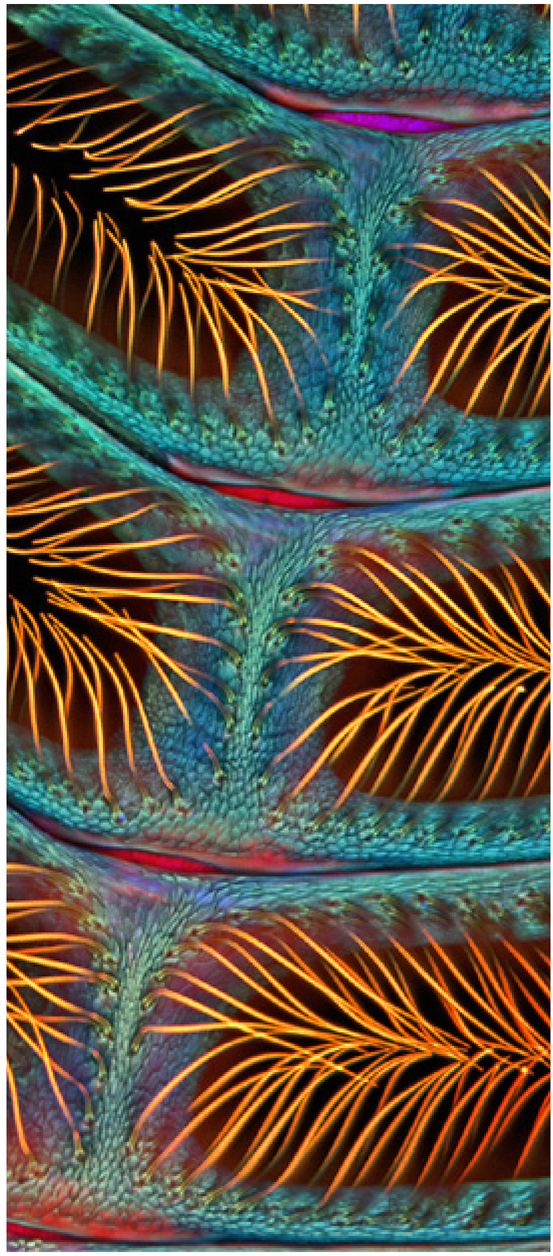
http://montalk.net/ because it opens my mind to refreshingly novel and alternative ways of looking at reality.

What's your favorite motto or quotation?

Words that are often on my mind, and even more so lately, come from French polymath and philosopher of science Jules Henri Poincare: "The scientist does not study nature because it is useful; he studies it because he delights in it, and he delights in it because it is beautiful." The idea is utopist in the era when applicability of research is often the key factor in receiving the funding; still, many scientists share that appreciation of beauty and are fully aware of the aesthetic aspects of their research. The Olympus BioScapes Competition is organized with such people in mind. Images are rewarded for the artistic merit and visual aspects on a par with and often above their scientific importance; that definitely grants the contest a broad appeal among non-experts and contributes to redeeming the image of science as a somber, wonder-less, unexciting affair utterly unintelligible for a layperson.

And because I don't have education in art or neurobiology but seem to succeed doing both, here is a bonus quote: "I get a kick out of being an outsider constantly. It allows me to be creative." –Bill Hicks

I can't resist adding another pearl of Bill's wisdom – because it's so true under all circumstances: "We are facilitators of our own creative evolution." ×

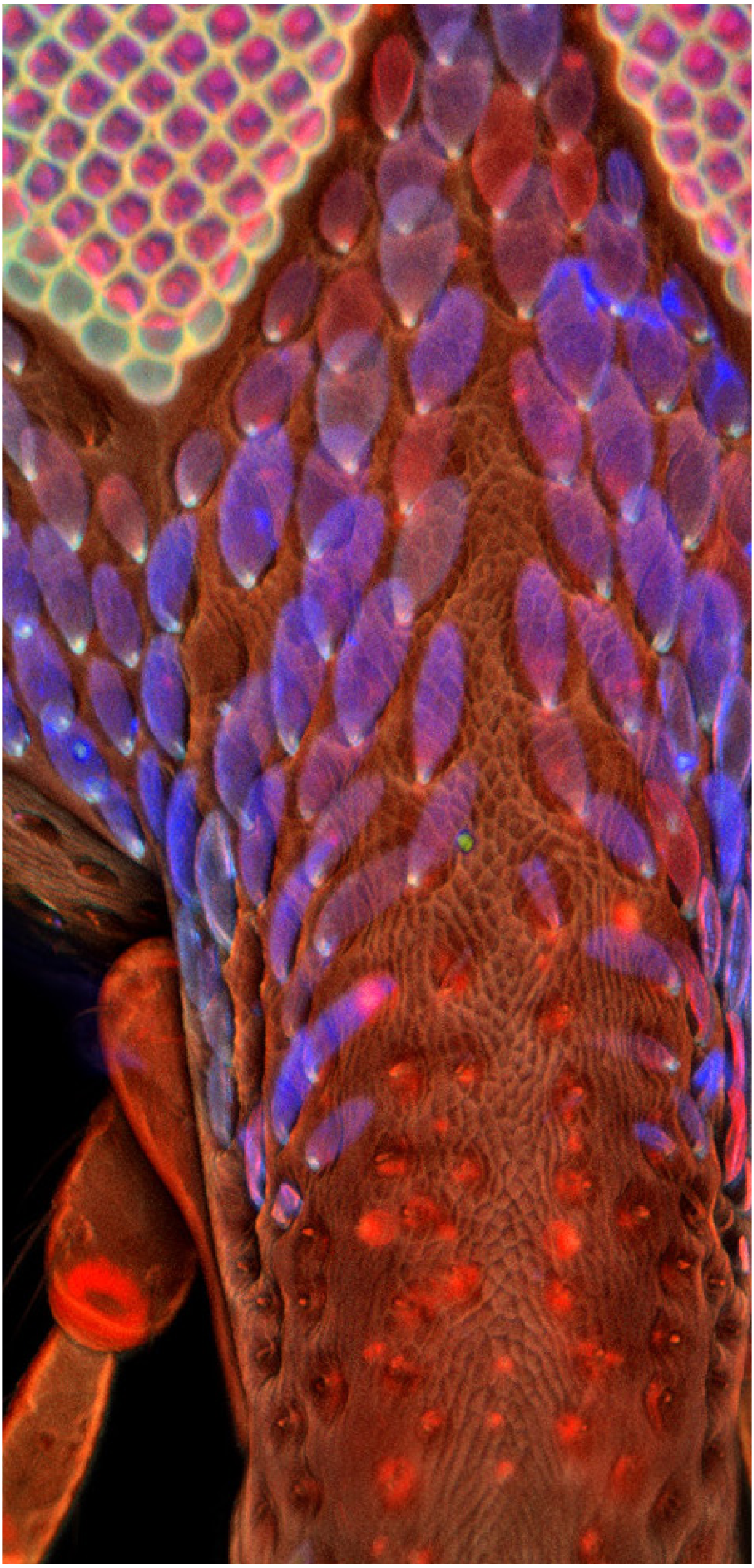


Moth antenna

Igor Siwanowicz | 2012

Amphipod | Igor Siwanowicz | 2012

Weevil | Igor Siwanowicz | 2012



Previous page: Amphipod: a juvenile marine amphipod.

Colors represent varied affinity of the crustacean's exoskeleton to chitin-binding dyes reflecting different structural properties of chitin.

The juvenile specimen is 1.5 mm long.

This page: Weevil: Portrait of a tiny weevil Tuchius sp.

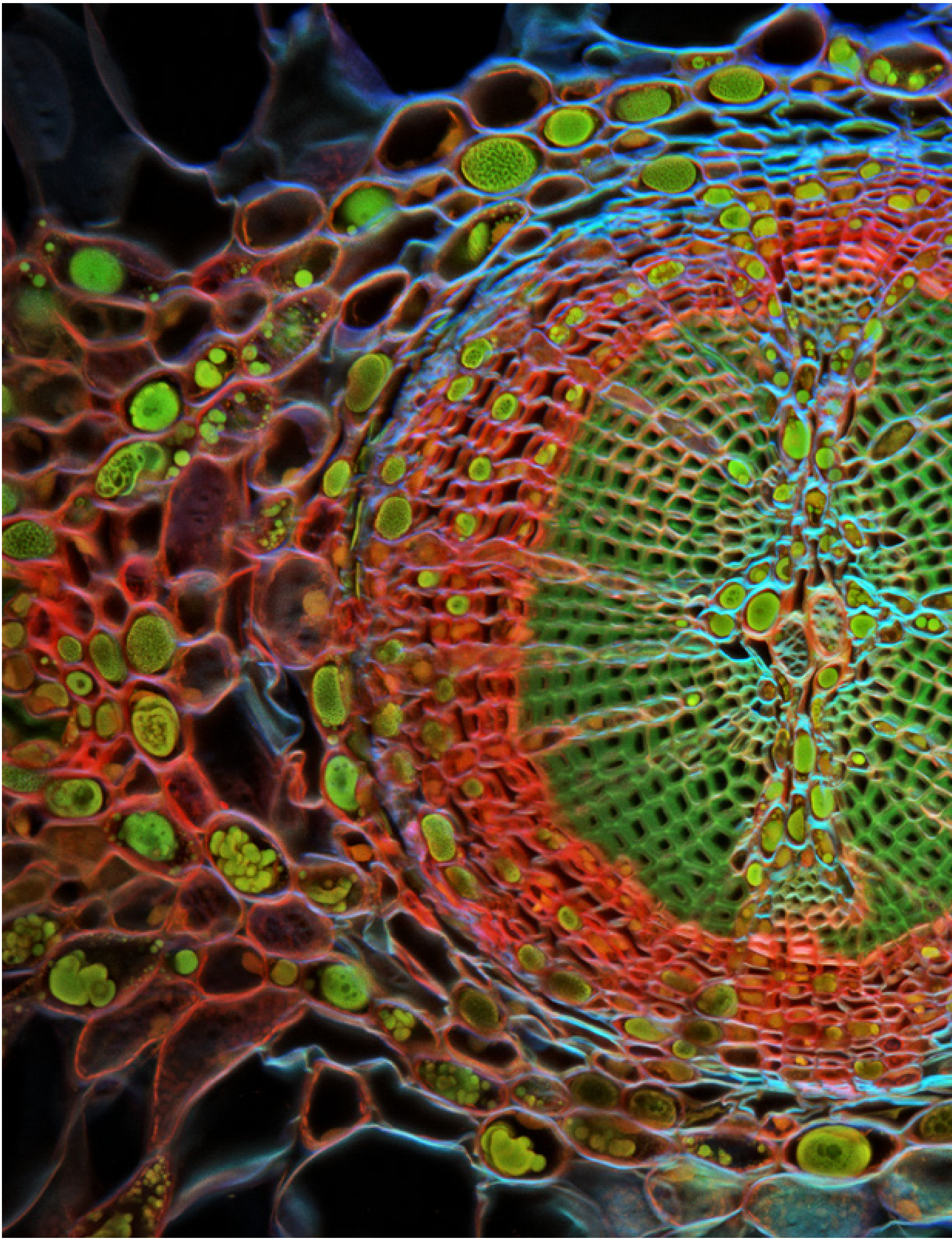
Colors represent varied affinity of the insect's exoskeleton to chitin-binding dyes reflecting different structural properties of chitin.

Slug moth caterpillar: Last instar caterpillar of a slug moth (*Limacodidae sp.*) ready to pupate.

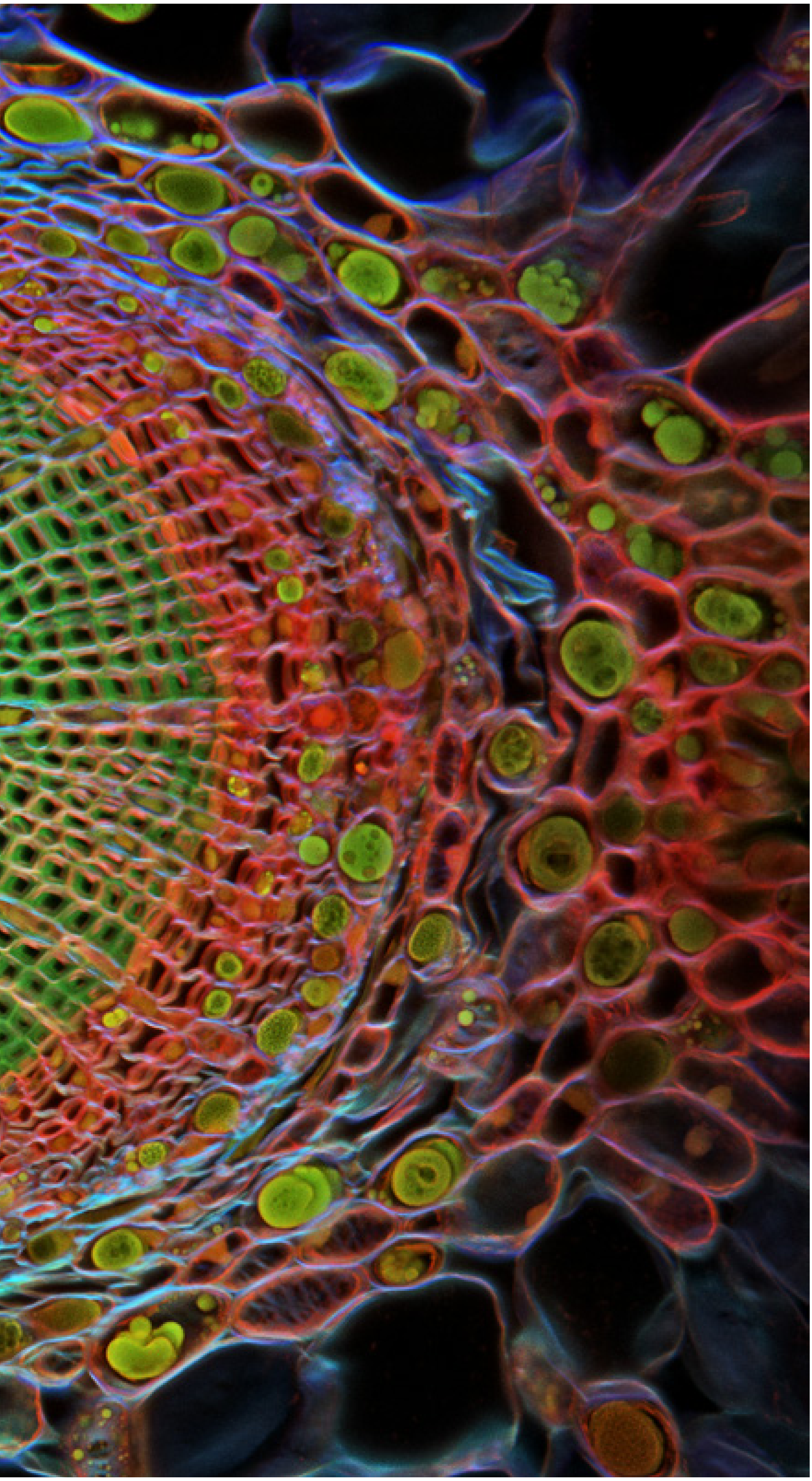
Colors represent varied affinity of the insect's exoskeleton to chitin-binding dyes reflecting different structural properties of chitin.

Eyes have six dome-shaped lenses each; unlike an adult with the large multi-faceted compound eyes, a caterpillar has simple eyes, usually 12 of them. They offer very poor resolution; to compensate for the poor vision, caterpillars use other senses, such as taste, smell and touch – they are virtually covered in relevant receptors; most of the hairs the caterpillar in the image is covered with are chemo- or mechanosensory.

Slug moth caterpillar | Igor Siwanowicz | 2012

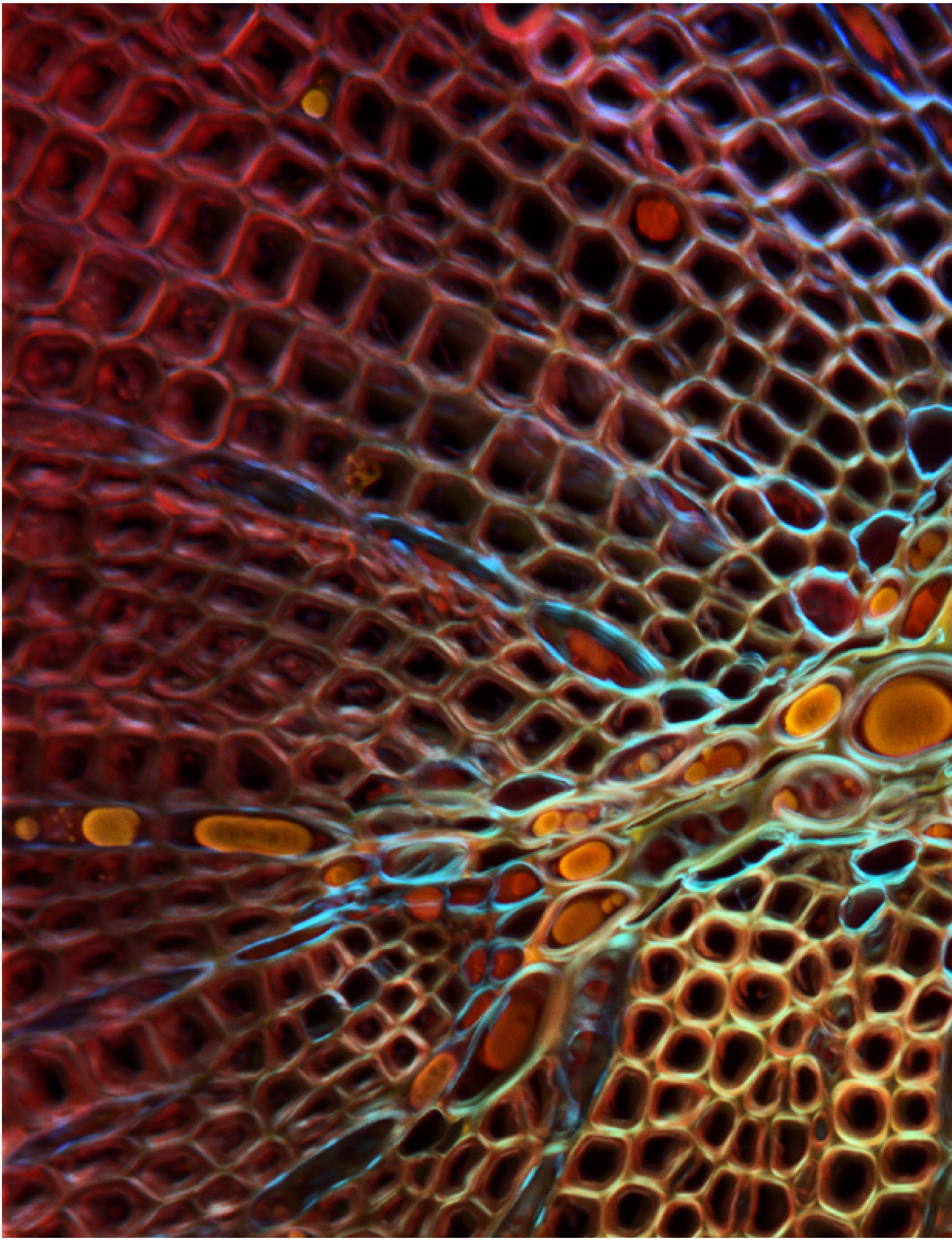


Juniper 3 | Igor Siwanowicz | 2012

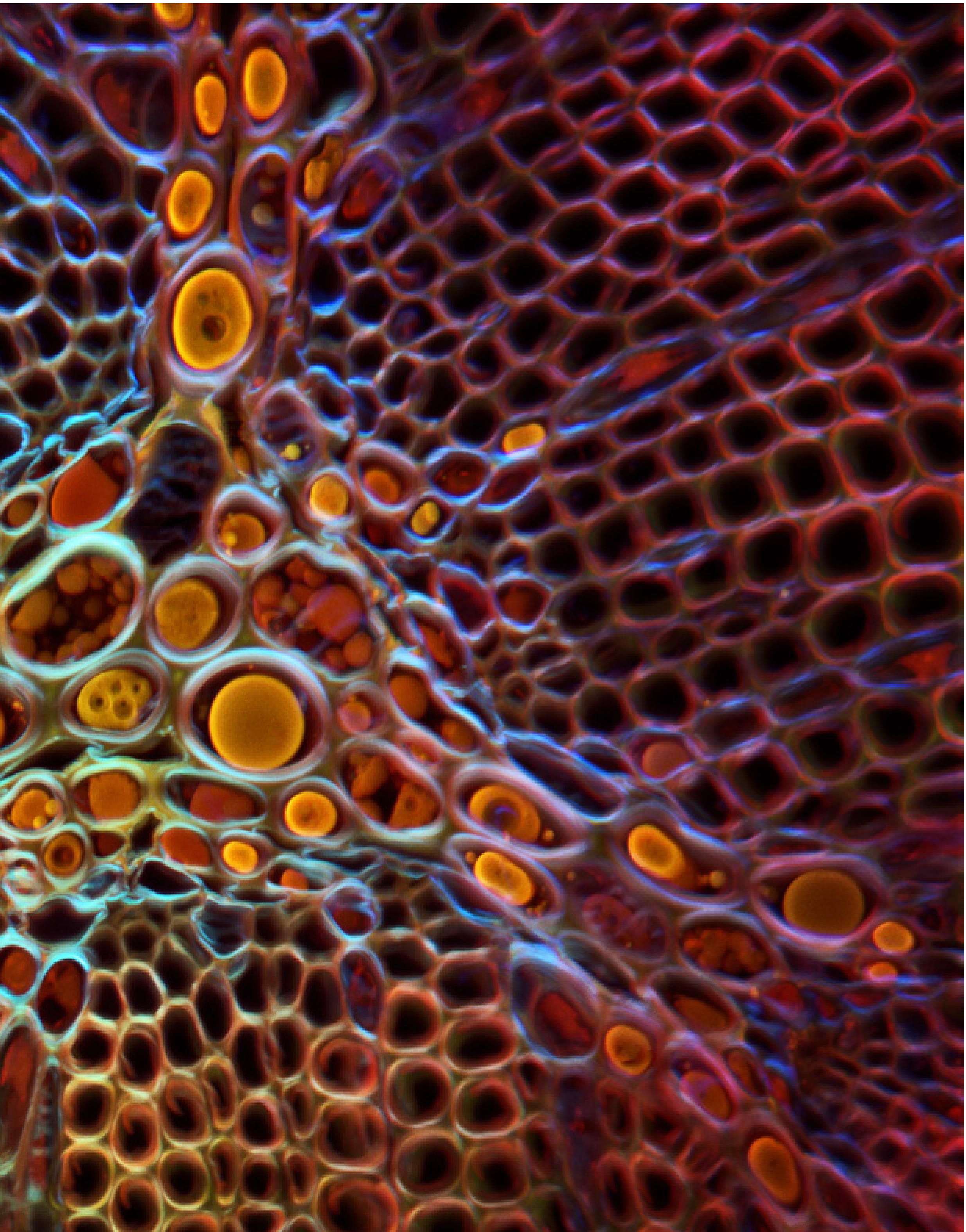


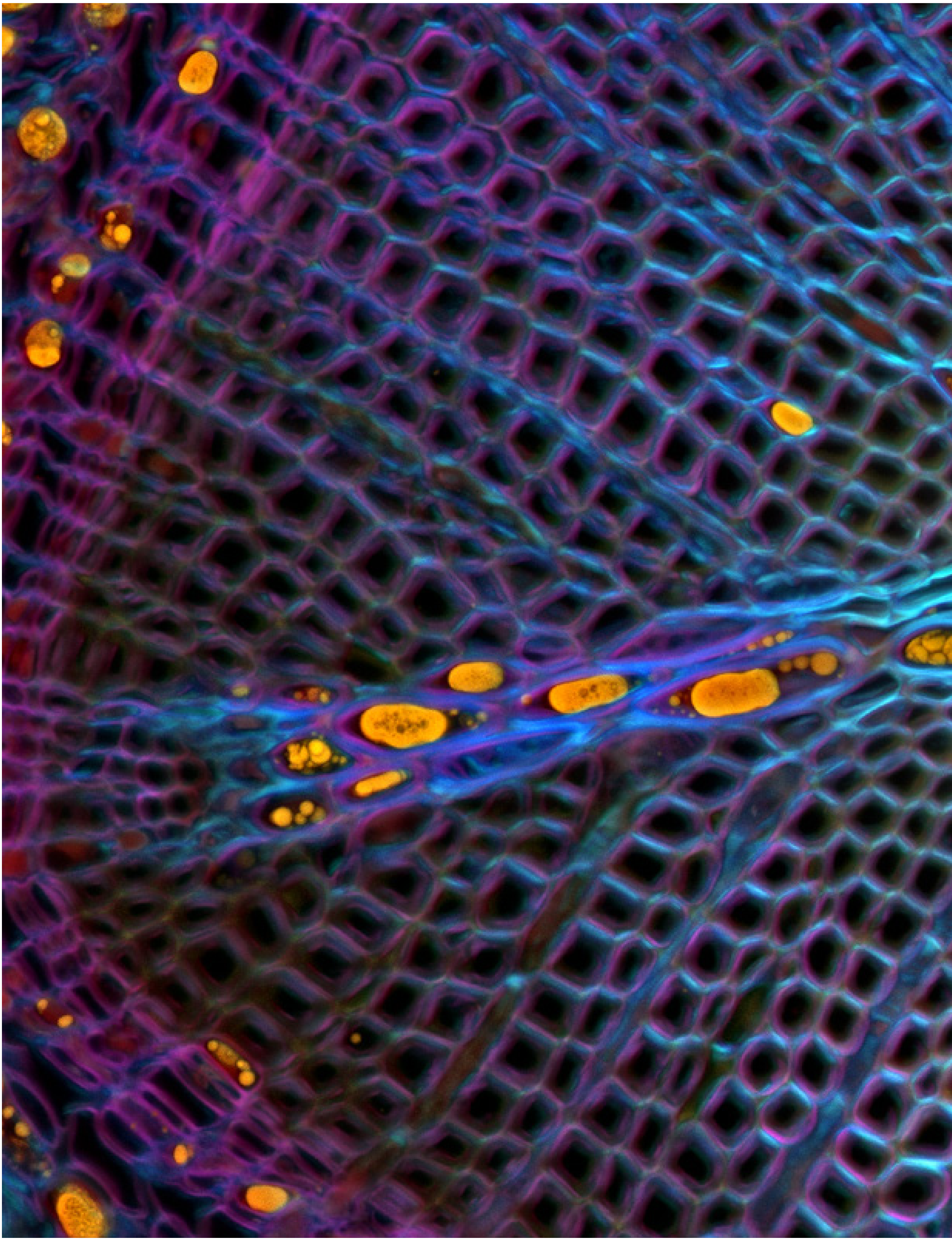
Cross-section through a young shoot of a juniper.

Pp. 126-127 and 128-129 show structure of xylem and cross-section of the central resin conducting channel respectively.

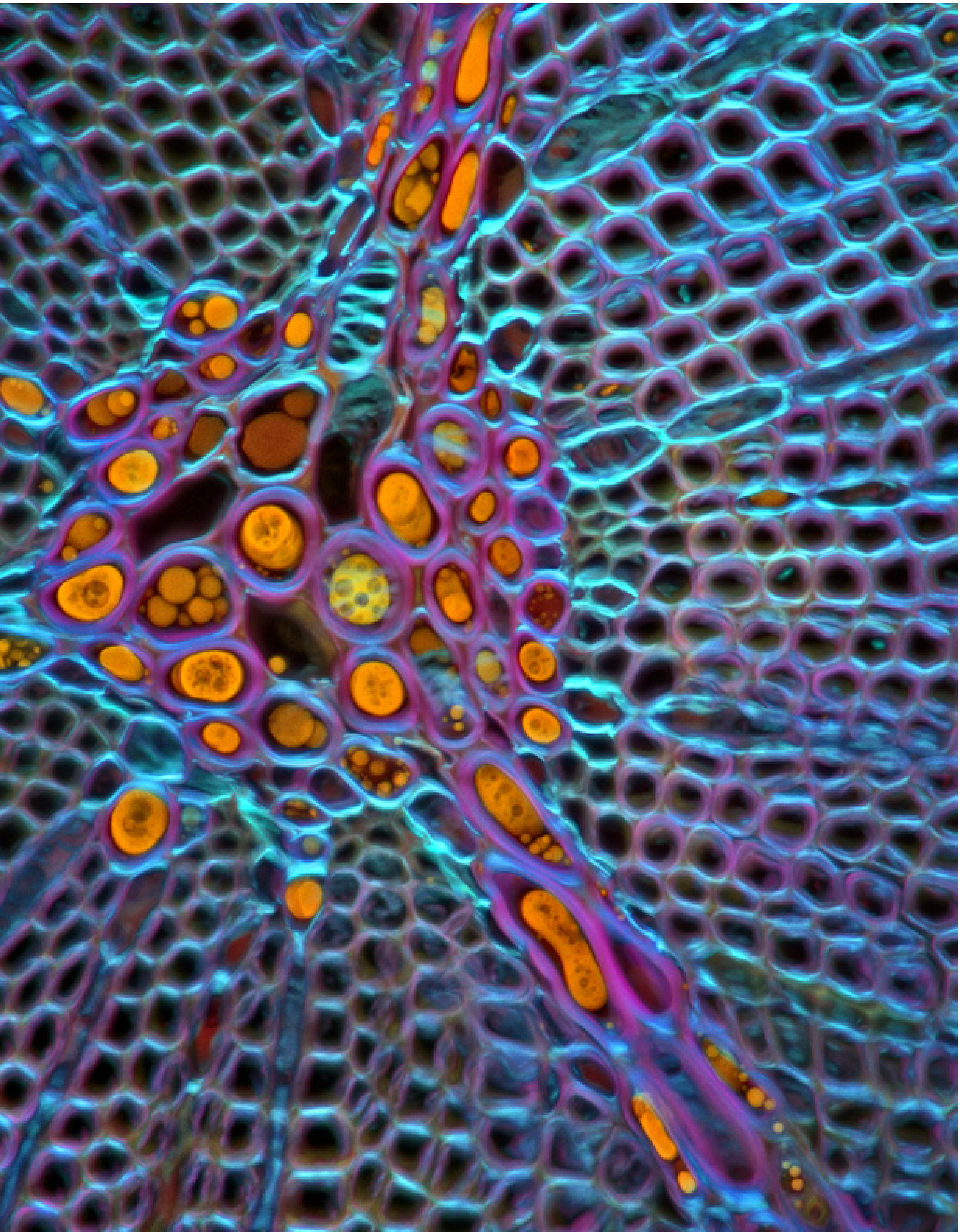


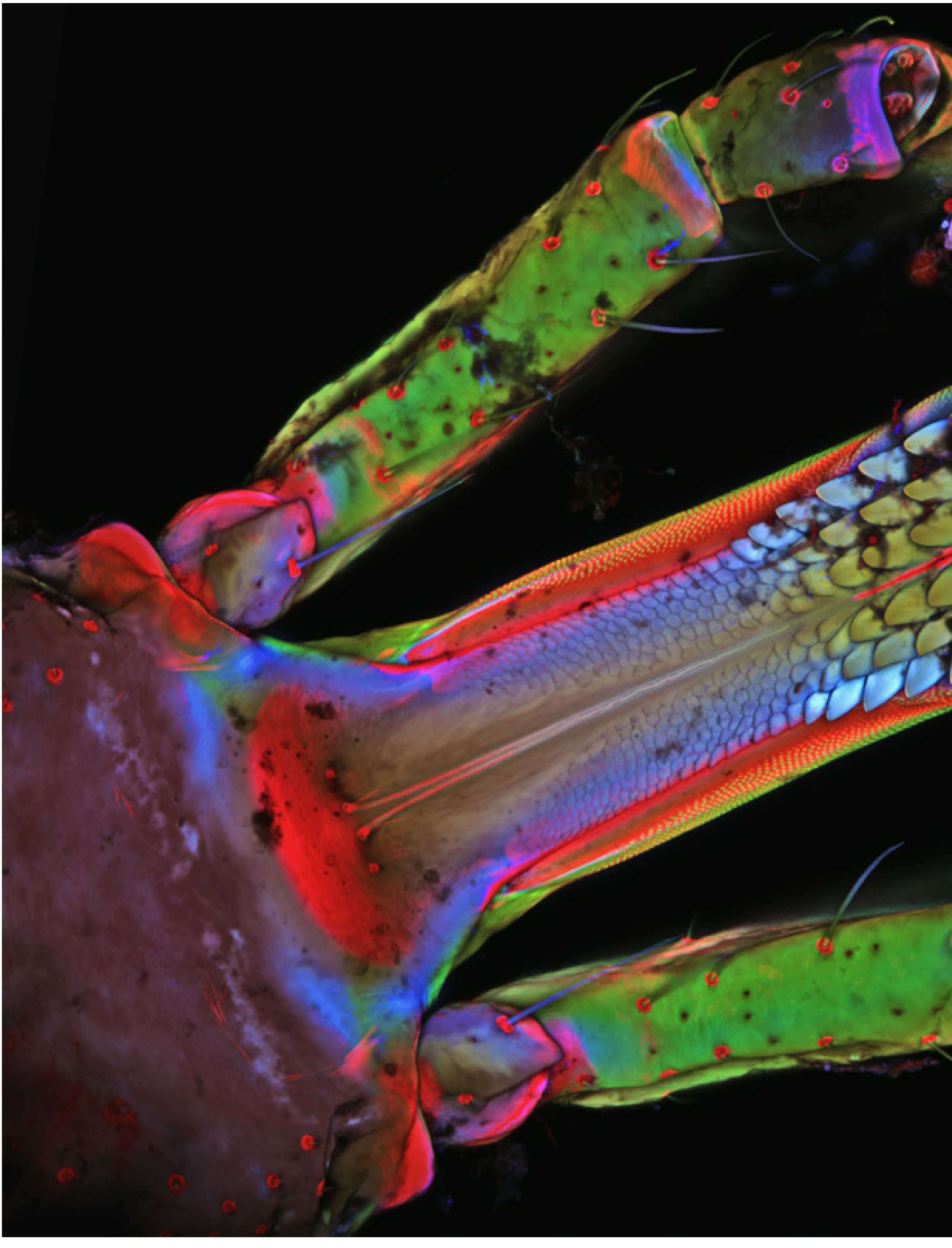
Juniper 1 | Igor Siwanowicz | 2012



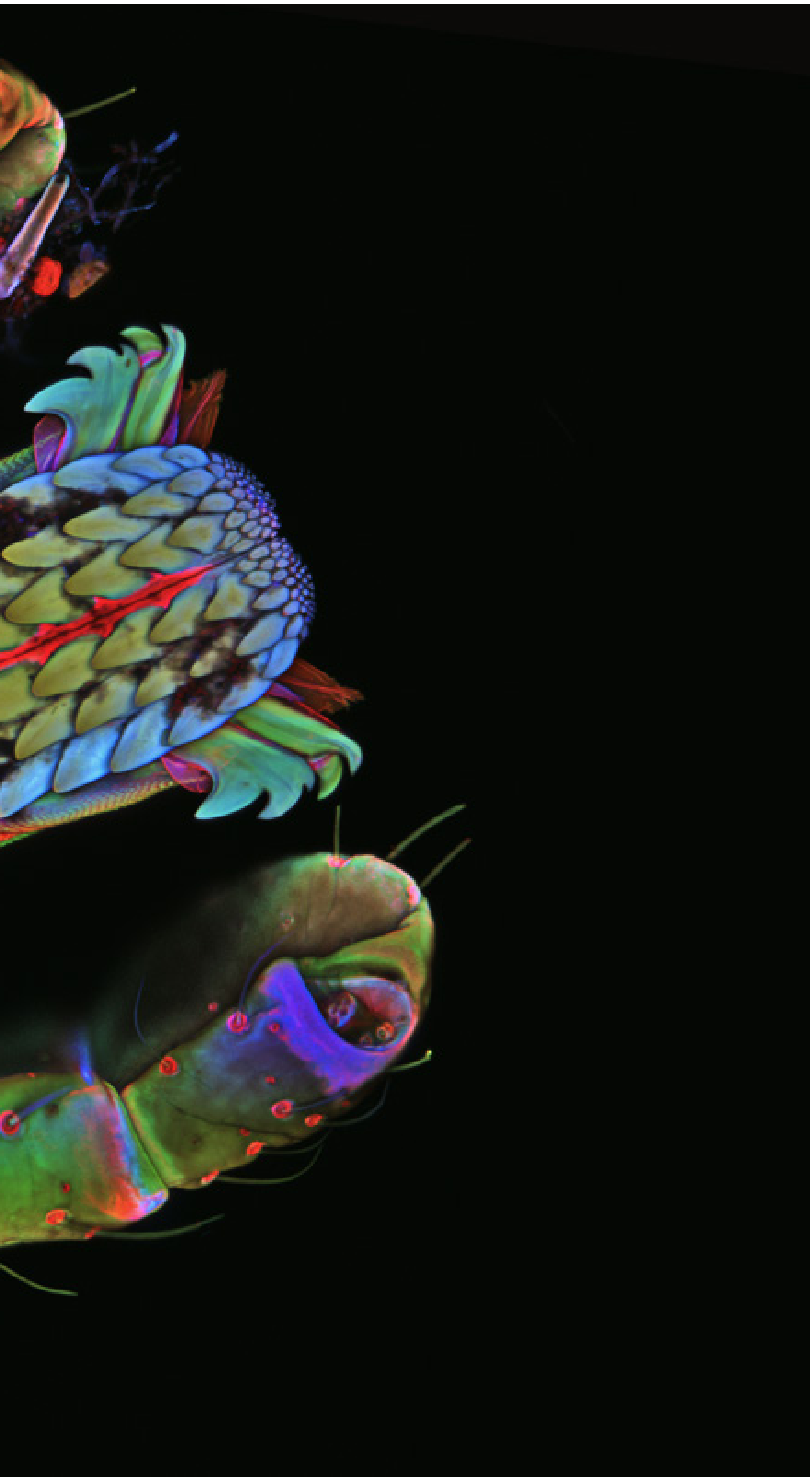


Juniper 2 | Igor Siwanowicz | 2012





Amblyomma mouthparts | Igor Siwanowicz | 2012

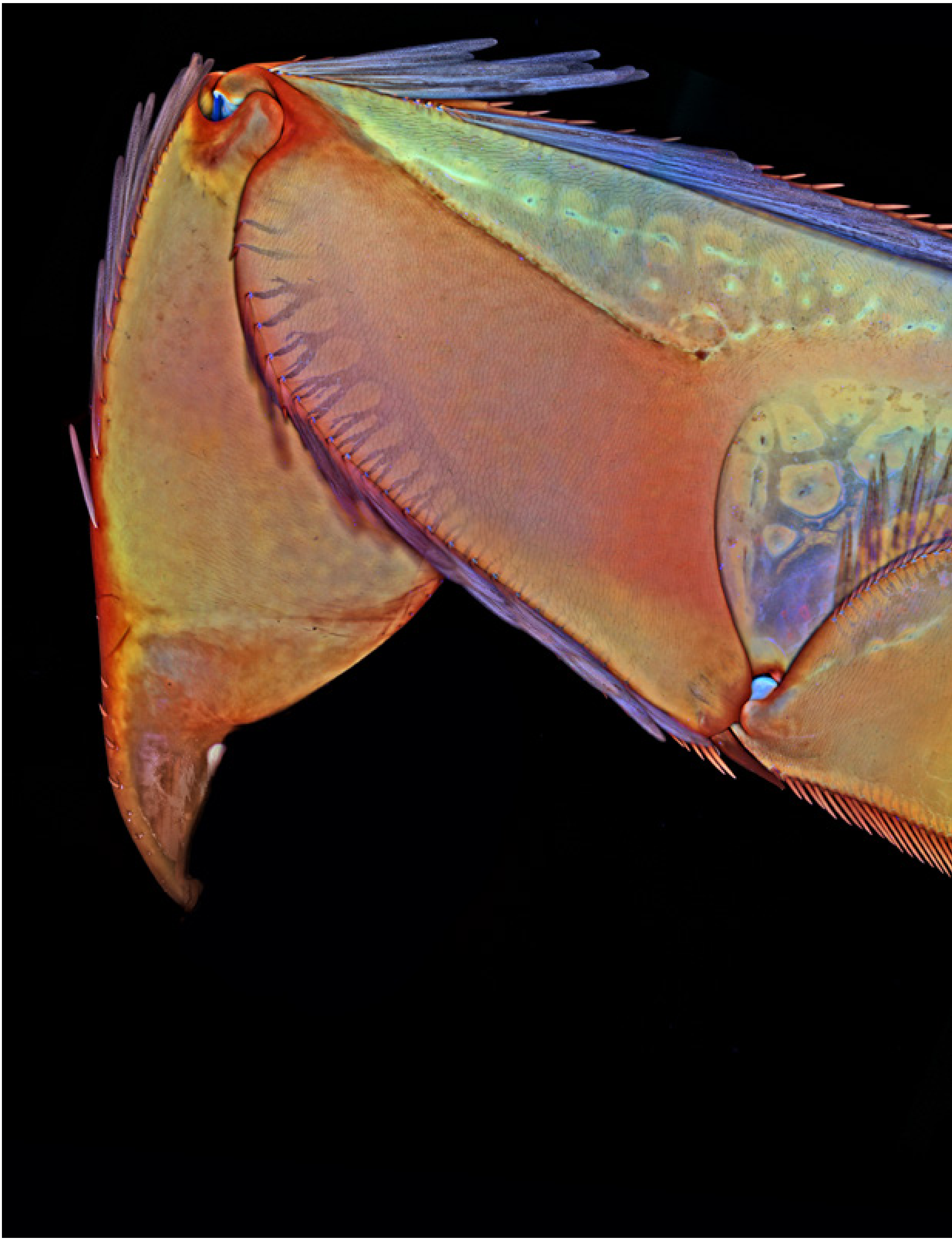


Mouthparts of a lone star tick (*Amblyomma americanum*), ventral side.

Colors represent varied affinity of the insect's exoskeleton to chitin-binding dyes reflecting different structural properties of chitin.

Jagged structure in the center is hypostome, the digits of chelicerae are visible as hook-like blades near hypostome's top; palps flank the structure from both sides.

Length 1 mm.



Whirligig beetle leg (Gyrinus sp.) | Igor Siwanowicz | 2012

This page: Colors represent varied affinity of the insect's exoskeleton to chitin-binding dyes reflecting different structural properties of chitin.

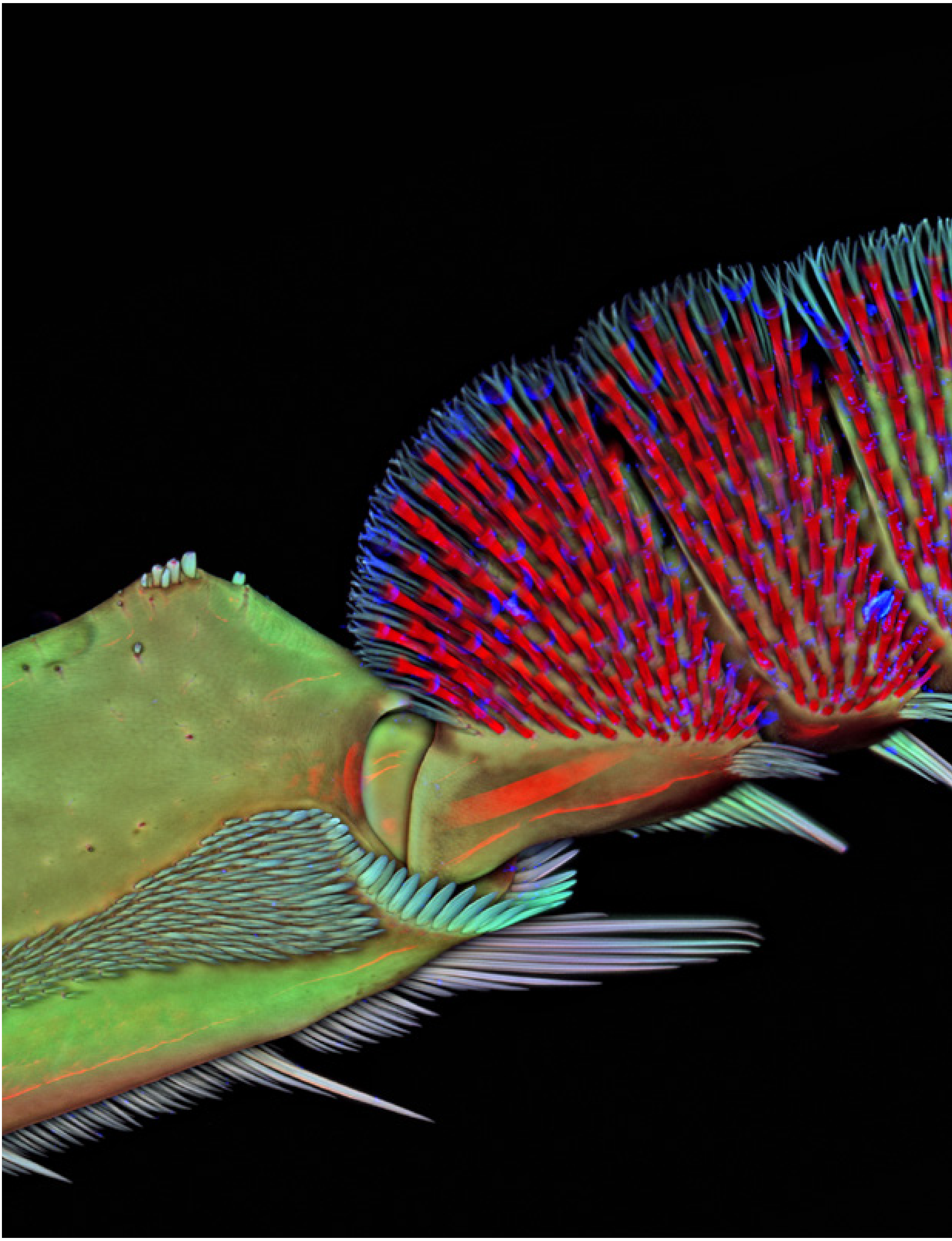
Whirligig beetles are semi-aquatic insects with a morphology and propulsion system highly adapted to their life at the air-water interface.

The 2 millimeter-long paddle-like appendage of this beetle is one of the most efficient propulsion systems known to biology.

Next page: The ventral side of tarsal segments of the beetle's front appendage are covered in thin, bifurcating hairs.

The foot resembles adhesive pads of gecko lizards and probably the same principles of attaining stickiness apply.

The adhesive pad is used by the beetle to capture pray and in mating – to attach to the female's carapace.



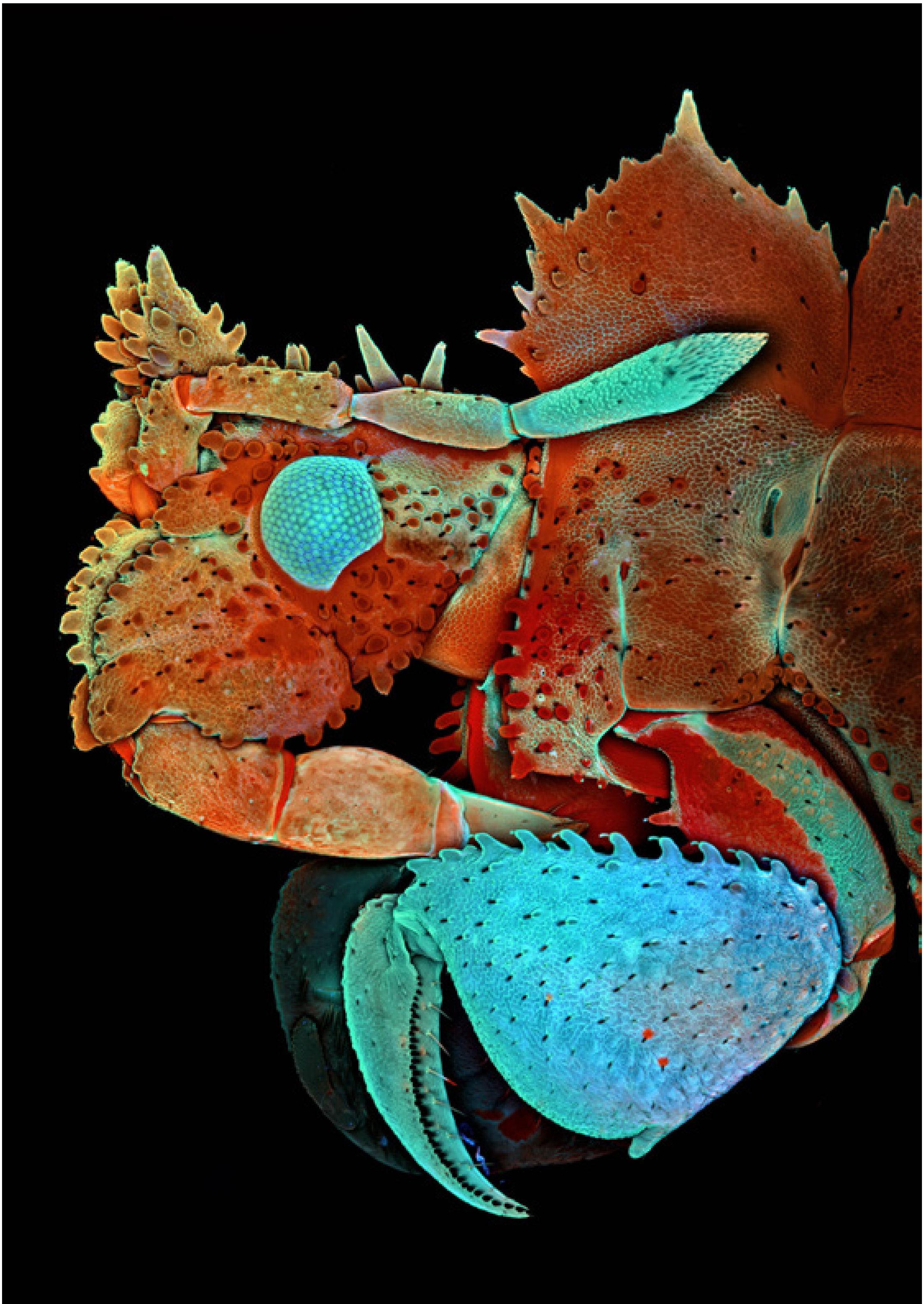
Front leg (part of tibia, tarsus, tarsal claws) of a whirligig beetle (*Gyrinus sp.*) | Igor Siwanowicz | 2012

Last instar of an Ambush bug (*Phymata sp.*)

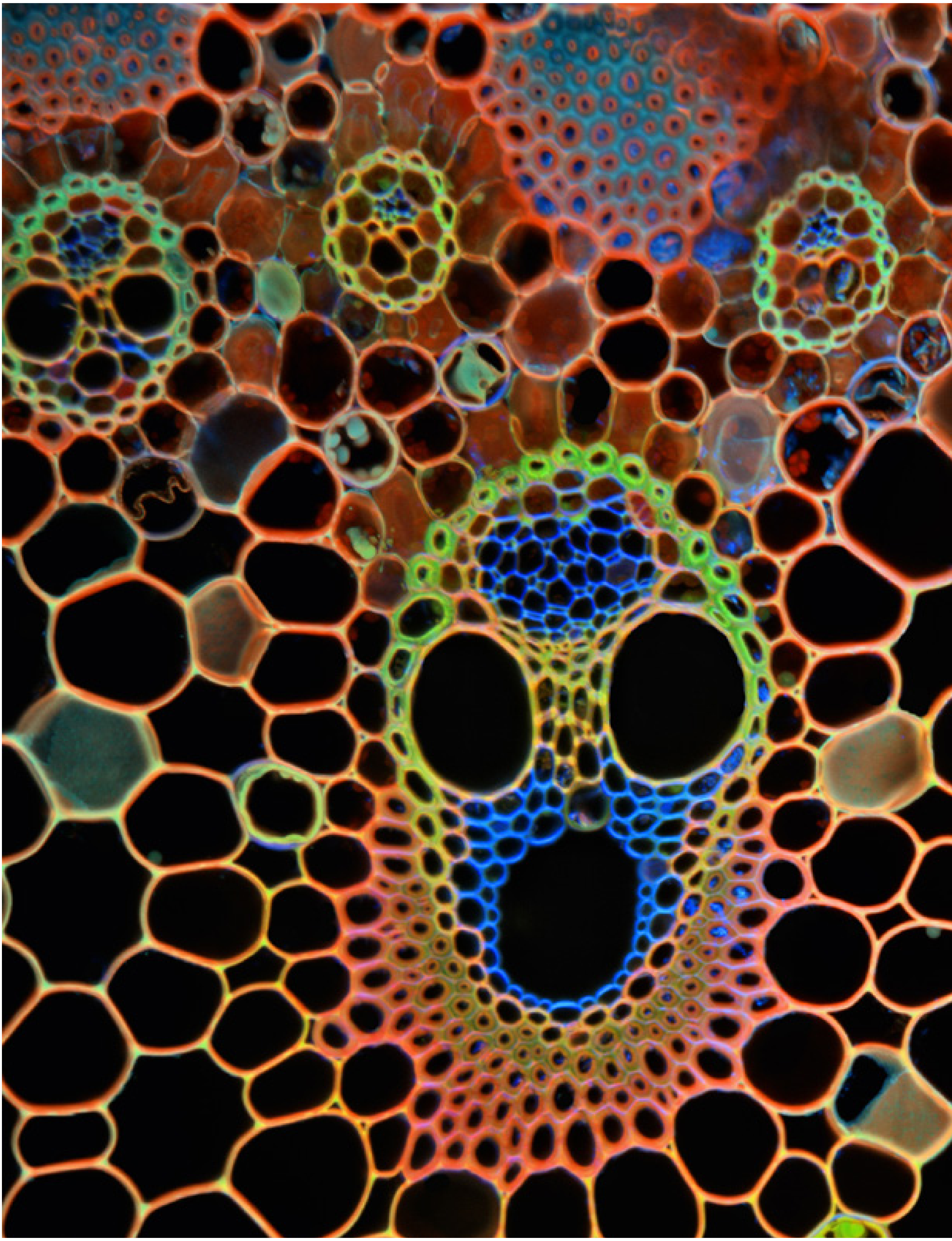
Colors represent varied affinity of the insect's exoskeleton to chitin-binding dyes reflecting different structural properties of chitin.

Insect's total length: 3 mm.

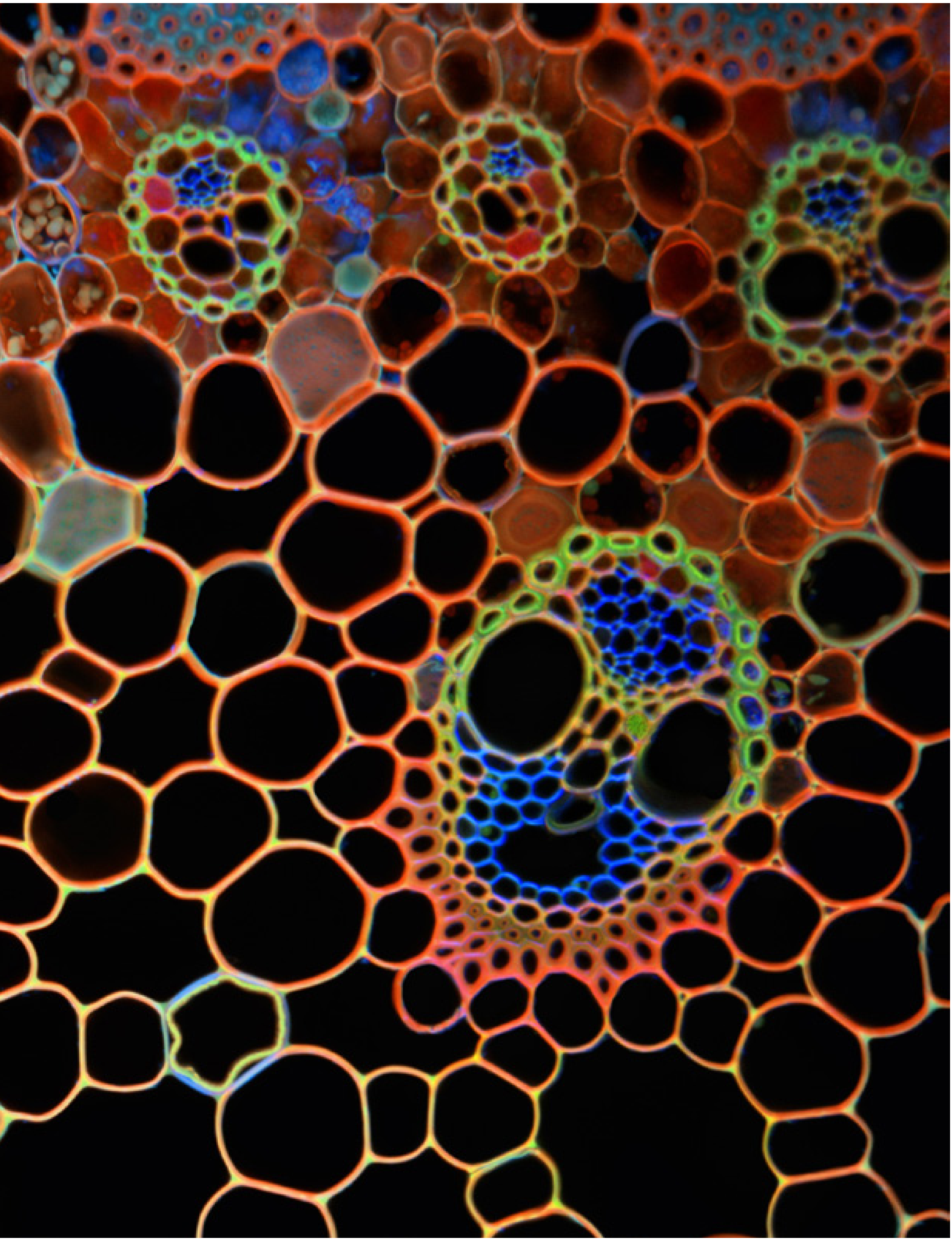
Piercing/sucking mouthparts and raptorial front legs are visible, as well as fragments of jagged pronotum.

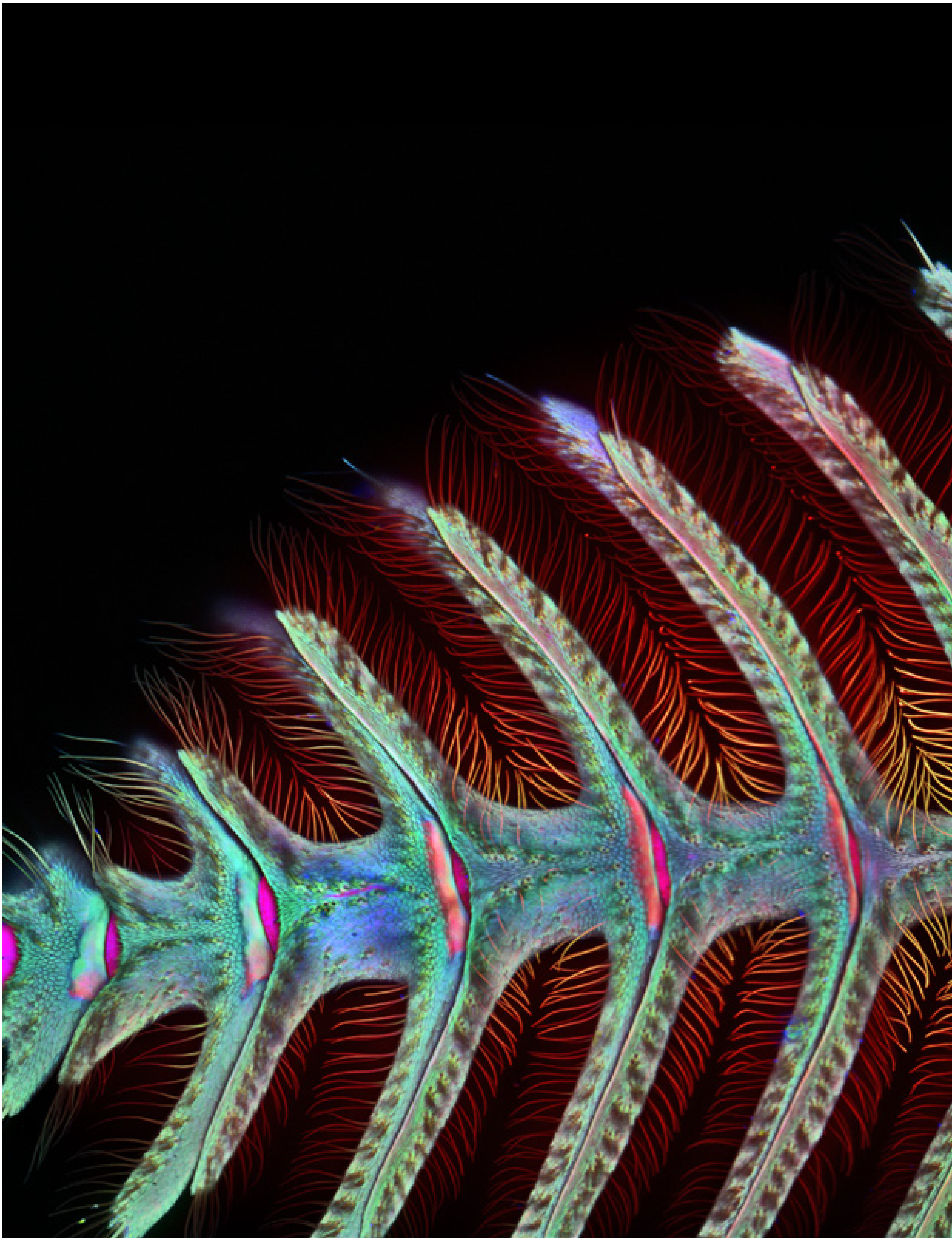


Assassin nymph | Igor Siwanowicz | 2012

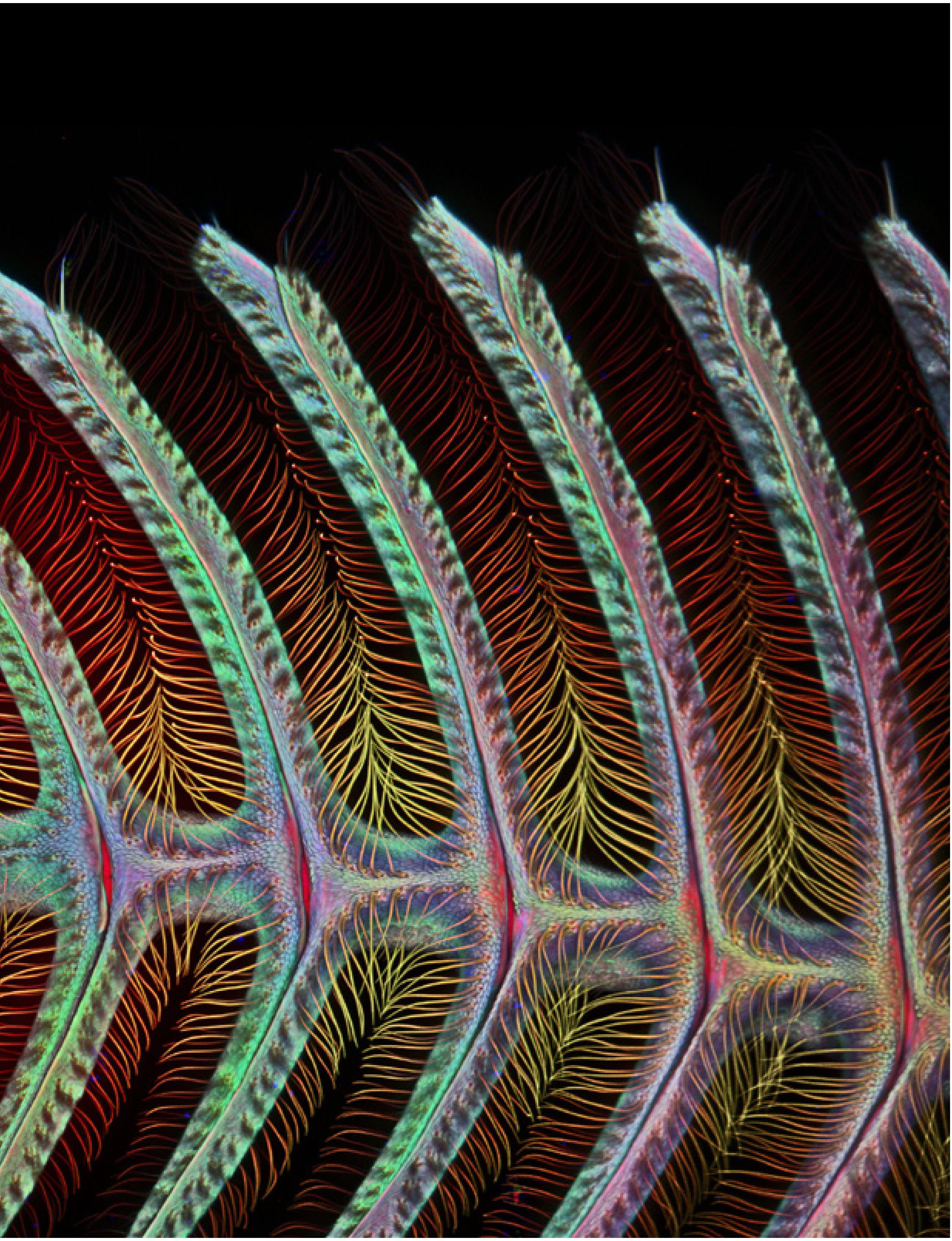


Grass: cross section through a stem of grass at 200x magnification | Igor Siwanowicz | 2012

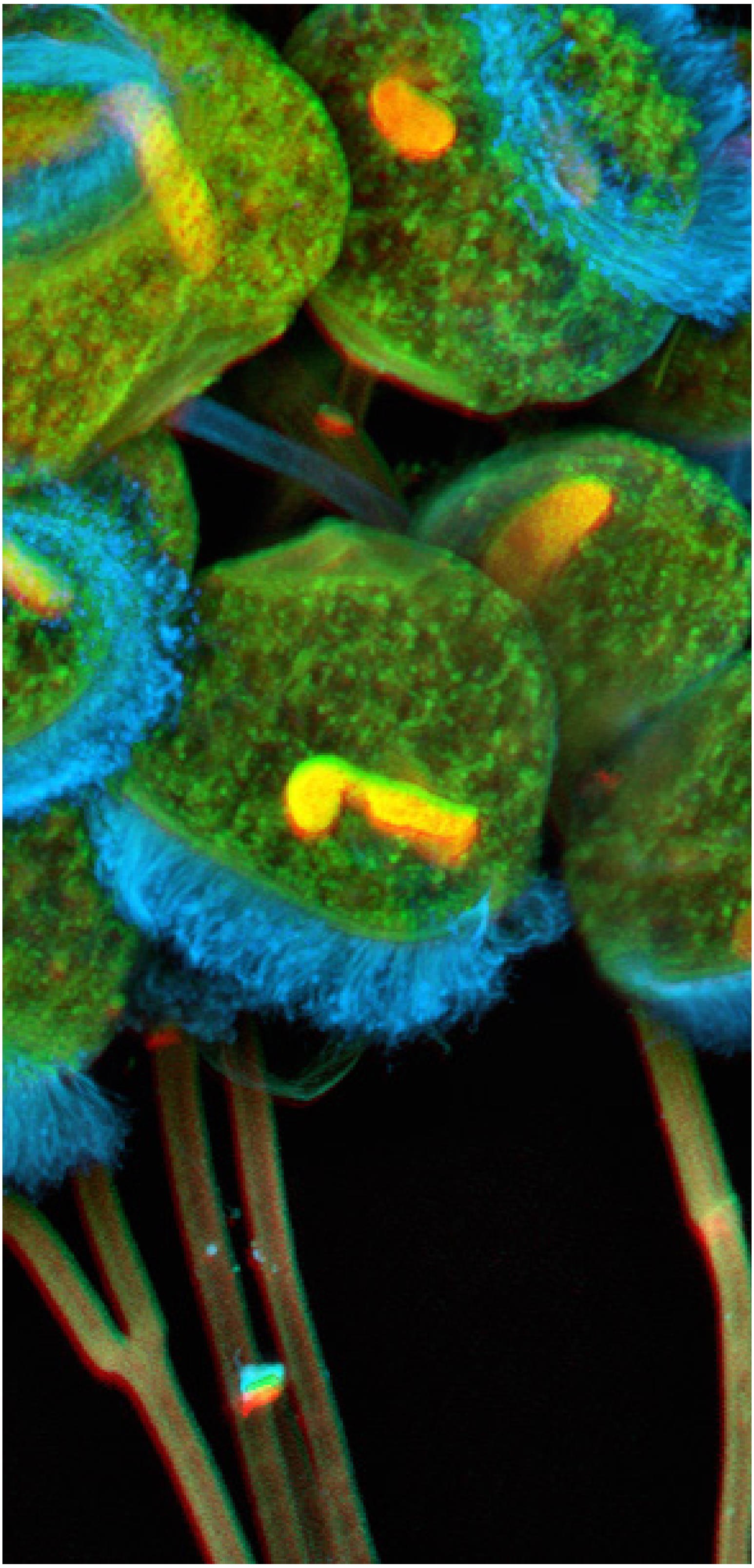




Moth antenna | Igor Siwanowicz | 2012



Carchesium | Igor Siwanowicz | 2012

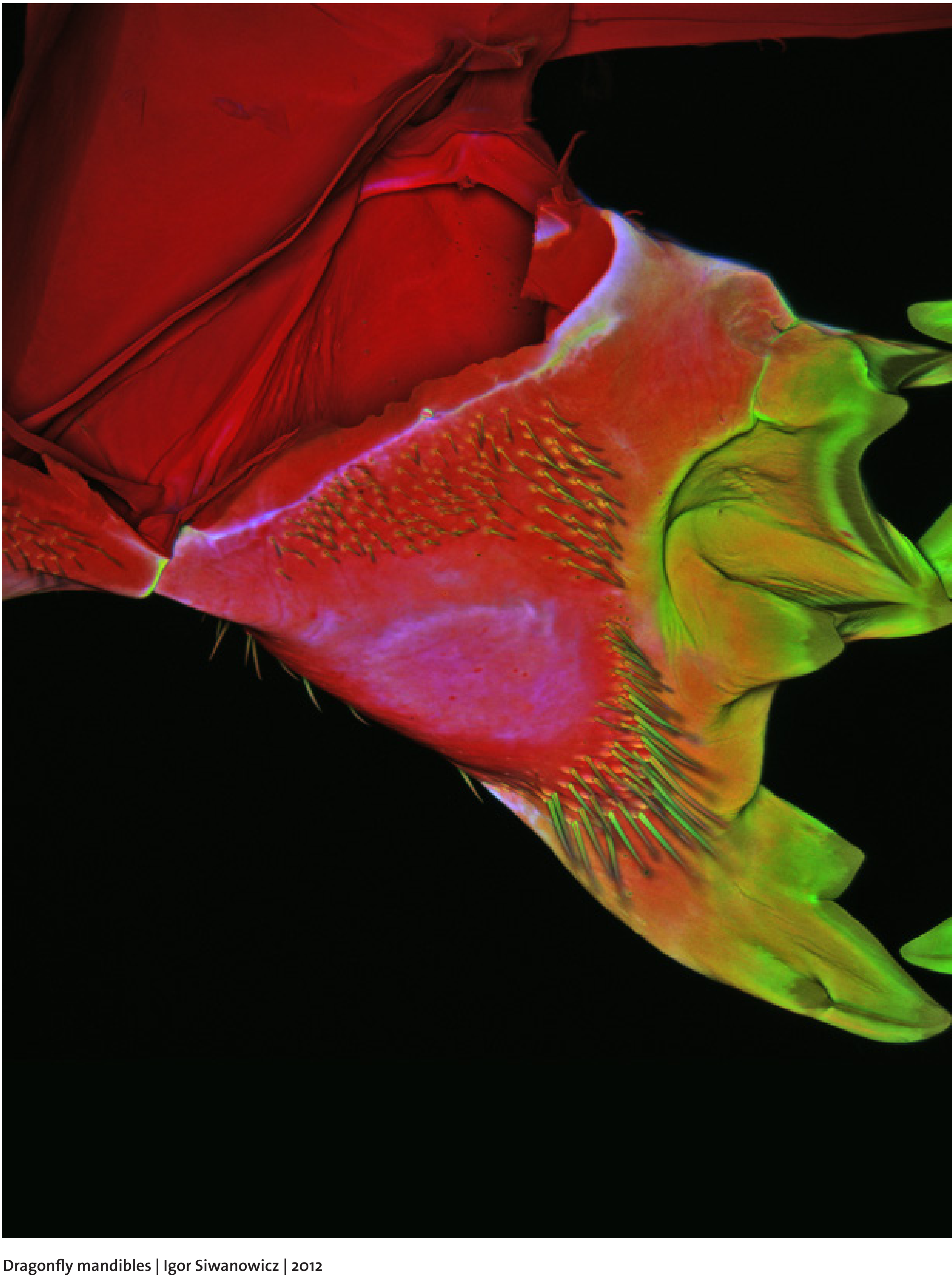


Colonial single-cell protozoan

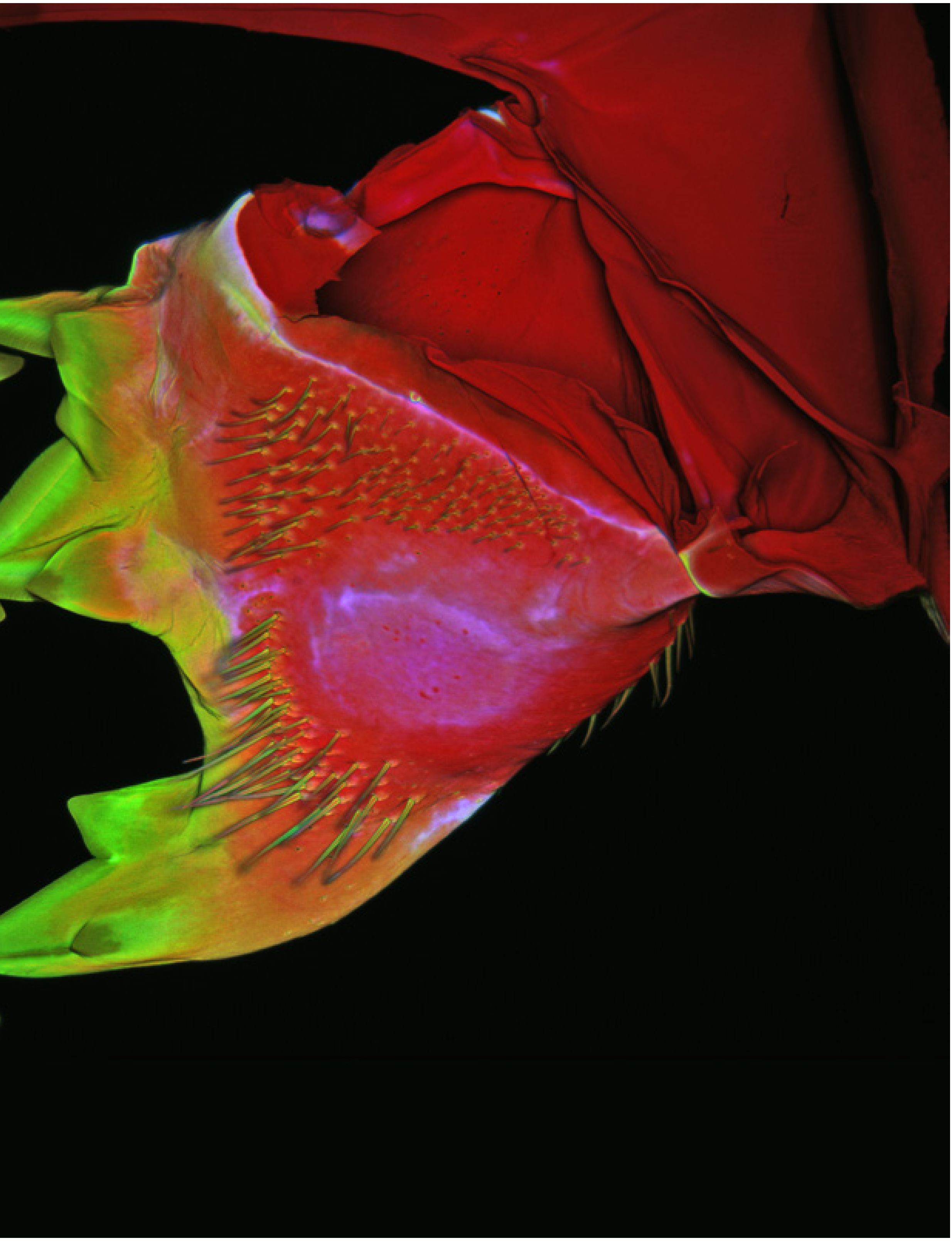
Nuclei are visible as yellow-orange elongated shapes, cilia – bright blue.

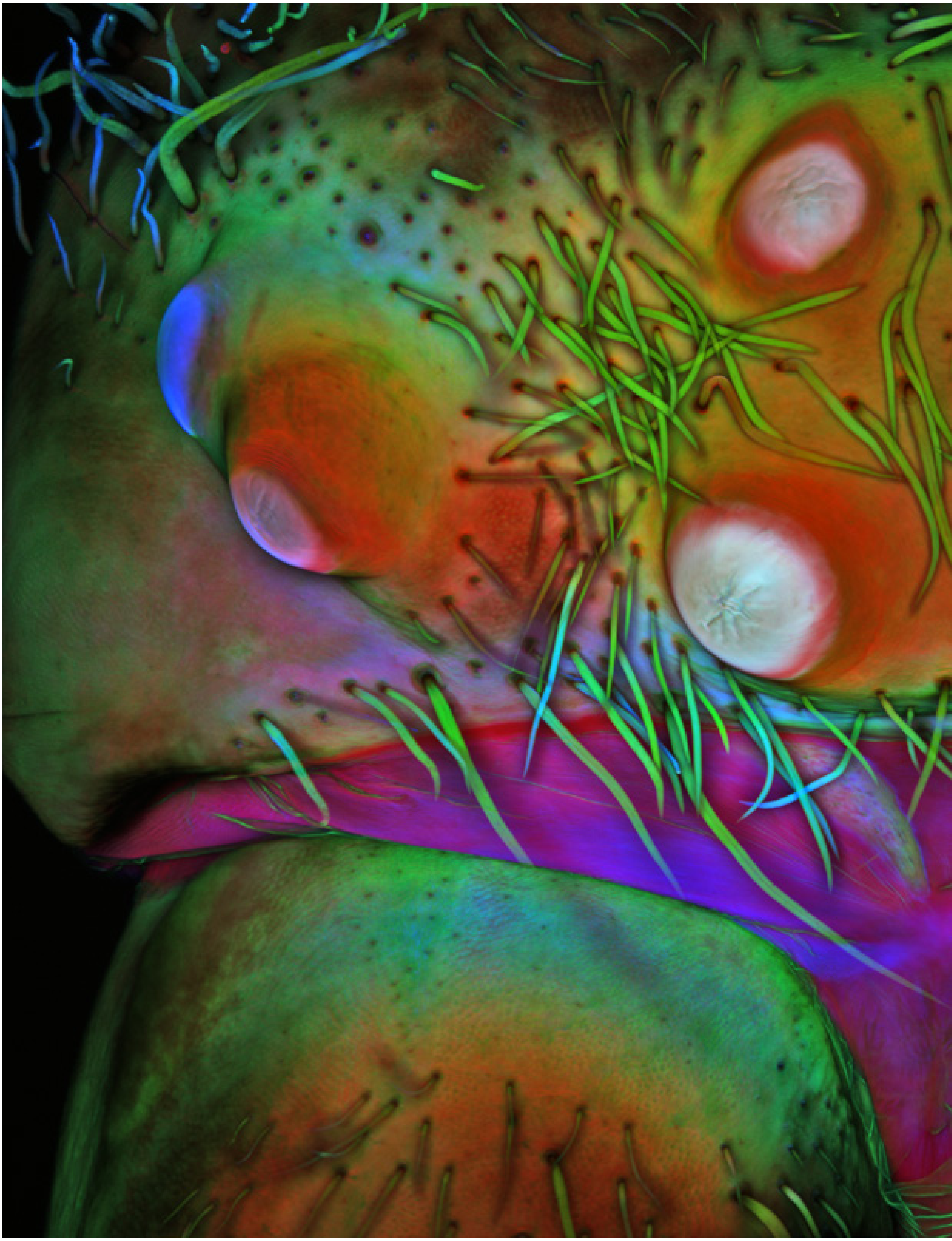
The Carchesium reproduce by budding, where the cell undergoes longitudinal fission and the two daughter cells form their own stalks, giving rise to the branching pattern of the colony.

Each cell is 100-150 micrometers in diameter.

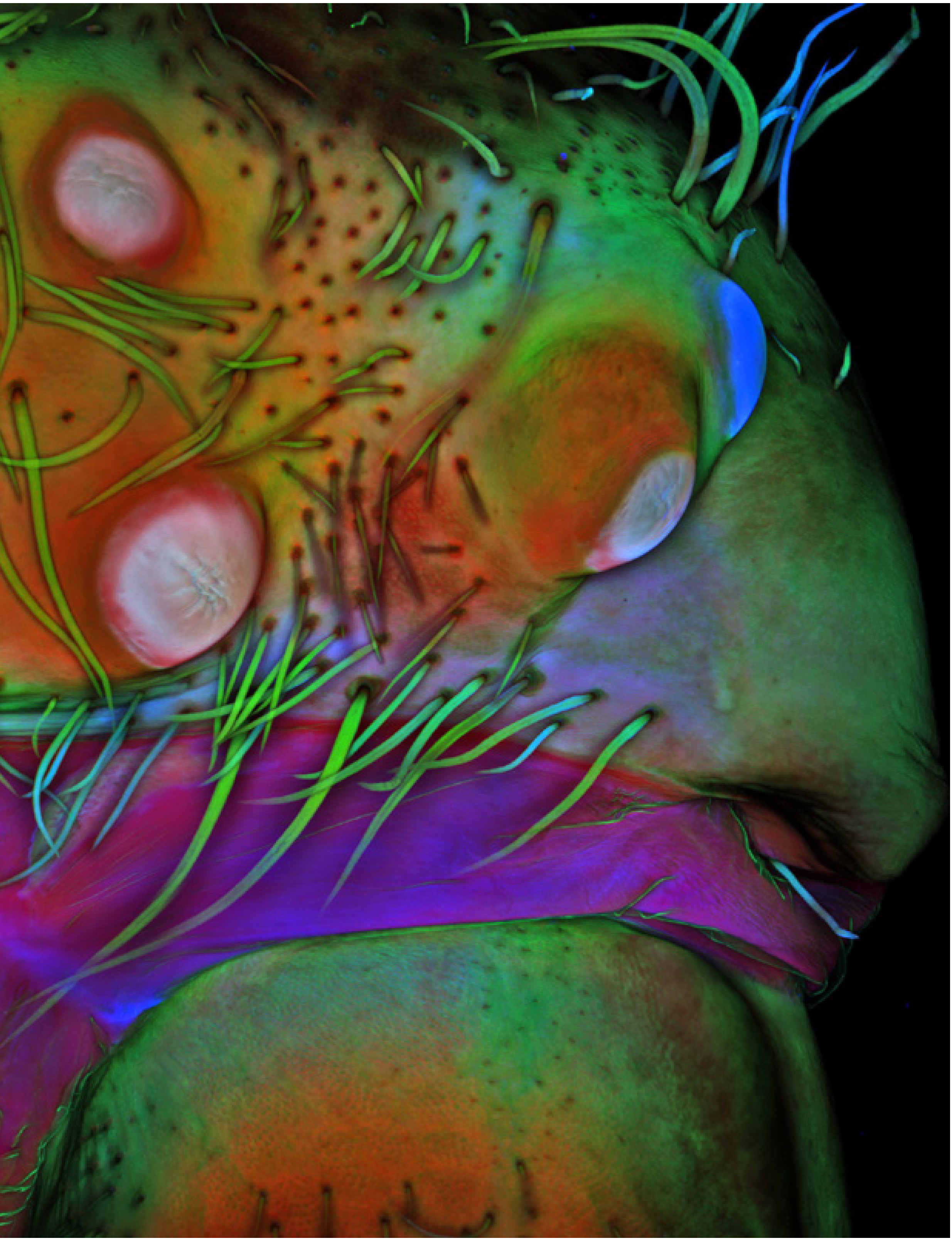


Dragonfly mandibles | Igor Siwanowicz | 2012

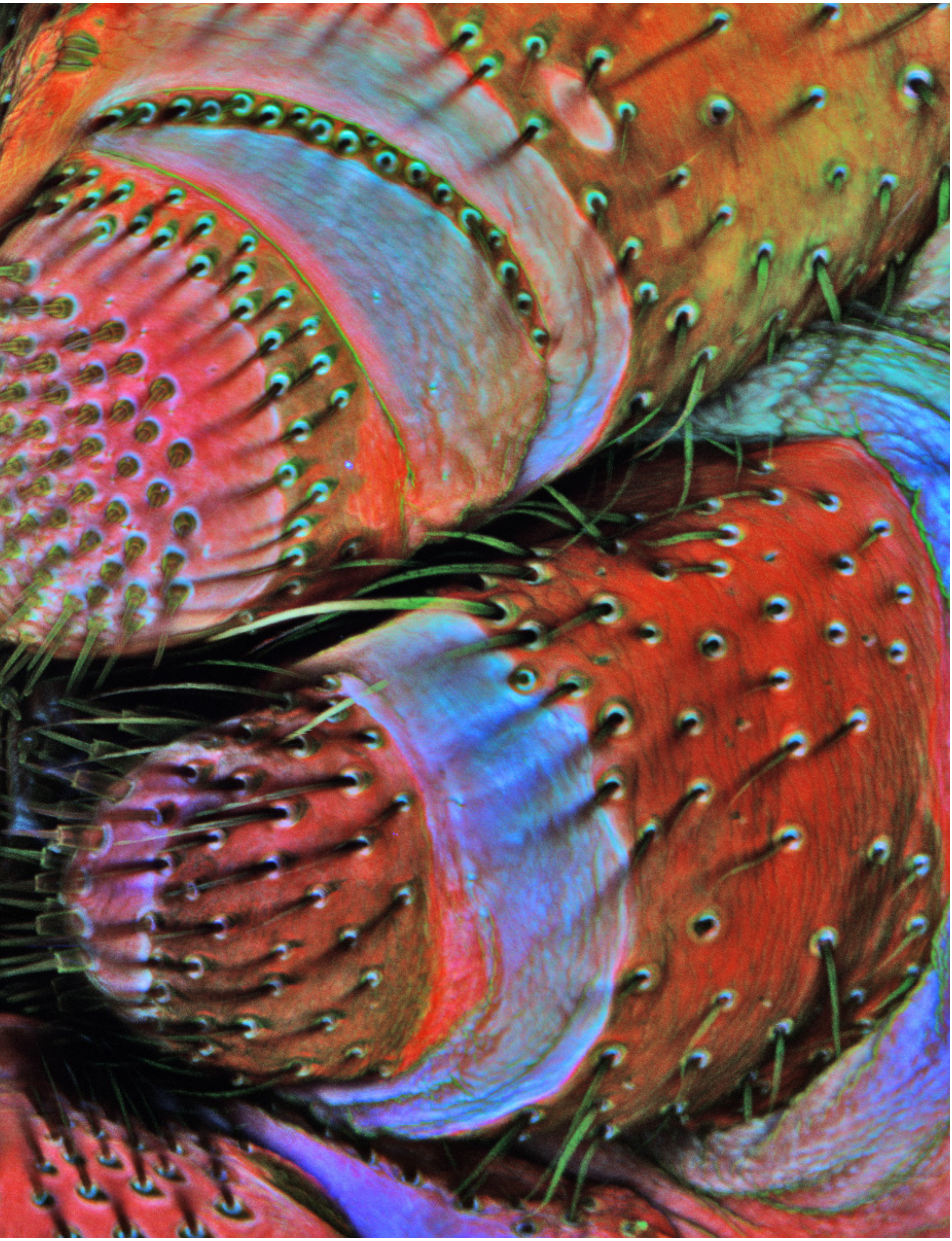




Garden spider face | Igor Siwanowicz | 2012



Spinnarets [detail] | Igor Siwanowicz | 2012



Barred owl flight

Photo: Photomatt28, 2006 | Flickr cc

Tools

Structure-Behavior-Function and Functional Modeling

Norbert Hoeller

Structure-Behavior-Function and Functional Modeling

What is the tool?

Originally developed for systems and software engineering, functional modeling provides a structured method of analyzing, documenting and communicating the components and behaviors of systems. Functional modeling is particularly useful for complex, nested systems involving cause-and-effect relationships where the emphasis is on what the system does, rather than what it is.

Structure-Behavior-Function (SBF) is one type of functional modeling developed by Ashok Goel and his team at the Georgia Tech's Design & Intelligence Lab (http://dilab.gatech.edu/). It has been used extensively by students in the Center for Biologically Inspired Design (http://cbid.gatech.edu/) to support inter-disciplinary problem-solving and analogical reasoning between the domains of biology and engineering.

Why is the tool needed?

As we fix the simple problems within a situation, we increasingly need to overcome more complicated challenges involving multiple agents and interactions. Rather than being single problems to be solved, these situations typically involve complex systems comprising sub-systems where interactions at one level may be driven by components and interactions at another level. Methods like SBF organize the structure (what), behavior (how) and function (why) of systems, sub-systems and the interactions between levels.

Who is the tool for?

In spite of advances in computer-aided design, designers have relied traditionally on relatively simple methods for analyzing and documenting systems. As the design space becomes more complex, new methods are required that can help designers understand, decompose and document the critical aspects of the systems that will influence the final design solution.

How could it be used?

Increasingly, designers need to work in interdisciplinary teams where differences in language and culture can make communication challenging. For example, a biologist studying the behavior of fish may focus on the functional aspects and the evolutionary drivers. In contrast, an engineer may focus on the aerodynamic properties. Both perspectives are correct and both can be relevant to a specific problem.

SBF can help team members develop a common, language-neutral method of communication that facilitates collaboration and effective teamwork. Application of structure-behavior-

Salmon attempting the climb

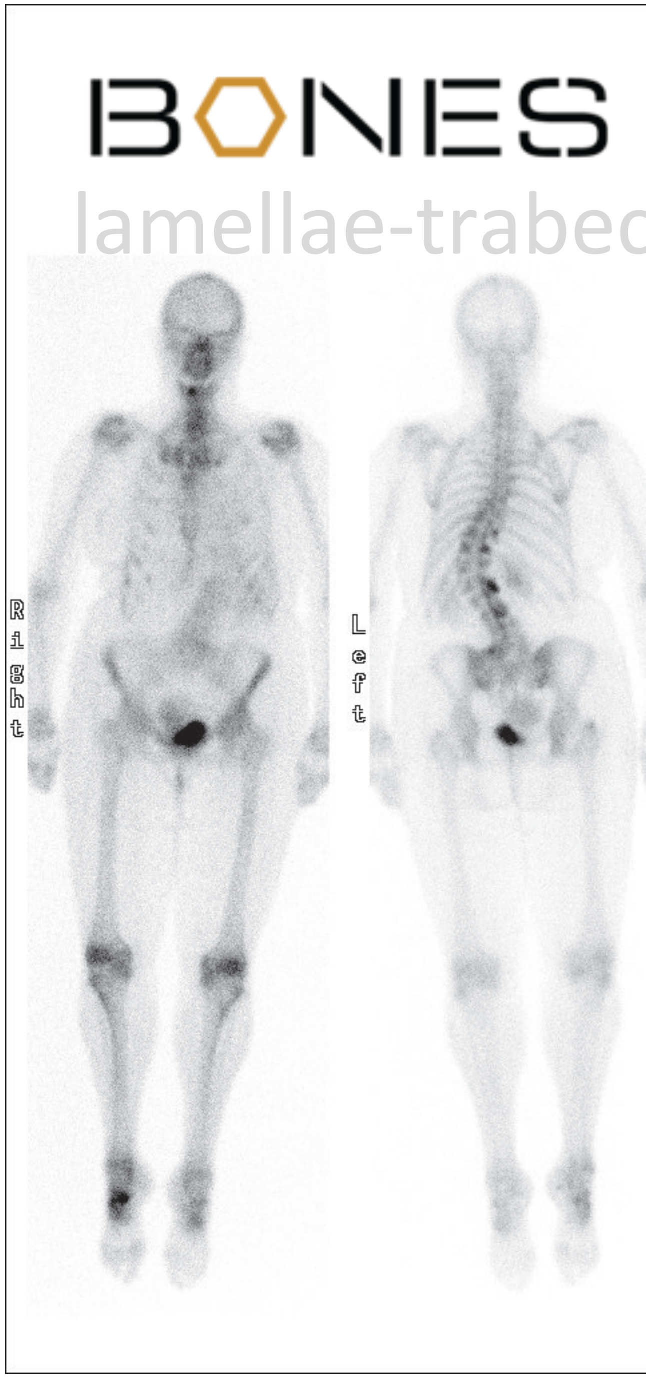
Photo: Scott Ableman, 2010 | Flickr cc

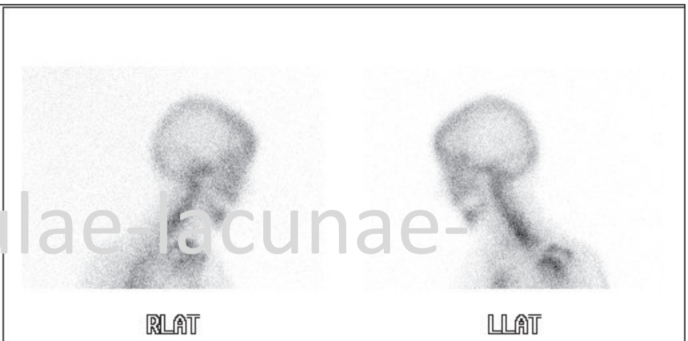
function in Georgia Tech's biologically inspired design class of 2010 enabled the interdisciplinary team to develop a common description of bone function and the transduction of mechanical energy to electrical energy, a key feature of their final design.

Lastly, bio-inspired designers often have difficulty focusing on functionality, causing them to develop inaccurate or incomplete analogies or fixating on irrelevant aspects of the problem or solution space. SBF is grounded in function while integrating it with an understanding of structure and behavior. Designers can start by modeling the technical system of interest, use the model to engage biologists and extend the model based on their biological analogies and insights.

What is the conceptual approach?

Although design is typically perceived as 'a blank sheet' process, designers often build upon existing solutions. In the late 1980s and early 1990s, formal ways of representing structure, behavior and function were developed as a way to study, describe and systematize this knowledge transfer process. Given a known functionality based on a set of components and behaviors, designers could develop a solution delivering a modified functionality by exploring changes to the known behavior and/or components. Structure-Behavior-Function modeling was developed by Ashok Goel and his colleagues at Georgia Tech's Design & Intelligence Laboratory, building upon Chandrasekaran's Functional Representation scheme.





What?

Mineralized connective tissue: both **organic** (fibrous, high-tensile collagen) & **inorganic** components (crystalline **hydroxyapatite** minerals) in a repeating **lamellar** or Haversian system organization

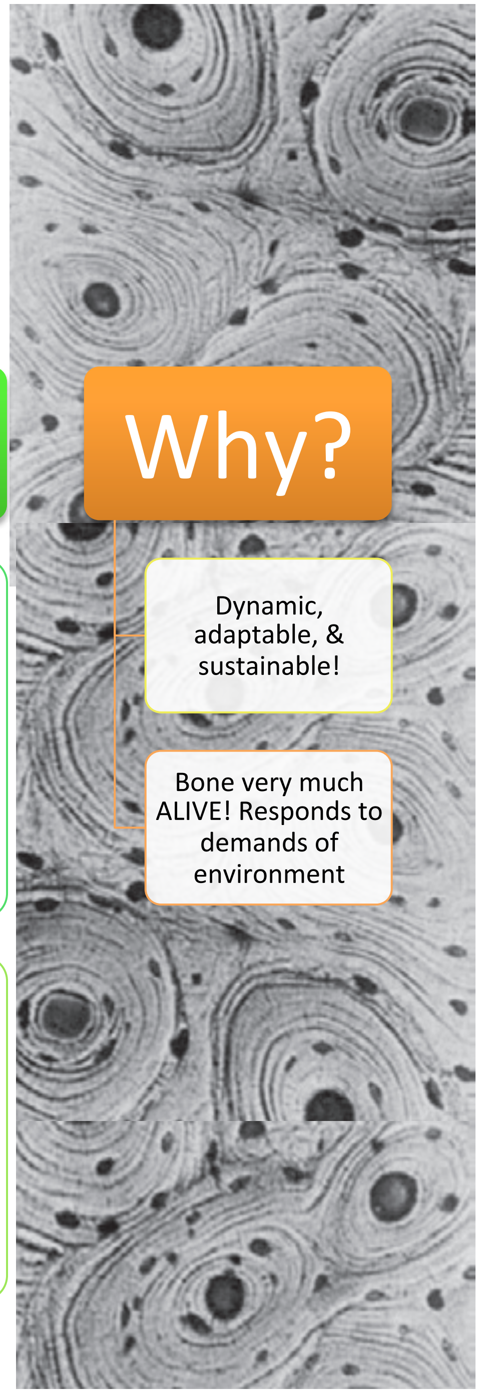
Together impart its piezoelectric properties

How?

Repeated mechanical stress such as in weight-bearing exercise, small electric potentials are generated

In compliance with **Wolff's law**, result in remodeling and thickening of the bone tissue at the points of maximum stress

Why?



Dynamic, adaptable, & sustainable!

Bone very much ALIVE! Responds to demands of environment

Bones | Center for Biologically Inspired Design, 2013 | Georgia Tech

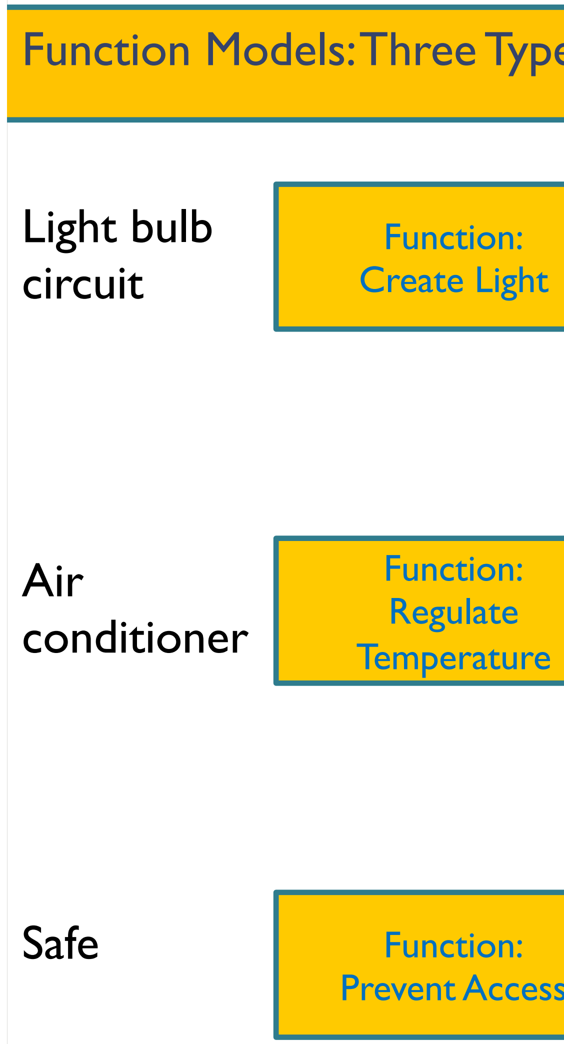
SBF is a structured way of describing three key aspects of a system:

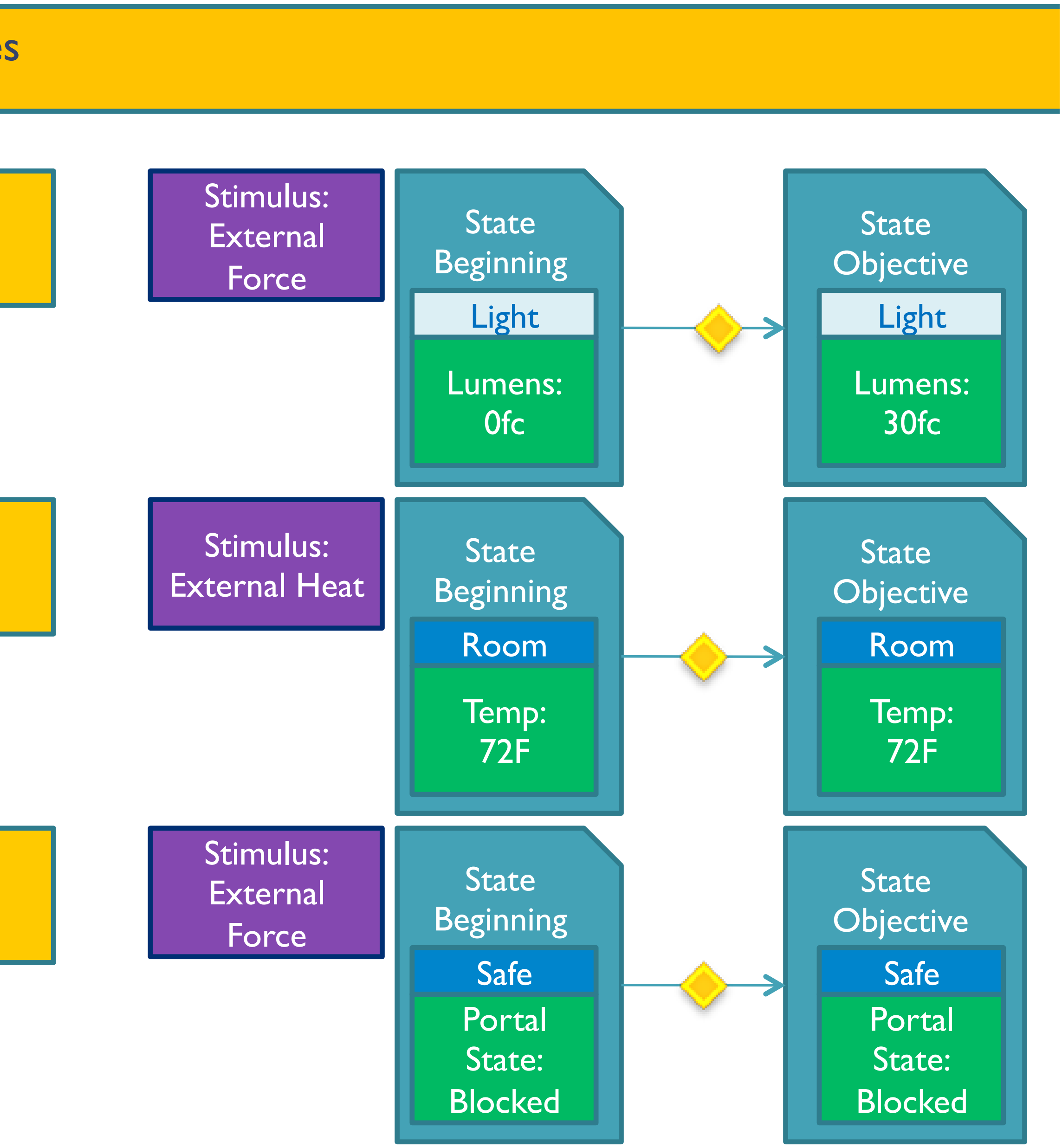
- What are the key elements of the system, their characteristics and their physical relationships? (Structure)
- How does the system change over time due to internal functions, external stimuli or state changes? (Behavior)
- Why does the system act in a certain way? (Function)

A key concept in SBF is the state, a set of the values associated with properties of relevant components of the system at a single point in time. Dynamic systems may have an infinite number of states: designers modeling a system are faced not only with the challenge of identifying the relevant components and properties but also of identifying those states that reflect key transition points.

SBF Function Models

Although the Structure model can be created first, it may be useful to start with the Function model to capture the key or intended functionality of the system of interest. For example, a sponge filters nutrients from water or a flashlight creates light. The long-form description of a function usually involves a subject (sponge, flashlight), a verb (filters, creates), an object (nutrients, light) and optional conditions (from water).





SBF Function Model

Image: Design & Intelligence Lab, Georgia Tech, 2013

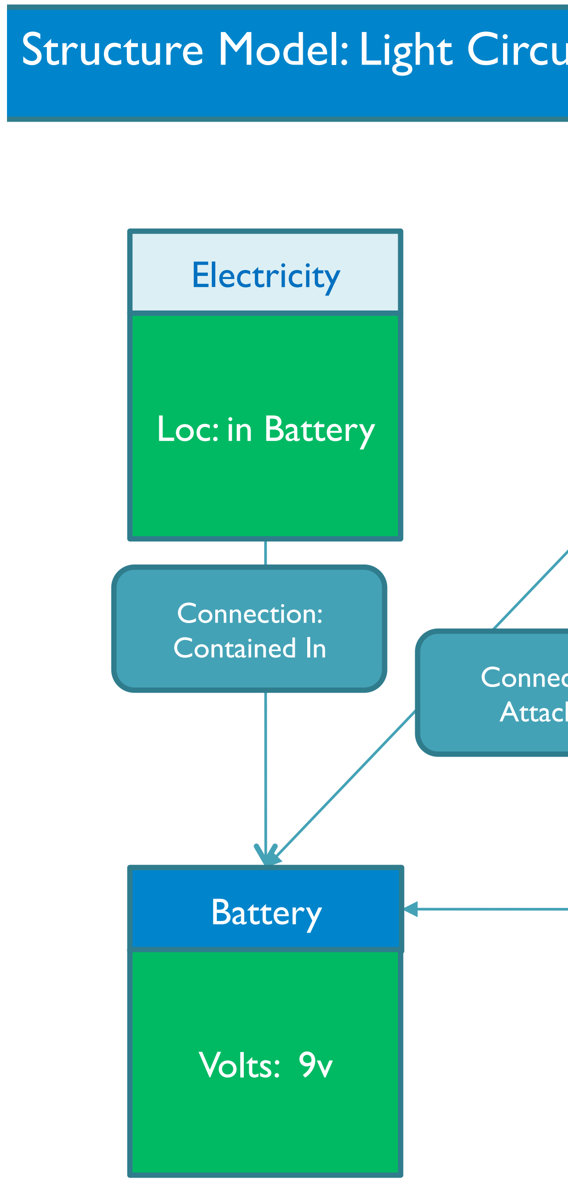
The Function model includes the following elements:

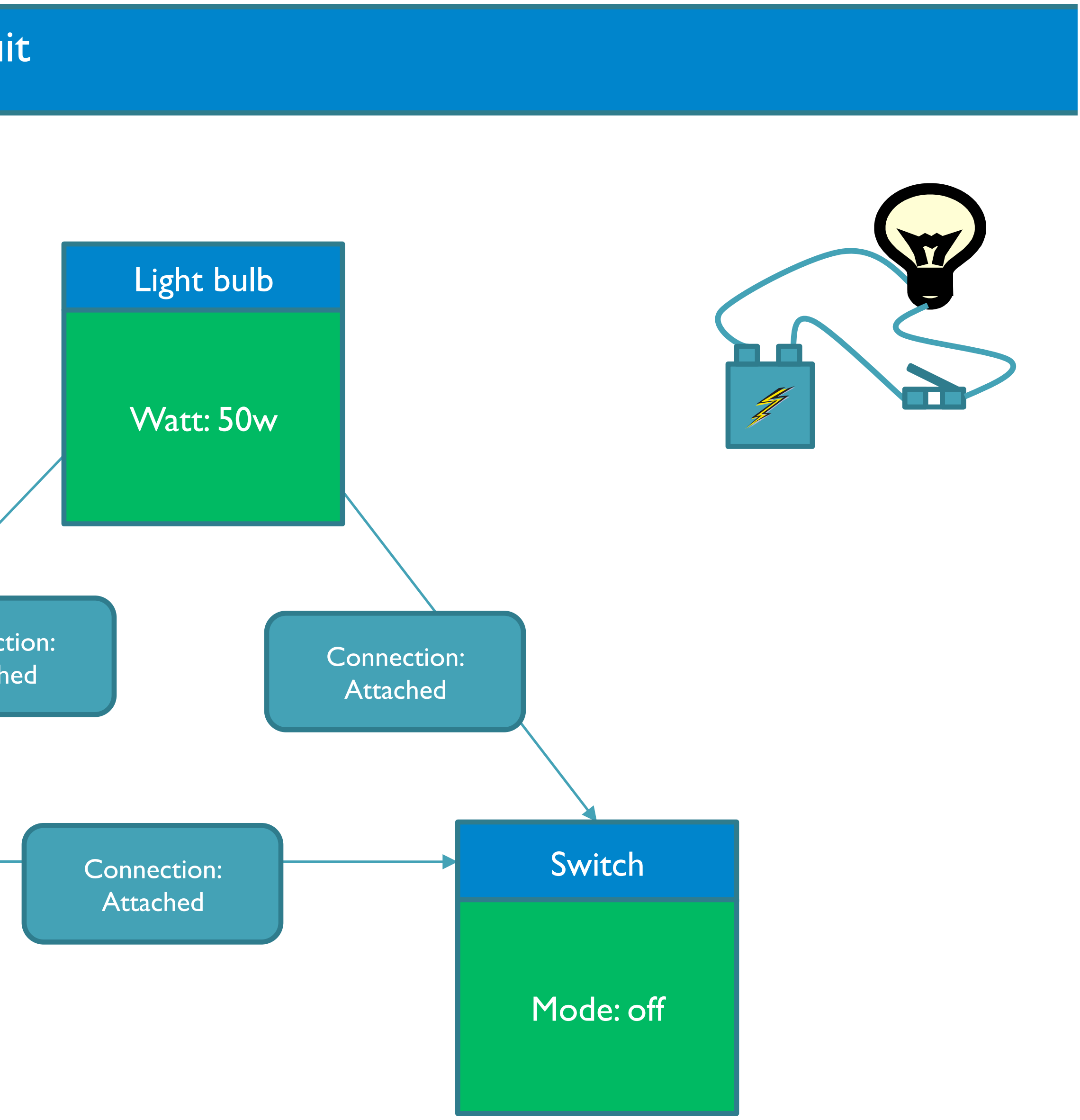
- the primary or intended function of the system
- the beginning state of the system
- the objective state after the function has been achieved
- any external stimuli that help accomplish the functions

Major types of functions include:

- accomplishment, where the objective state is different from the beginning state
- maintenance, where the objective state is the same as the beginning state but intermediate states may be different (e.g., a heating system that maintains a constant temperature)
- preventative, similar to maintenance but the intermediate states are the same (e.g., a security safe that blocks access to the contents)

In addition to describing the changes in the internal state of the system, function models also specify how the system interacts with the external world through external stimuli. These may be conditions that trigger or enable the function to occur.





SBF Structure Model

Image: Design & Intelligence Lab, Georgia Tech, 2013

SBF Structure Models

Structure models comprise:

- components or physical elements of the systems
- substances (can include materials as well as energy and information) that move through the system
- connections that enable interactions between components

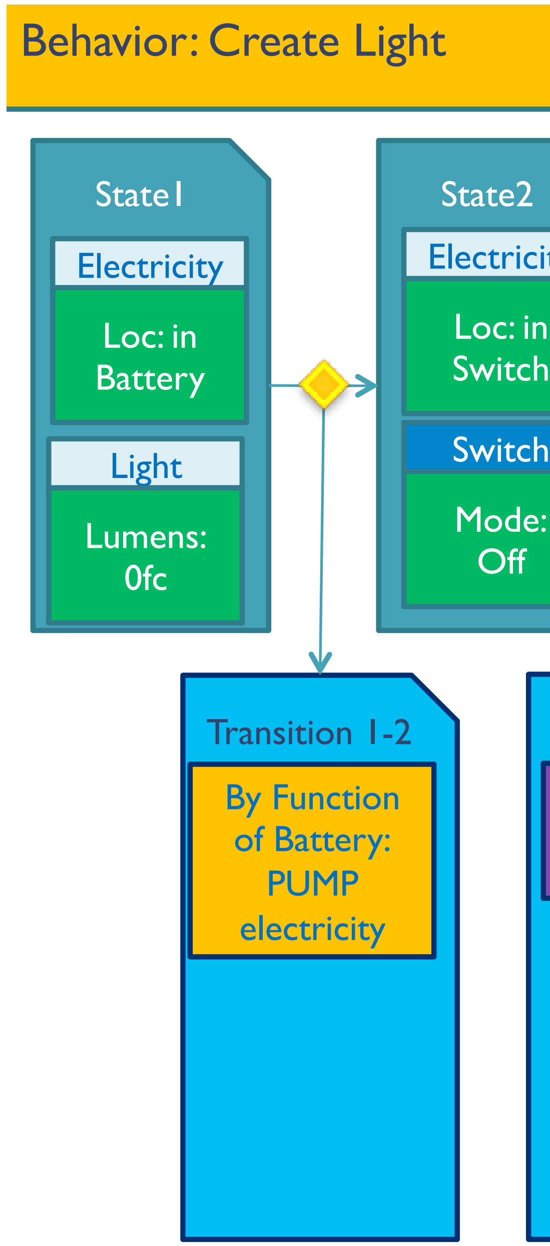
Structure models associate properties with components. Depending on the state of the system, properties are associated with specific values, which can be quantitative (measurable) or qualitative (descriptive).

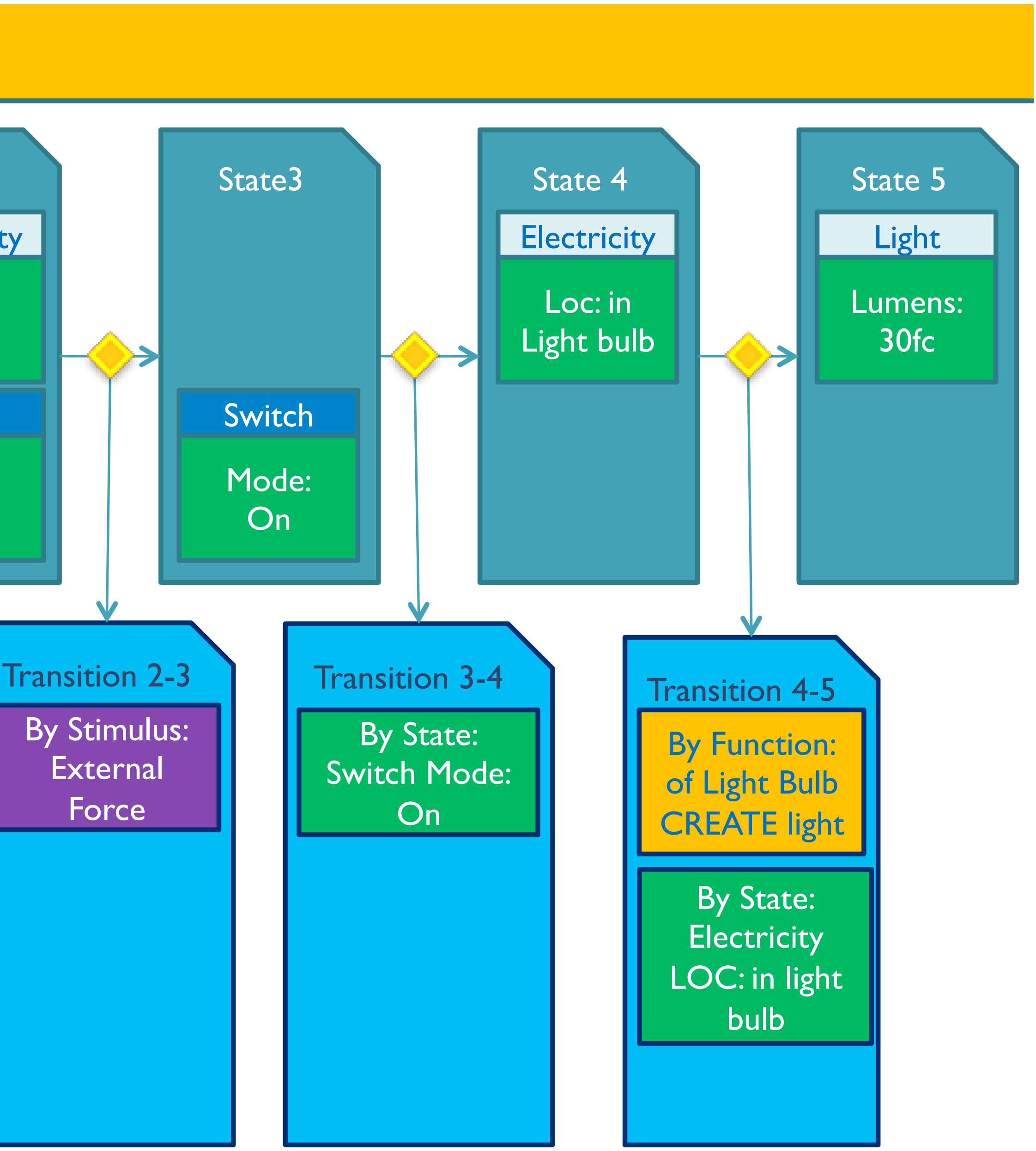
SBF Behavior Models

In complex systems, there may be numerous transitional states between the initial and the objective state. The Behavior model provides a step-by-step description of dynamic systems by describing a time-ordered chain of states, the transitions between these states and the properties that have changed or will change with the next transition.

Each transition is linked to one or more explanations that typically fall into one of the following categories:

- by function of a subsystem, which in turn can be described by its own SBF model
- by principle or natural law
- by structural connection, such as the motion of a door swinging on a hinge





SBF Behavior Model

Image: Design & Intelligence Lab, Georgia Tech, 2013

- by transition in another state, such as interconnected solid body systems of gears, levers and joints
- by state changing in other part of the system, such as the flipping of a switch
- by external stimulus occurring outside of the system

Explanation by function of a sub-system enables creation of nested SBF models arranged in a functional hierarchy.

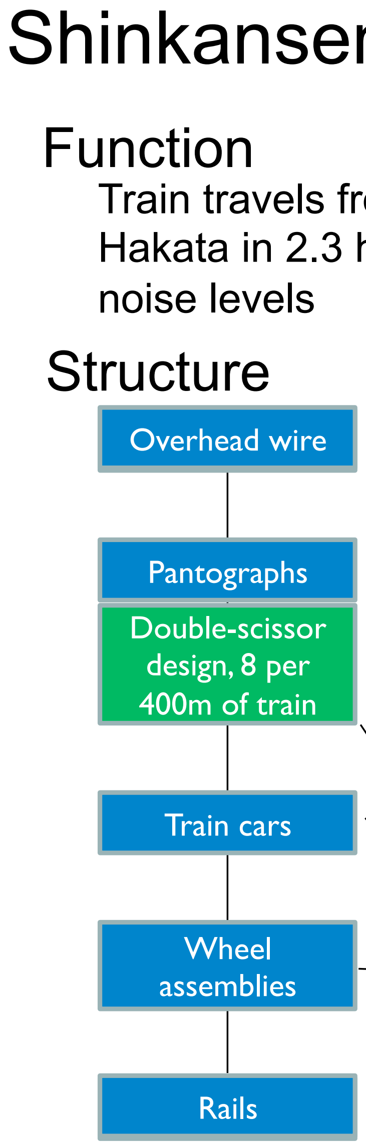
Additional detail on SBF modeling is available in a five-part tutorial at http://dilab.cc.gatech.edu/dane/?page=LearningAboutSBFModels.

How does one use it?

SBF models were created using information from the Shinkansen case study (*ZQ2*, Auspicious Forms) as well as papers on the silent flight of owls. The first diagram captures the function as well as the high level structure. Normally, the Pantograph would be treated as a sub-system and would have its own SBF model which could then be related with the SBF model of the owl wing. For clarity, only one level of detail has been included.

The second diagram explores the behavioral characteristics of both systems. In the case of the train, turbulence becomes the predominant contributor to noise at speeds exceeding 200 kilometers per hour. Mr. Nakatsu's challenge was to reduce this noise to levels below 70-75 dB(A).

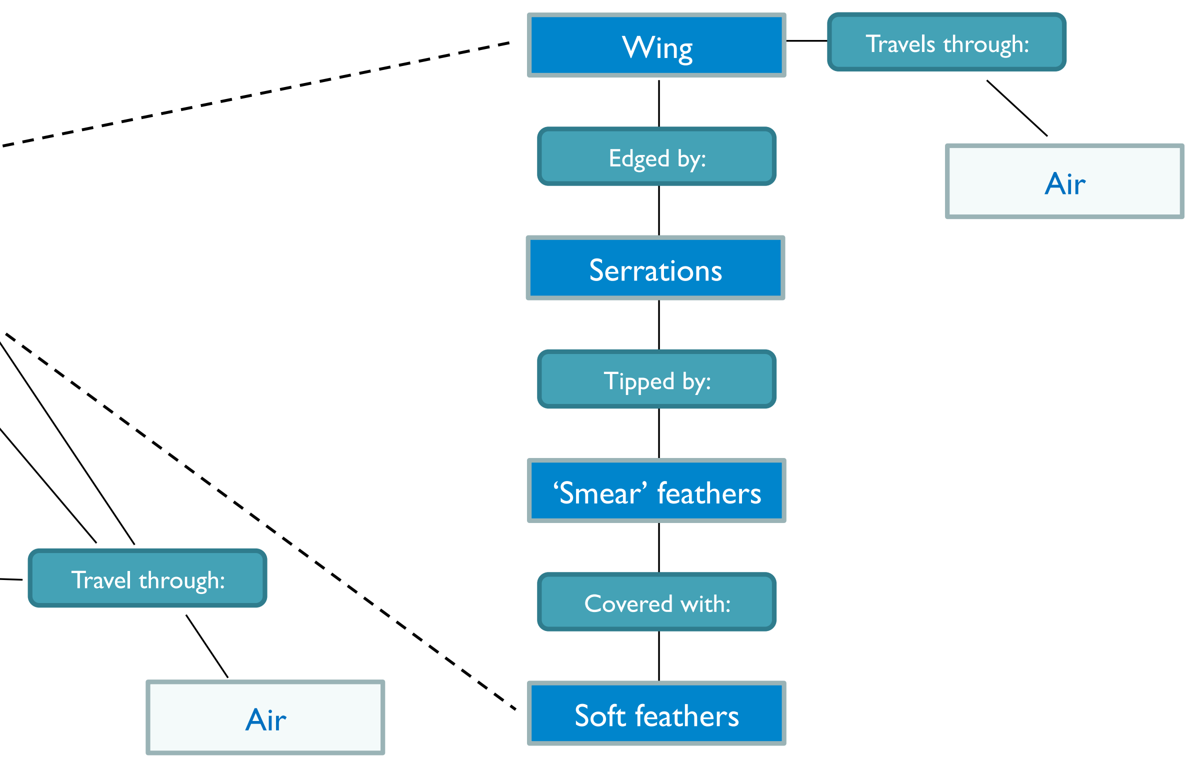
The ability of owls to fly silently as they hunt provided the inspiration for a redesign of the



n Train and Owl Wings

om Shin-Osaka to
hours with acceptable

Owl flies silently to capture prey



Shinkansen/owl wing SBF Function and Structure models

Image: Norbert Hoeller, 2013

pantograph. The number of pantographs was reduced from eight to two or three for each 400 meters of train. The construction of the pantograph was changed from the traditional double-scissor design to a more streamlined slider plate on a single post. Lastly, vortex generators inspired by the serrated edge of owl wings reduced the Karman vortex street turbulence extending from the surfaces of the pantograph at high speeds.

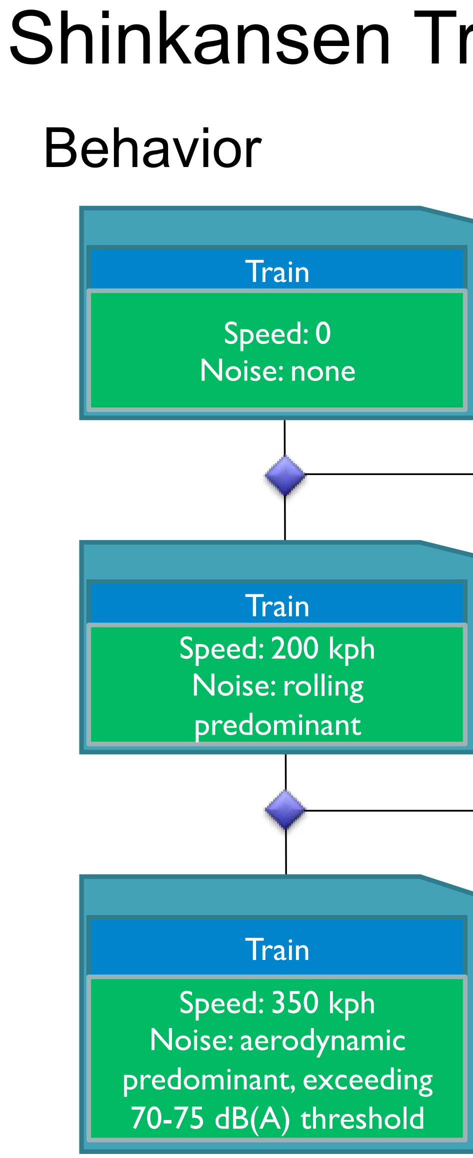
Although Mr. Nakatsu and his team did not use SBF models, this example demonstrates how the models can capture the key functions, structure and behavior of the technical system in ways that can facilitate communication with other disciplines such as biology. SBF models of potential biological systems can be developed to aid in analogical reasoning leading towards a practical application of the biological phenomena.

What additional development is planned?

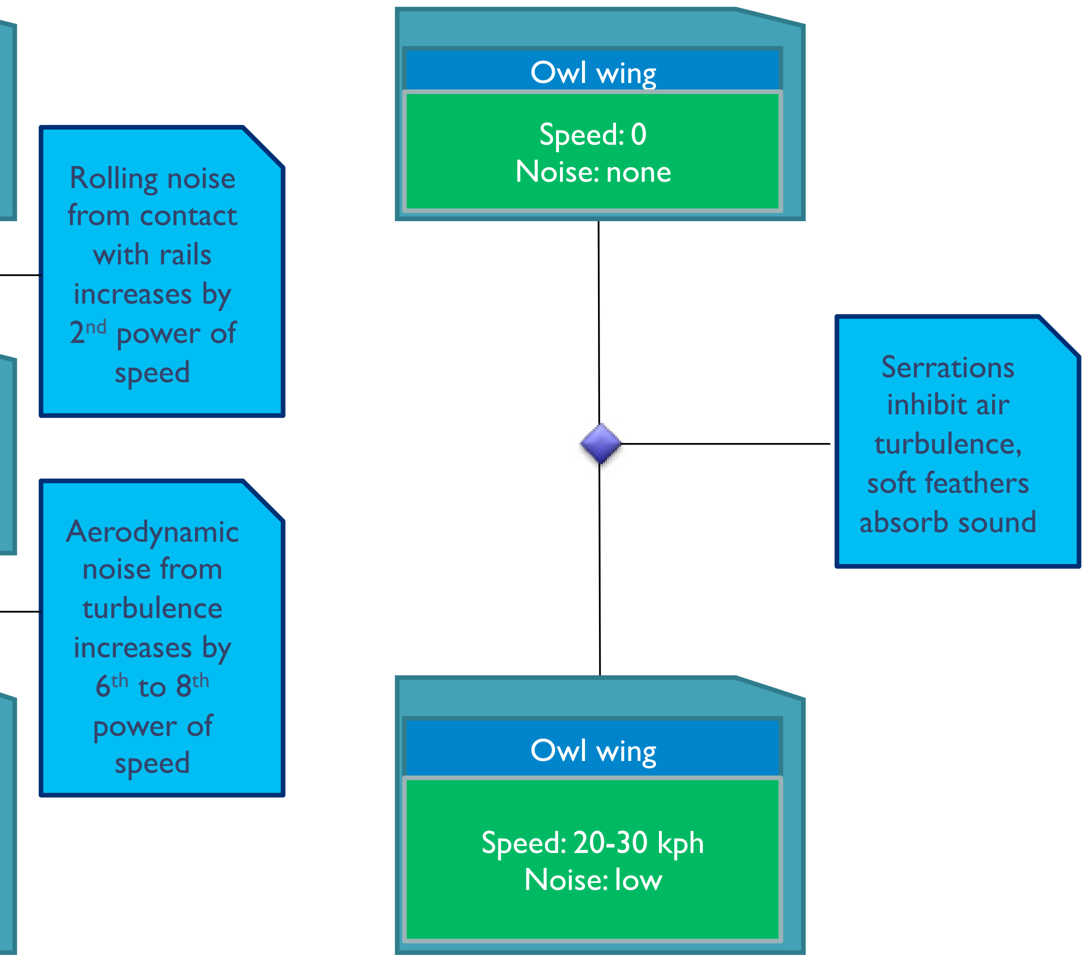
The SBF model is being extended by the Design & Intelligence Lab to incorporate the notion of the system's operating environment as well as design requirements and performance criteria, based on CBID course feedback.

Creating a structured way of describing systems has allowed the development of several computer programs that support generation of SBF models and guide designers in identifying appropriate cross-domain analogies:

1. The Aquarium Construction Toolkit (ACT) was developed to help middle school students model and gain a deeper understanding of complex systems such as an aquarium.



rain and Owl Wings



Shinkansen/owl wing SBF Behavior models

Image: Norbert Hoeller, 2013

2. SBFAuthor enables interactive construction of SBF models.

3. DANE (http://dilab.cc.gatech.edu/dane/) provides an interactive environment for representing biological systems.

The formal structure of SBF models potentially enables the automatic mapping between technical and biological systems. This works best if the function desired in the technical system is similar to that delivered by the biological system, such as in the "Eye in the Sea" project (Helms, Vattam, & Goel, 2008). In the case of larger differences, designers often need to search for related but not obviously analogous information. The tools described above support building libraries of SBF patterns based on technical and biological systems. These patterns, alone or in combination, can be incorporated into more creative solutions.

SBF modeling has been used at CBID in a wide range of contexts including development of a biologically inspired design for solar panels, understanding computer programs and analyzing robot behaviors. Researchers have used SBF modeling to analyze how novices and experts think of biological systems. Other functional modeling schemes similar to SBF have modeled a range of systems from computer software to mechanical systems and large industrial plants. Systematic design (Pahl and Beitz) and axiomatic design (Suh) are examples of functional modeling used in industry when the decomposition of complex systems is required. Designers can benefit from SBF models both in understanding complex systems and facilitating interdisciplinary communication.

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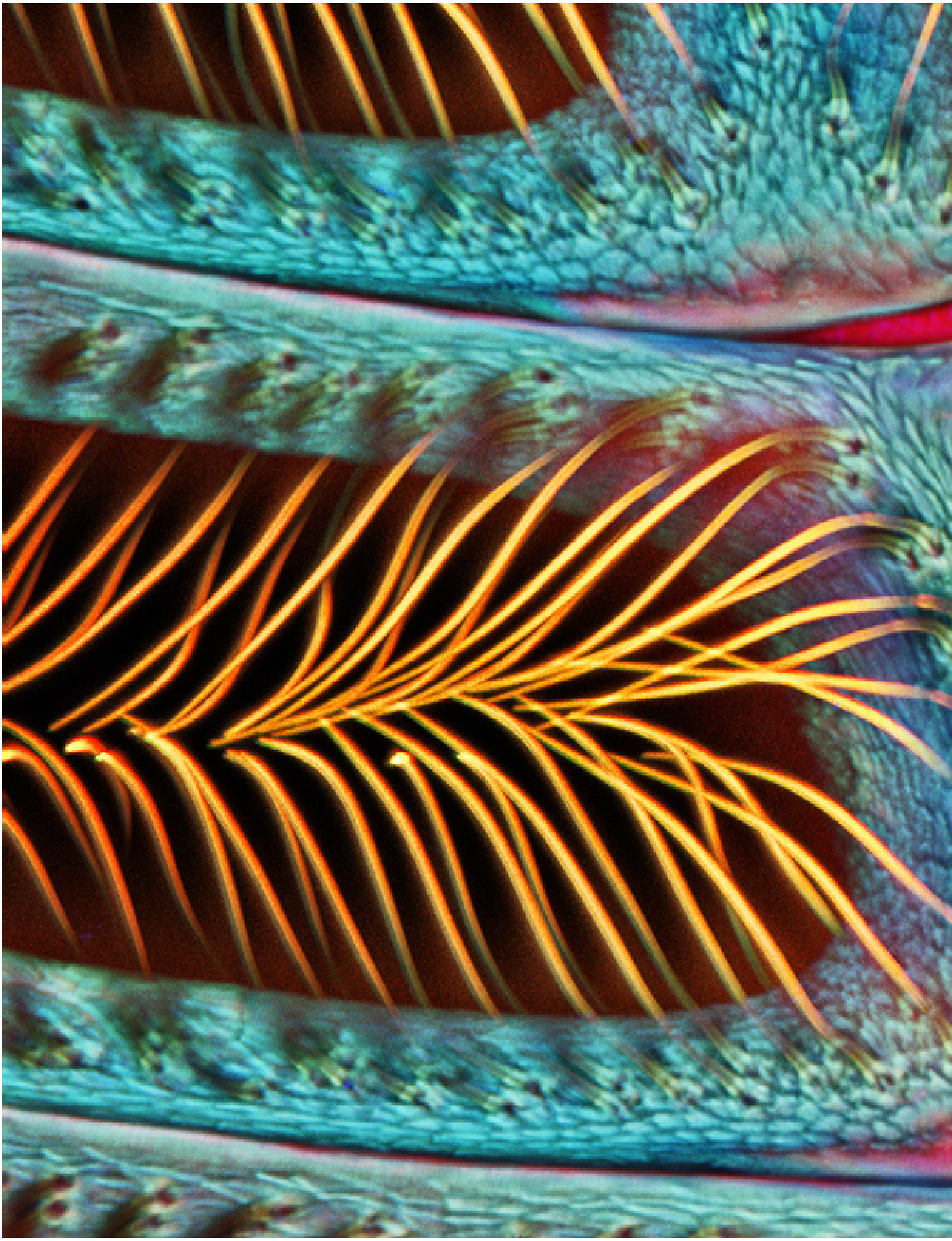
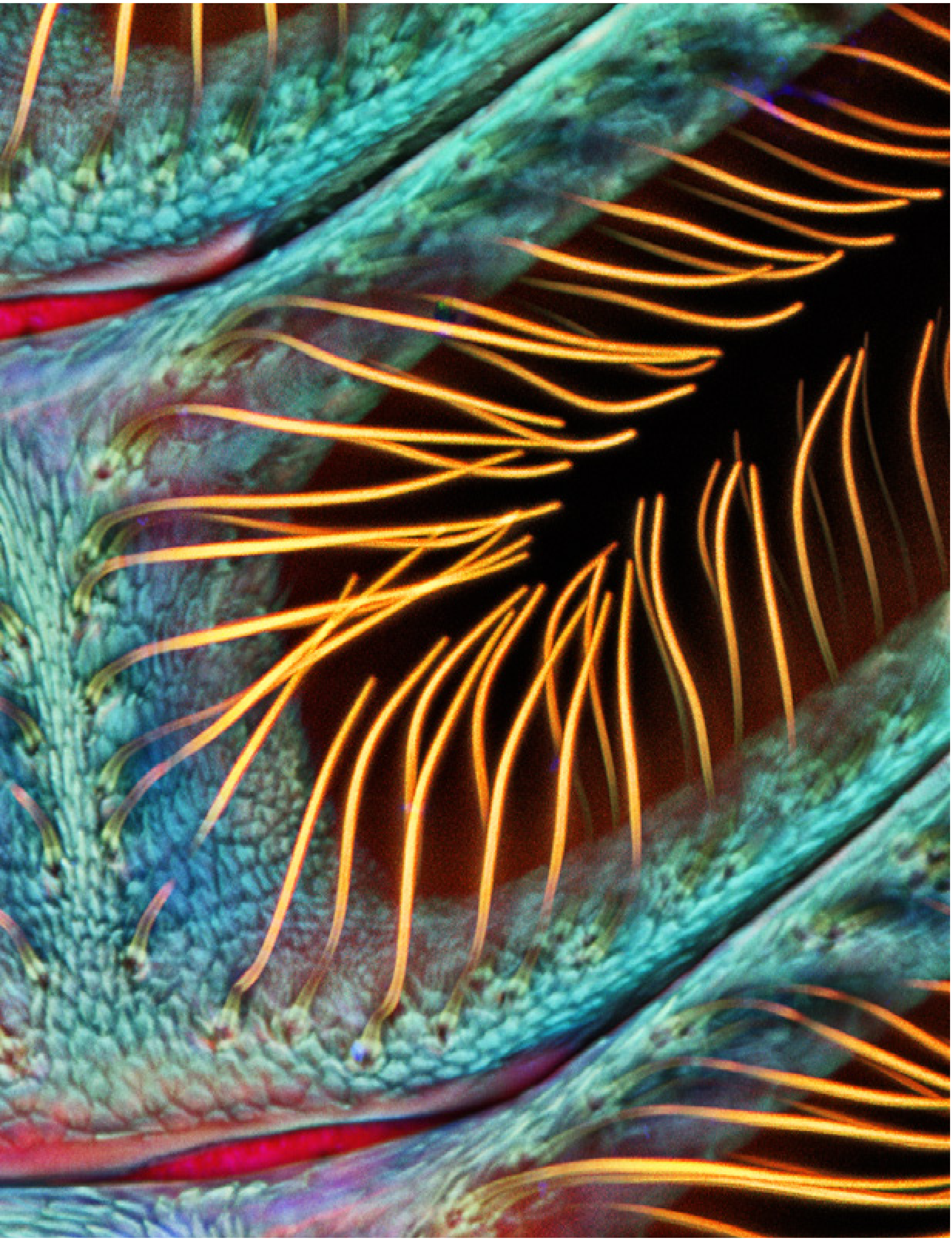
Snowy Owl Flight #2

Photo: {ErinKphoto} aka redcargurl, 2012 | Flickr cc





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