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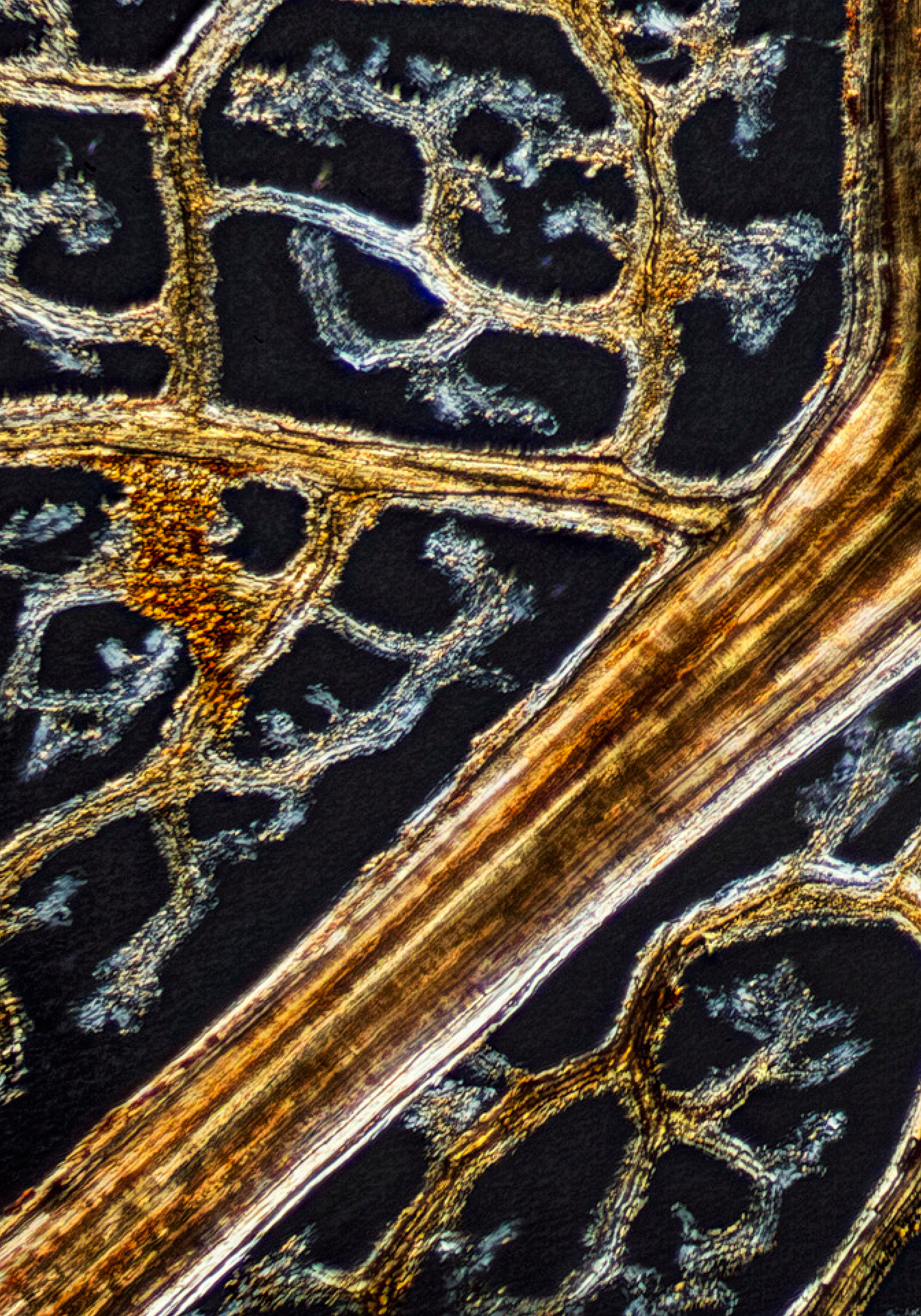

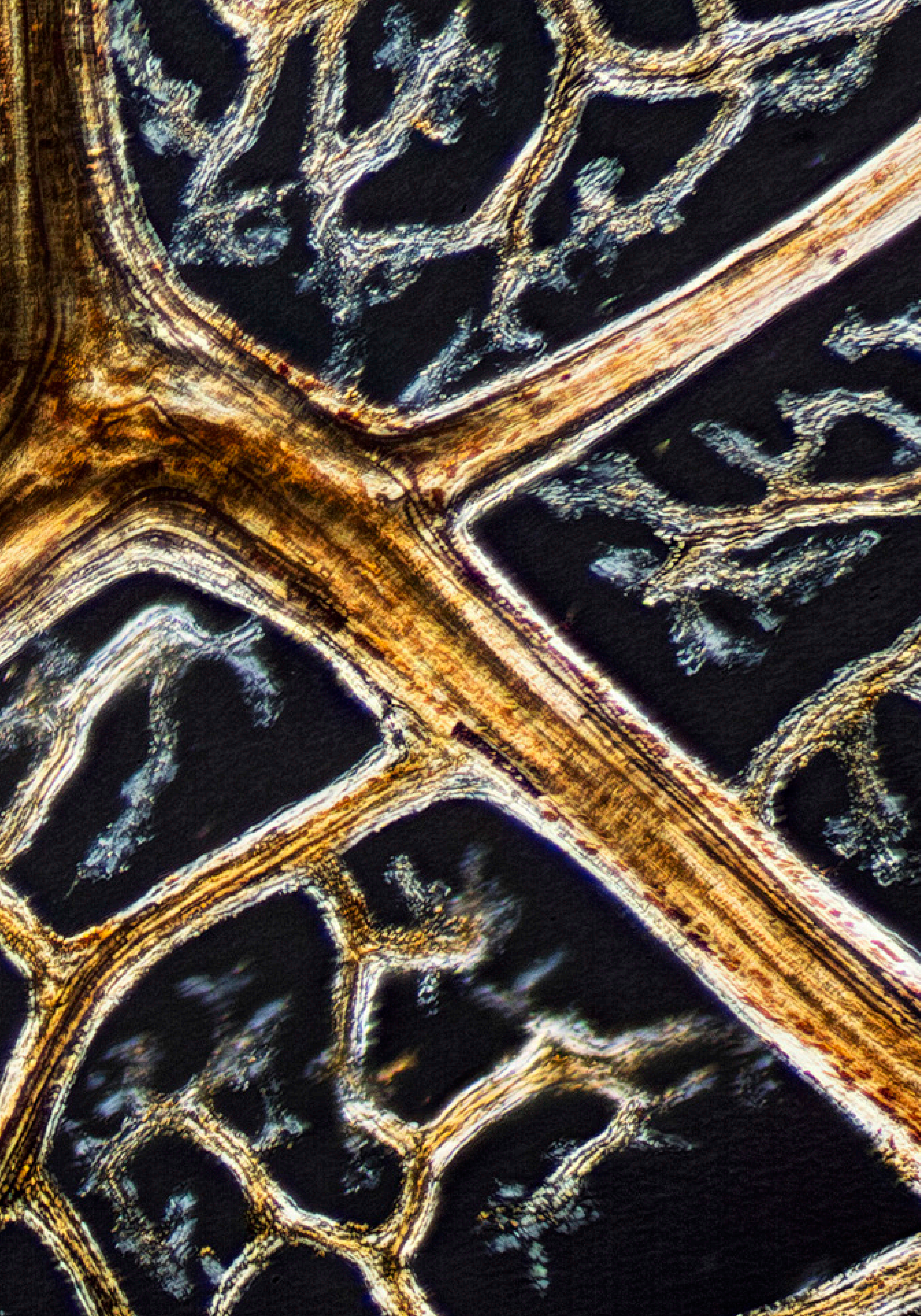

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Grasshopper

Photo: jeffsmallwood, 2006 | Flickr cc

Editorial

We are pleased to offer you a broad gamut of subjects in this issue that highlight some main threads within the realm of bio-inspired design. These stories continue to fuel our fascination with this wide-ranging field. Robotics, nanoscience, 3D printing, regenerative design, scientists making art and making awe work for you are all covered here.

Festo AG, one of the pioneers of nature-inspired robotics, explains its educational outreach program The Bionic Learning Network and displays some of its wildly innovative inventions. Our case study explores the nuts and bolts of the Sahara Forest Project and the challenges of making the desert green using an integrative and bio-inspired approach. Heidi Fischer plumbs the psychological depths of awe, and how this core emotion is related to our daily lives. Nervous System shows us why their 3D printed jewelry designs are so cool, and we review another good read: Peter Forbes' new book Nanoscience. Finally, we get a peek at the more artistic side of working scientists with our portfolio piece on Princeton's recent Art of Science exhibition.

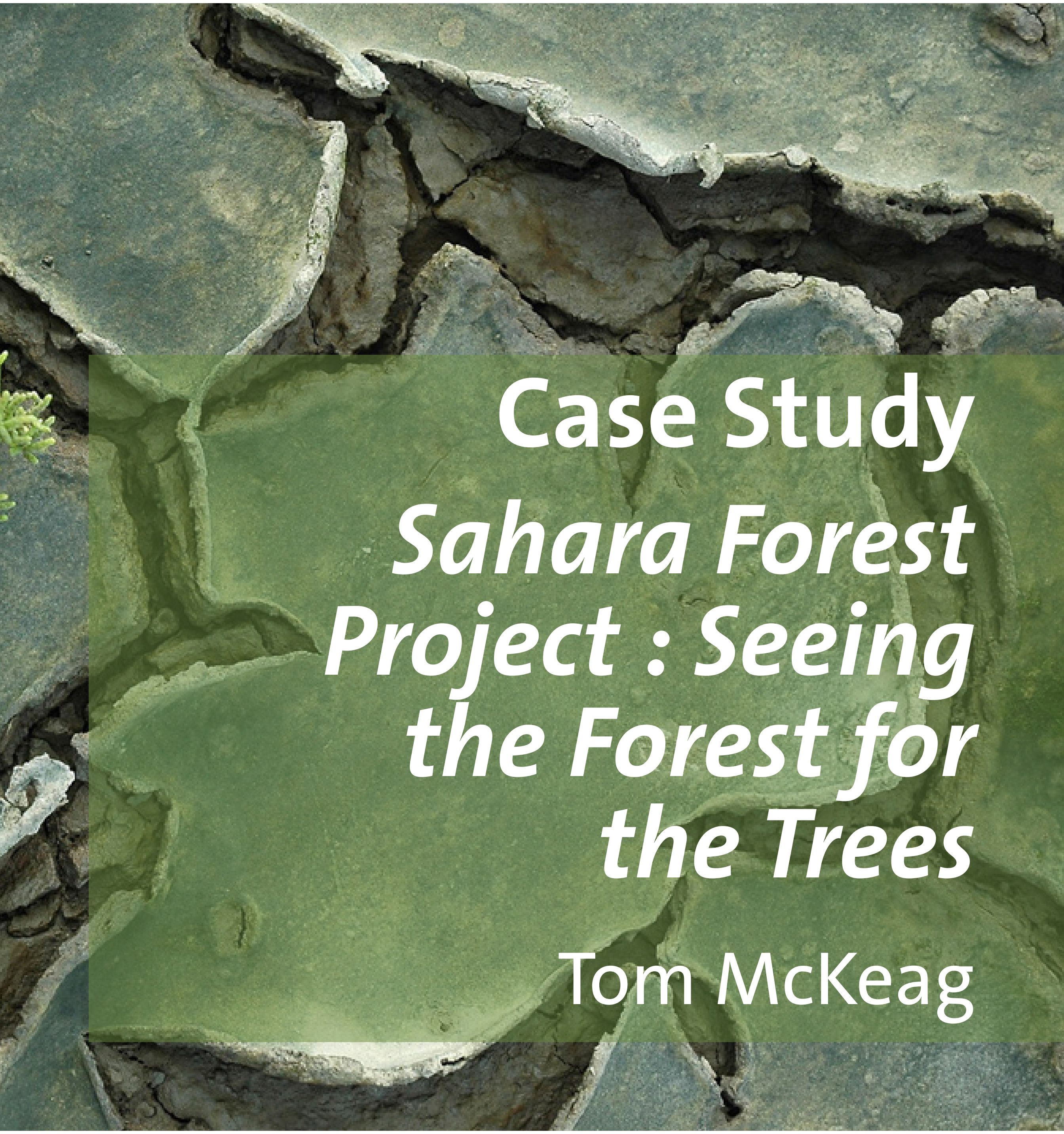
Happy reading! ×

Tom Norbert Marjan

Tom McKeag, Norbert Hoeller, and Marjan Eggermont

Salicornia plant in a mixture of algae and mud

Photo: Bas Kers (NL), 2007 | Flickr cc



Case Study

Sahara Forest Project : Seeing the Forest for the Trees

Tom McKeag

vol 4 | 2014 **Case Study** Seeing the Forest for the Trees **Author:** Tom McKeag

Sahara Forest Project: Seeing the Forest for the Trees

A changed landscape

Six thousand years ago, before any pyramid had been built, the lower Nile River and the lands surrounding it in present day Egypt were a different place. The area teemed with lush vegetation and large animals like elephants, rhinoceroses, and giraffes. It was the end of the so-called African Humid Period, and in one thousand years it would all start to change. Humans would multiply and till the land and create complex civilizations that would flourish and collapse. The climate would change in a series of extreme dry periods that would help bring both the Old and New Kingdoms of the pharaohs to an end.

More recently, in the time of Julius Caesar (47 BCE), Rome's North African province was the richest in the western part of the empire, producing a million tons of cereals per year and exporting olive oil, fruit, wool, wine, timber, and exotic animals to the Italian capital. The Roman town of Volubilis in present day Morocco, for example, would eventually supply two-thirds of the city's food. By ca 240 CE the Barbary lion, Atlas bear and native elephant populations of the region had been largely wiped out; slaughtered for sport in the Coliseum, but the region of the Maghreb would still be a granary to the Mediterranean world well through the 19th century. By the time Rommel and Montgomery were fighting over Tobruk in WWII, however, the fertile fields of ancient Cyrenaica had turned to sand. The dominant landscape of Egypt and North Africa was what one sees today, a dry and mostly treeless expanse of sand and rock: the Sahara Desert.

The immensity of the Saharan desert is daunting. Over nine million square kilometers, it equals ten percent of the land area of the continent of Africa, from the Red Sea to the Atlantic Ocean and from the Mediterranean to the Sahel. It is the world's largest hot desert, where annual rainfall is less than 25 mm per year, and some of the planet's hottest temperatures (58° C) have been recorded. And, it is growing.

In 2010 its southern boundary of the Sahel, a semi-arid region of dry shrubland, grass and savannah, experienced a devastating drought that destroyed the dry grazing and crop lands of the tribespeople of Mauritania, Mali, Niger, Chad and the Sudan, putting 1.2 million people at risk of famine. This drought was just one in a series of recent events that have pushed the boundaries of the Sahara south. "Sahel" means "coast" in Arabic, the green southern edge of the great sea of sand.

Drylands occupy approximately 40% of the earth's land area and such desertification threatens nearly one billion people. Desertification, along with climate change and biodiversity loss, was identified as one of the greatest challenges to sustainable development during the 1992

Nile River and delta from orbit

Photo: Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC, 2003 | Wikimedia Commons

Western Sahara Desert Meets Atlantic Ocean

Photo: NASA's Marshall Space Flight Center, 2014 | Flickr cc

Rio Earth Summit. Since then the United Nations Convention to Combat Desertification was established in 1994, and 195 parties are signatories to this treaty which links environment and development to sustainable land management.

Sustainable land management (SLM) is any number of practices which husband the land and soil for continued production without the erosion and natural vegetation loss now being caused by overpopulation, overgrazing and farming. Drylands are where some of the most vulnerable populations and ecosystems exist, and returning the land to productive use is the only way, in many instances, of preventing widespread poverty and famine.

Restoring the forest

Michael Pawlyn and his partners at the Sahara Forest Project did not set out to cure the world of famine, but they are proving that a cleverly integrated system of high-tech farming can work to return water and greenery to the desert. Along the way they are testing how we can best combine some basic production methods to make clean fresh water, grow more crops, and provide cheap energy.

The Sahara Forest Project is both audacious in its ambitions and focused in the details needed to achieve them. Its proponents hope for no less than the revegetation of large areas of the Sahara and other low-lying deserts where the sea meets the sand. Key to their plan is the conversion of readily available saltwater to fresh, and the nurturing of crops for food and forage and native plants for reclaiming the soil. Greenhouses are proposed as giant stills to convert the seawater, with the water being evaporated by the sun within the buildings and then condensed at night to yield fresh water. This water is then used for growing crops both inside and out, where solar panels and fences shield nascent native plantings. It also provides a feedstock for a concentrated solar power (CSP) plant. The intent is to restore the land sufficiently to implement an historical ecological landscape in a later phase.

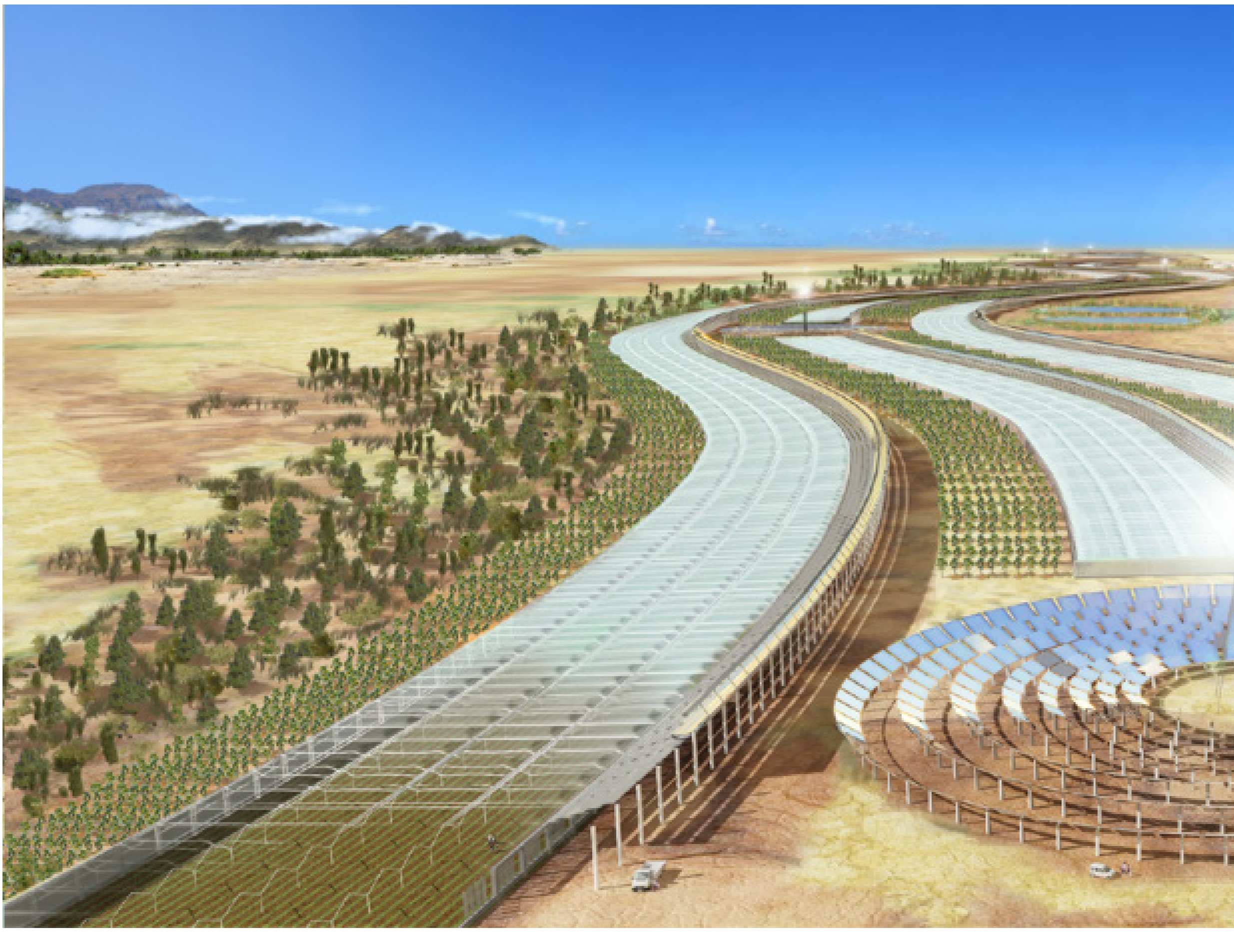
To date a year-long pilot project has been completed in Qatar in September, 2013, and the first step towards a full-scale Sahara Forest Project Centre in Jordan has been taken. The planners hope that the experience from both Qatar and Jordan will inform the scaling up of the system to commercial capabilities. It has taken seven years of effort to reach this stage, but the results from the Qatar pilot plant have been encouraging and the SFP team is excited about expanding it in Jordan.

An idea gains force

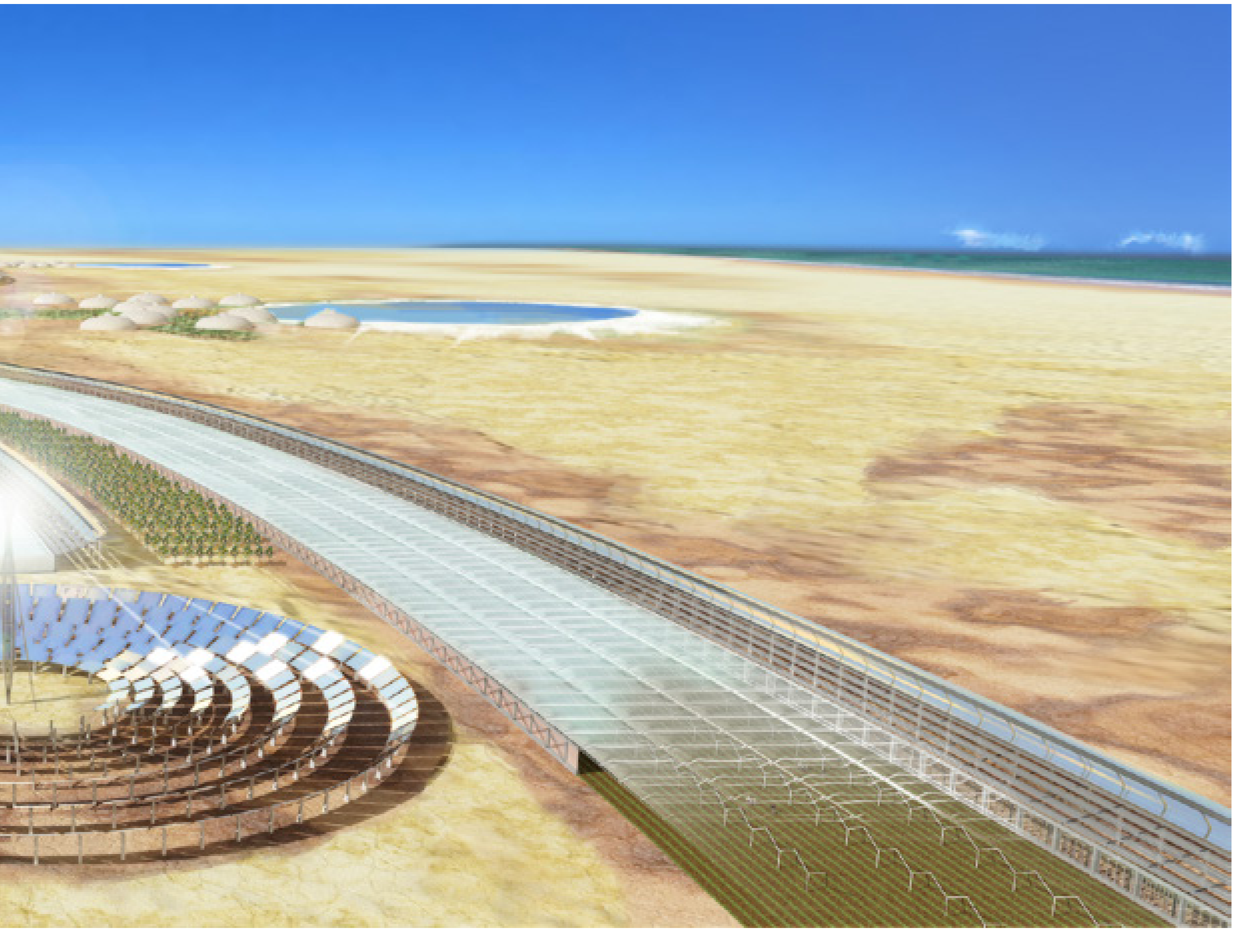
The Sahara Forest Project concept was launched in 2009 and is organised as two entities, a foundation and a private limited company. The founding team behind the company (The Sahara Forest Project AS) was composed of Bill Watts, Michael Pawlyn and the Bellona Foundation (http://bellona.org/about-bellona).

The initial discussion of the founders centered around three intersecting technologies: a greenhouse that would make fresh water by distilling seawater and cool a concentrated solar power plant (CSP), a concentrated solar power (CSP) plant that would create steam from partially desalinated water for electricity generat-

Cucumbers growing inside one of the greenhouses in Qatar. The greenhouses can produce as much as a European farm but are powered by only sunlight and seawater.
Photo courtesy of Elsa Naumann/Sahara Forest Project



Artist conception of the Sahara Forest Project is a scheme to reclaim desert lands by using solar-powered distillation of seawater to water crops and bands of vegetation. A year long pilot project has been completed in Qatar. An agreement has been reached with the country of Jordan to host a second demonstration facility when construction funds have been raised. | Image courtesy of Sahara Forest Project



Case Study
Seeing the Forest for the Trees

Author:
Tom McKeag

Eden Project, Cornwall

Photo: antidigital da, 2012 | Flickr cc

ing turbines and send waste heat back to the greenhouse, and sheltering shade from the CSP mirrors that would aid the propagation of native plants. The team in particular had been influenced in their thinking by David McKay who wrote "Sustainable Energy without the Hot Air" (http://www.withouthotair.com/). In this tract, McKay argues that the solar energy striking desert regions comprise a great untapped resource.

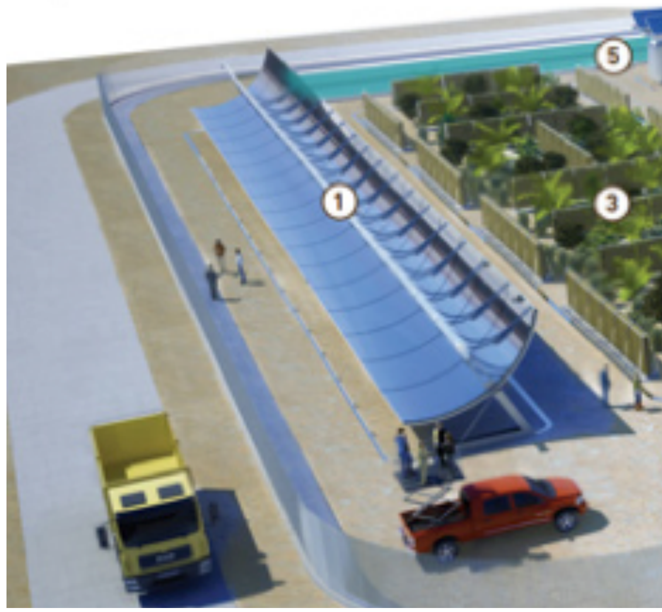
Pawlyn, now founder and director at Exploration Architecture Ltd., had been the project architect for the firm Grimshaw on the Eden Project, a series of giant geodesic domes housing artificial ecosystems in Cornwall, UK (http://www.edenproject.com/). He had led the design of the Warm Temperate and Humid Tropics Biomes and the subsequent phases that included proposals for a third Biome for plants from dry tropical regions.

The group prepared some visualization images and gained some press coverage in the autumn of 2008. While there was no funding target as yet, Pawlyn hoped to lay out a reasonably clear idea of what the project could achieve and garner some informed predictions from professional peers. One of his press releases had gone out to Frederic Hauge whom Pawlyn had met at a Google Zeitgeist conference in 2007.

Frederic Hauge connected the group to an organization run by his brother, Joakim, the Bellona Foundation, an international environmental NGO based in Oslo, Norway After a meeting in the UK, the group was provided with funding for its first feasibility study and this was presented at the 2009 Climate Change talks in Copenhagen, Denmark. Then two important agreements were secured, one with the Norwegian government for feasibility studies in Jordan and one for a feasibility study in Qatar with the Yara International ASA of Norway and Qafco, the Qatar Fertilizer Company. Yara is the world's largest supplier of fertilizer, and Qafco is the world's largest producer of urea and ammonia.

While three new feasibility studies were ongoing in Jordan, the partners for the Qatari activities (SFP, Yara and Qafco) signed an agreement to realize a pilot facility. The signing ceremony in February was under the patronage of the prime ministers of Norway and Qatar. The pilot facility was fully operational in November 2012, and hosted visits for delegates at the UN climate talks held in Qatar's capital, Doha. The project team expanded the scope of work to include investigations of algae, production of brine, planting of halophytes, and the testing of a chemical accretion technique called Biorock™.

"What we did was take some mature technologies and bring them together in synergy", says Pawlyn, "...We are exploring a new paradigm based on ecosystem models. Conventional systems tend to be linear, simple, wasteful and run on fossil fuels – we are aiming to create a more complex, interconnected system that moves towards zero waste, running entirely on solar energy and is optimized as a whole system". Indeed if the SFP is in any way biomimetic, it is in this approach of systems thinking and the ultimate goal of recreating the complex ecosystem of a region. Thus the group has had to develop both an industrial and natural ecological model, but neither has been formed from known examples. Instead, the team chose individual elements that met their sustainable success criteria. Their investigation of the botany and ecology of the region is still very much a path of discovery, but they have been encouraged by the quantified results from their first pilot in Qatar.



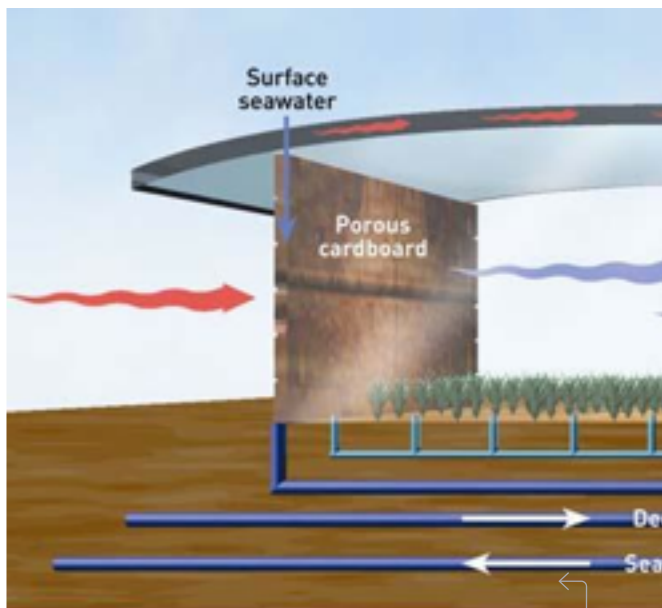
The Qatar pilot

The Qatar pilot plant was a one-year test facility located on an industrial site owned by Qafco. It operated from November, 2012 through September, 2013. The purpose of the facility was to test the proposed systems and gather some quantifiable results from the synthesis of the three technologies: evaporative distillation, concentrated solar power, and crop production.

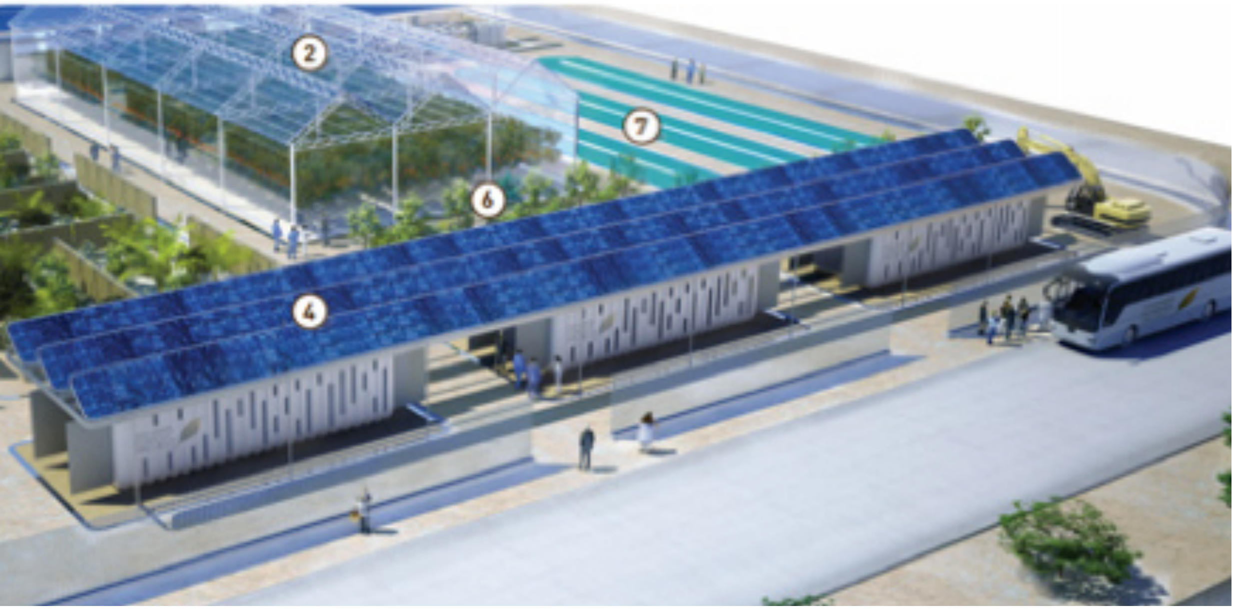
The physical plant comprised a greenhouse, pipes and pumps for collecting and distributing seawater, evaporative hedges for humidification and irrigation of outdoor plants, a concentrated solar power (CSP) test array of reflective mirrors to produce heat for the evaporative process, photovoltaic (PV) panels to directly generate electricity, and algae and halophyte growing areas.

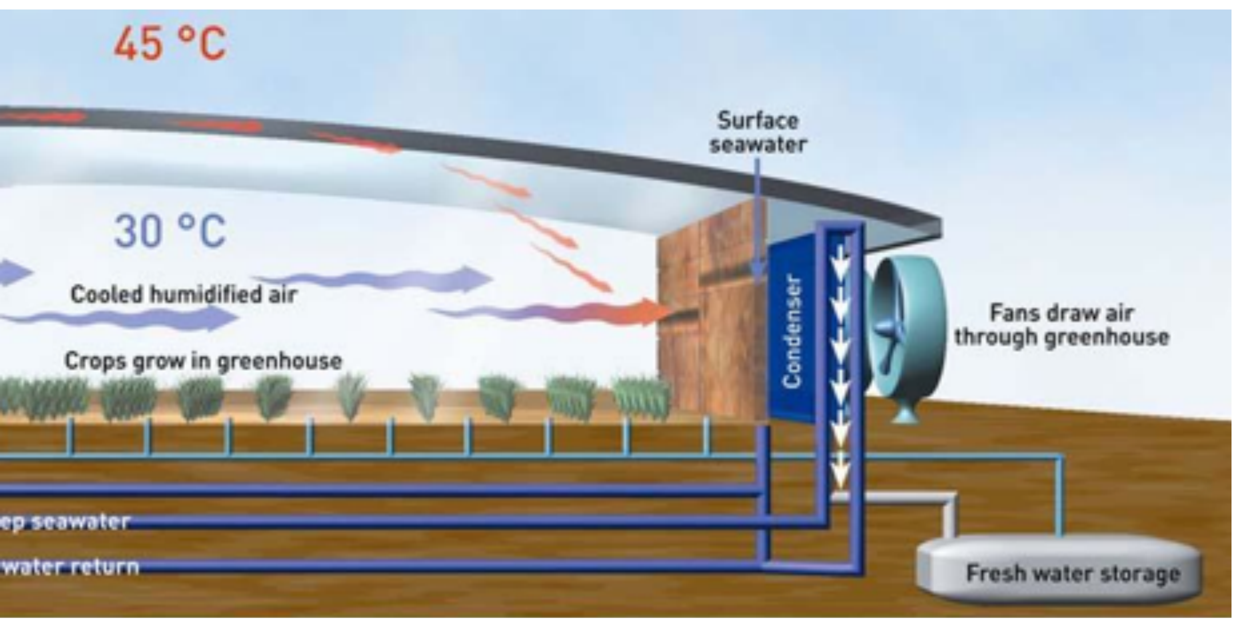
Bill Watts is a founding director and the technology manager at SFP, and is a consulting building services engineer at Max Fordham LLP in the UK. He has thirty years in the building climate control business, but saw this project as different:

"We had a lot of different parts to this system at the pilot and some of them were quite mature technologies but others were not and frankly if those ones just "showed a positive signal" then I was satisfied. We did much better than that in some cases, being able, in going up the scale, to calibrate something and in still some others, to finesse its operation."



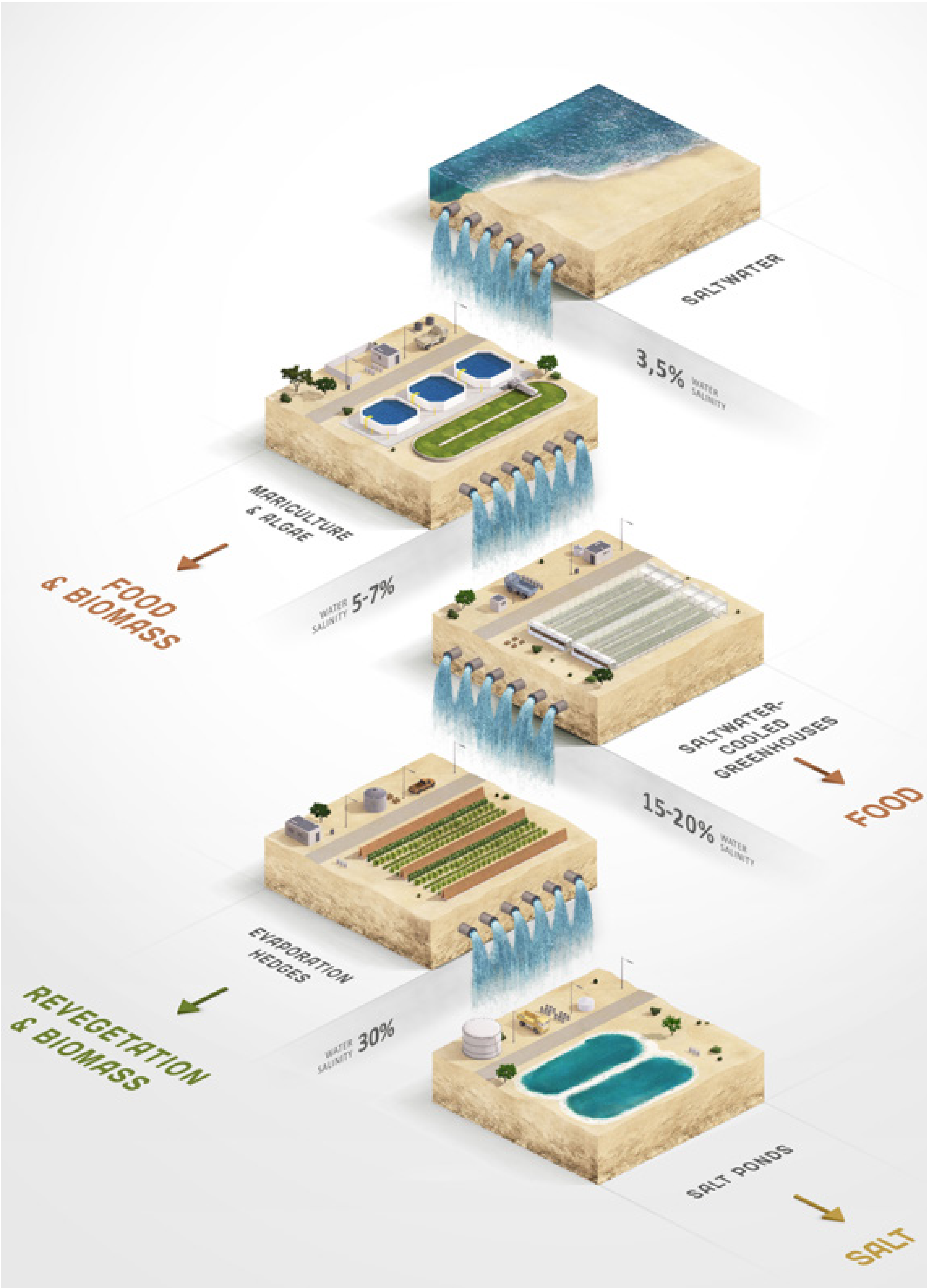
Typical saltwater greenhouse cross-section. Qatar pilot did not use deep seawater to condense water vapor at end of greenhouse, but used the ambient temperature difference of the night sky in a double membrane roof.
Image courtesy of Sahara Forest Project





Overview of the Qatar Pilot Plant: 1. Concentrated Solar Power; 2. Saltwater greenhouses; 3. Outside vegetation and evaporative hedges; 4. Photovoltaic Solar Power; 5. Salt production; 6. Halophytes; 7. Algae production

Image courtesy of Sahara Forest Project



The Saltwater Infrastructure | Image courtesy of Sahara Forest Project

Virginia Corless is the Science and Development Manager of the FSP, and her role has been as the liaison to botanists, ecologists, farmers and officials in developing the horticultural potential of the works. She spoke of the progress of the Qatar pilot.

"The pilot accomplished what we wanted: we proved that we could grow vegetables in the hot Qatari summer, and got some quantitative measurements about the feasibility of growing them economically comparable to a greenhouse operation in Europe. It also gave us confidence in trying out interconnections amongst the systems."

The results were encouraging enough for the SFP to make the claim that the operation could produce three seasons of crops for a total yield of at least 75g/square meter for half the freshwater of comparable Qatari operations. In ten months of operation the 600 square meter greenhouse produced 290,000 cucumbers at no more than five liters per square meter per day of irrigation.

How it all works

Water

Water is the foundation of this restorative project and it is put to work in several different ways: as a coolant in the evaporative process, as a sustainer of life for three basic categories of plants, and as a transport medium for harvested brine and other chemicals. Its source is the sea, and managers have carefully calibrated varying degrees of salinity as it is shunted off to its different tasks.

The fresh seawater at about 4% salinity is used by the so-called Multi Effect Distillation (MED) unit that distills out the fresh water using high grade solar energy collected by the parabolic collectors. This water is also used in the marine micro algae raceways and to irrigate the Halophytes [salt loving desert adapted plants]. Both of these plant types don't need fresh water and can be used to grow fodder for animals or produce biofuels

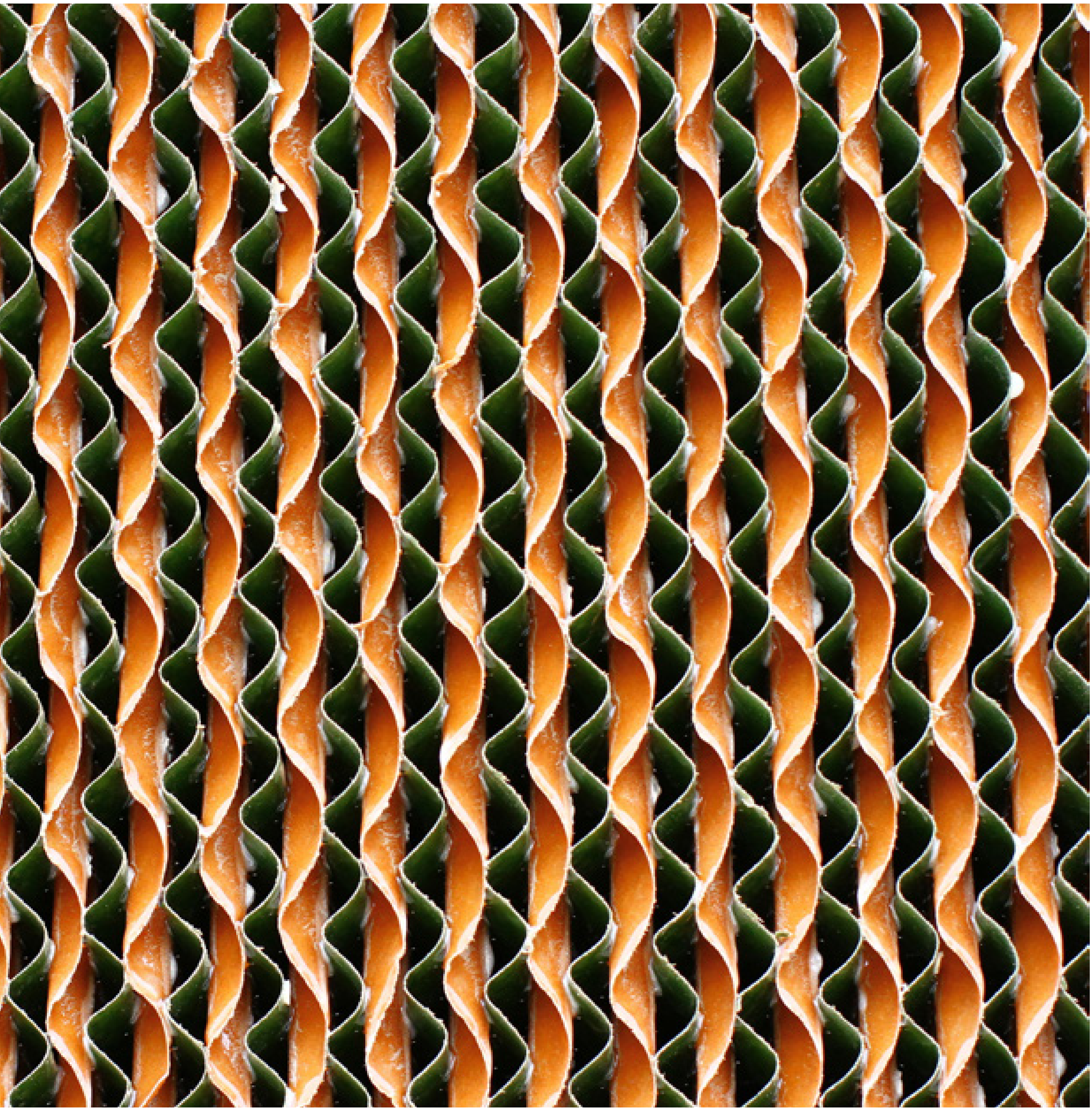
The salt water from all these processes is at a higher salinity as some of the fresh water has been evaporated off. This water is then used to cool the greenhouses during the day by passing the hot dry desert air though the cardboard pads, wetted with this higher concentration brine which then cools and humidifies the air. This takes the salinity from 7-8% up to 12-15%.

As a further advance the team made use of the waste heat from the solar system at night to drive evaporation from the brine and circulate hot humid air around a cavity formed in a double membrane roof of one bay of the greenhouse. The roof acted as a big cooling surface to condense out fresh water that was collected and used in the greenhouse.

Seawater, at 3.5-4.0% salinity, is pumped from the sea to the greenhouses where solar heat evaporates the water, turning the liquid to the gas of water vapor. The evaporation relieves the water of much of its chemical content, and at night this vapor is run along a double membrane roof where it condenses and is collected in troughs. At the two pilot project sites the seas are relatively shallow, so unlike other desalination sites, cold deep water is not available for use of chilling condensation plates. At this salinity it is also pumped to ponds growing marine algae for biofuel, and to landscapes planted with halophytes, salt loving plants locally adapted to the harsh Sahara conditions.

After condensation has siphoned off freshwater the water feedstock is at approximately 7-8% salinity and is further evaporated in the greenhouse for the purpose of cooling. Now at 12-15% the feedstock is run outdoors to do more work. Here it is sent two ways: to the shelter hedges to be further evaporated for outdoor cooling and humidification for the seedlings being grown for revegetation and for the cooling of the MED unit. After this step the water is at a 25% salinity level, with most of its water potential wrung out of it. It is channeled into a settling pond where the sun will do the rest and leave the dried salt to be harvested.

The greenhouse was divided into three bays with evaporative coolers at each end made of honeycombed cardboard. Warm air flowing through these baffles was cooled and then distributed under the plants through polythene ducts and, after rising as it heated, expelled through openings high in the end wall. In the middle bay a double layer roof of Ethylene trifluoroethylene (ETFE) was installed as a mechanism for condensation. The hot air created by the evaporation of saltwater was channeled to this roof area and chilled by cool nighttime temperatures back into water, but without the salt: distillation. Measurements comparing this roof with the other polythene roofs were taken. ETFE is a proprietary plastic film from Dupont of the type that had been used in the Eden project and in the Water Cube building at the Beijing Olympics.



The “evaporative hedge” — honeycombed cardboard pads shown up close below. Saltwater runs down these as hot desert air is pulled through, generating cooler, humid air. These hedges are used both in the greenhouses and in the adjacent plots of land, allowing vegetation to grow outside that otherwise would not survive.
Photo courtesy of Elsa Naumann/Sahara Forest Project

Energy

Solar energy was used in two ways at the Qatar pilot, directly in the greenhouses and outdoors for evaporation, and indirectly in the CSP for heating oil to heat the greenhouses and to evaporate saltwater for cooling. In an expanded operation like the one proposed for Jordan, the CSP heat could also be used to make steam to drive turbines for electricity. A typical CSP tower is a tall stalk with a bulb tank at the top that is surrounded by an array of mirrored reflectors that concentrate the sun on the bulb and heat the water in the bulb tank to boiling. At the Qatar site, parabolic trough collectors comprising a row of curved reflectors concentrated the heat onto a central horizontal pipe at the focus of the parabola rather than a vertical tower. The pipe was filled with oil and the heat transferred to the greenhouse.

Food

The waters of the SFP Qatar pilot sustained three types of plants: food crops within the greenhouse, food or forage crops outside, and salt-tolerant plants, halophytes. In addition, researchers raised photosynthesizing algae in controlled seawater ponds. High value crops like cucumbers, tomatoes, peppers and aubergines were the targets. For the pilot, cucumbers were chosen as the test crop. The halophytes would be useful as fodder crops and the algae would be useful in the production of biofuel, neutriceuticals or fodder. While most of the growing environments were carefully controlled the team found that a very hardy local variety of algae flourished in the salt ponds, presumably brought there by the birds that frequented the site.

The Devil in the details

Air

Water was not the only fluid that had to be moved about in the project. A large part of the greenhouse operation, both inside and out, involved changing the temperature and humidity of air.

“Typically I have been concerned with people’s comfort and the new challenge here has been applying the physics that I know to the nurturing of plants. The greenhouse environment was new and demanding, and I had to do a lot of translating to shift from satisfying people to plants ”, says Watts.

“Getting the air distribution right was a challenge for us. Mixing natural ventilation with artificial was a particular challenge. Fans create pressure differentials and air tends to sneak around back when they are in use and when they are not they are an obstruction. Tunnel fans avoid this somewhat. In the greenhouse (therefore) we ran cool air in “socks” under the plant trays that were about 1.2 meters off the deck. Getting an even distribution of air from these was tricky, but we were able to use the buoyancy of air to our advantage.”

Greenhouses tend to be hot and humid and this needed to be controlled as well and Watts is really pleased with the results of the strategy that they chose. SFP claims a 15 percentage point reduction in humidity with their methods.

“A humid environment in a greenhouse is fine during the day as the sun makes sure that the levels never get too high. At night however the space cools down and the relative humidity goes up towards 100% with the risk of dew forming.

This is bad for the plants that suffer from mildew in these conditions. Typically heat is added to reduce the humidity.

Instead we used a liquid dessicant system of Magnesium chloride and evaporative pads. When you evaporate water you lower temperature, and when you condense it out of air (what the dessicant does) you raise the temperature. The advantage of the dessicant is that it is stored energy because you dry out the desiccant in the sun during the day. It is much more compact to store “dryness” than heat to achieve the same result.”

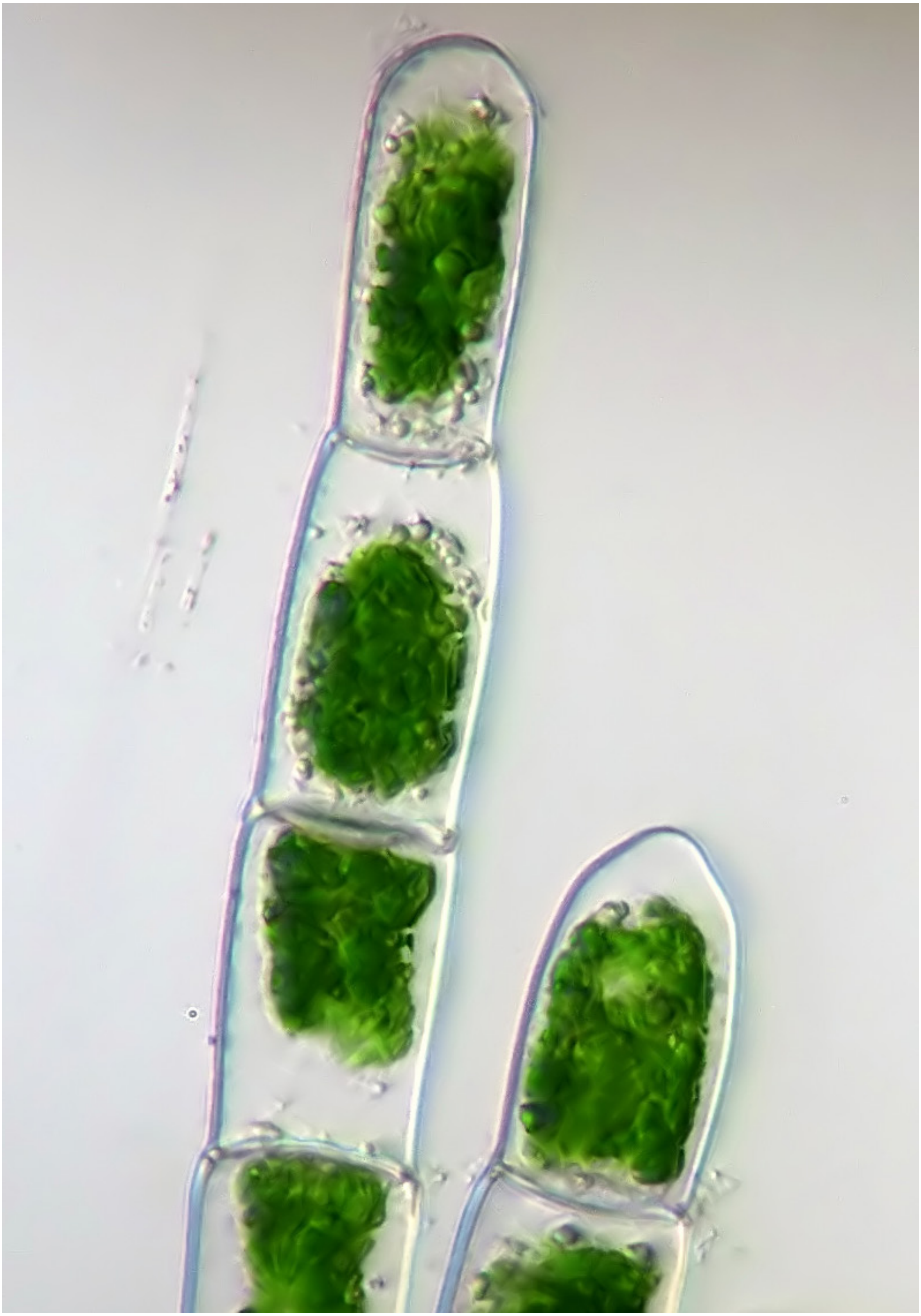
Liquid dessicant systems work on two basic principles: the bipolarity of water and the second law of thermodynamics. The water molecule has a positively and a negatively charged end and because of this bonds readily with oppositely charged molecules like the magnesium chloride in the dessicant. Because of the second law, materials will tend to move from high concentrations to low. In this case the highly concentrated magnesium chloride will tend to bond with the water in the air and pull it into the pad. This works well enough as long as there is a decided difference in concentrations, but eventually, as the dessicant pulls more and more water out of the air it becomes more diluted until it loses its attractive power. At this point it needs to be refreshed, the water wrung out of it so it can become more concentrated again and continue its air-drying work. The desiccant was regenerated by the sun in an open pond next to the salt ponds.

Water

Water is the essential ingredient to this project and getting the most value from every liter requires understanding its performance, particularly at different stages of salinity. Indeed, just how the water is desalinated continues to be an ongoing consideration. Watts explained some of the discoveries: “...we learned quite a bit about MED or multi-effect distillation that we used in Qatar (it evaporates using heat) and I am considering replacing that method with reverse osmosis that uses power because of the relative energy consumptions.”

“Another example is the twin skin approach to making fresh water which was my idea and everyone loved it: use the night sky to provide the coolness to condense the water on the roof of the greenhouse. (It’s a) reasonable idea but it is energy intensive and the heat has to be free. Although heat is considered less expensive than electricity as a source of energy, moving this stuff around leads to sloppy thought. While you might be able to use the night temperature for passive cooling, you still need to recover or collect the heat to evaporate the water; rarely is this heat free by the time you have got it to do something useful.”

“(Moreover) I learned that plants need careful treatment and my assumptions about temperature proved wrong. I had assumed that the plants would need to be heated at night to protect them from the cooler temps. But this was true only during a short part of the year. ‘No need for it through most of the year, in fact, the plants needed this diurnal range that cooler night temps provided to shut them down and with some species to get them to flower. Heat-



Green algae | Photo: Micropix, 2012 | Flickr cc ing up the ceiling was at odds with that. Additionally the double ETFE skins were blocking a significant amount of natural light which is an issue at the beginning and end of the day if not the middle."

Several other issues came up and some of them proved to be possible opportunities. Pawlyn gives an example of such a challenge. When saltwater is carried through pipes a certain amount of minerals build up on the inside of the pipes and eventually clog the system. The traditional treatment is to use a strong bleach and/or mechanical scrubbing, but this harms sea life, so he wondered if there might be a better way to not only solve the clogging problem, but to make use of the minerals.

He is proposing that the SFP test a mineral harvesting system based on Biorock ™, an electodeposition process devised originally for the creation of artificial coral reefs. In the process, a low voltage is applied to metal underwater creating a bipolar charge and it precipitates magnesium hydroxide and calcium carbonate which slowly accrete to whatever metal form has been sunk. Pawlyn is proposing that removable lightweight, steel frames be installed in the seawater intake pipes to harvest these minerals while reducing the conditions that cause the clogging further in the pipes. The encrusted steel frames can be removed once grown and used as structural elements . Pawlyn says: "There is something very appealing about the potential of growing elements to expand the project within the sea pipe that is supplying it, while solving problems of pipe-scaling."

It is Bill Watts' job is to see if such a thing is feasible. He says that there is a 98% difference between an idea and a reality and "that is the space that I live in". He is intrigued by the idea but as the hard-nosed engineer he will be looking to test all of its possible flaws.

"Well, Michael (Pawlyn) travels all over the world and brings back these ideas and lands them like a fresh fish on my desk", he says with a laugh. "Luckily at Max Fordham we have quite a bit of science background and capability and were able to do a sanity check through a friend with a PhD in inorganic chemistry. It does look feasible, but all the factors, temperature, pH, salinity, and the current for the electro-deposition have to be just right.

He explained that the magnesium is soft and not useful for building, but over time will be replaced by calcium which is hard and therefore useful as a building material. Hydrogen, Oxygen and Chlorine are produced: the O2 and Cl are oxidizing agents, and the Hydrogen can be stored as fuel. According to Watts the Cl does not seem to be a problem, despite it being a poison gas, because it is highly soluble in water and bubbling off decreases over time. It's a handy material and the team has demonstrated that it does decrease the pH of the pipe environment so shows promise as a bio-fouling preventative and possibly a good alternate to the chlorine that is typically used to clean pipes.

"Michael built some amazing 3m long spars made from fine steel wire that I took out to Qatar. After a few months they had accumulated a good 10 mm of deposit and was well on the way to becoming a very promising bit of structure."

Energy

Air, water and energy are inextricably entwined in this system and the fine-grained accounting for every liter is tied to every joule. Because the system's advantages are based on synergies or interrelationships among the components, sometimes the optimum methods shift.

"All of these things were moving targets", says Bill Watts. "For example PV panels are now about 5 times cheaper than when we started, changing the relative advantages weighed in a decision (on whether to use CSP). We learned quite a bit about MED or multi-effect distillation that we used in Qatar (it evaporates using heat) and I am considering replacing that method with reverse osmosis because of energy usage. Our goal henceforth will be to never add heat to the greenhouse in order to evaporate water."

He walks me through the type of energy accounting that is de rigeur for this type of project:

A. Both heat and electricity are measured in kilowatt hours, but electricity is more expensive. To evaporate one cubic meter of water you need 650 kWh of heat, and to condense that vapor back to water you need to remove the same 650 kWh of heat in a cooling process. That completes one cycle.

B. Multi effect distillation or MED uses 650 kWh to evaporate one m³ of water but the heat released on condensation is used to evaporate more water at a slightly lower temperature. This is done in a stepped approach in a partial vacuum and produces distilled fresh water. This stepped approach could possibly have 10 steps. Therefore in this half of the cycle, 650 kWh divided by 10 yields a cost of 65 kWh/cycle. To move this heat around, however, is expensive because you need pumps and electricity to do it, so you add about 6 kWh/cubic meter of water to the 65.

C. Reverse Osmosis (RO) has been reduced in energy consumption to about 3 kWh/cubic meter and you can retrieve some of this energy, so that 2-4 kWh/cubic meter is now achievable. There are other complications, such as the membrane type or sieve, is critical, as is the pump. Moreover, it does not yield water as pure as MED.

Food

The freshwater initially produced in the system went to irrigate the crops in the greenhouse and to both irrigate and cool the plants outdoors: arugula, barley, some traditional fodders and an array of desert plants, including halophytes.

There were some surprising results where the rubber met the road, according to Virginia Corless, particularly in the adaptability of certain plants.

"One interesting lesson learned: the (irrigating) hedges did not seem to impact many of the desert plants in the least-they could not have cared less whether that new moisture was there or not. As a matter of fact, when we tried to transplant some of them (always tricky), they were not doing well and our head grower, Stephen Clarkson, directed us to stop watering them at all- and they perked right up despite the fact that the water we had been giving them was minimal. This was a reminder of how wide-ranging but specific these adaptations can be. One example

Tangled Tamarisk (*tamarix ramosissima*) - Salt cedar

Photo: Bobby McKay, 2013 | Flickr cc

was the tamarisk tree which did not do so well in some of our managed plots, but was growing happily 20 meters away in a vacant spot."

The team also experienced the happy results of creating conditions that were conducive to life.

"While the desert species did not seem to be affected by the water, we found that nutrient levels were just as important a 'chokepoint' as water in the hedges experiment, and that these nutrients called forth a whole unforeseen population of opportunists, that grew to massive size, harbored insects, shaded and sheltered other plants that happily coexisted with them. None of this was planned but showed that these changed conditions did reap an unexpected bounty. We of course looked closely at who these 'invaders' were since they were so successful. Native grasses did especially well and could be an opportunity for improved forage crops within this system."

While the hedges may not have had the decisive effect on plants predicted, like many of the parts of the SFP system, they served more than one function. In this case, they also served to cool the CSP/MED apparatus.

"The hedges are important for two reasons: as a method to concentrate the brine in the saltwater sequence, and for cooling of the CSP water. Our lowly hedges, using a saline solution of 30% and evaporative cooling can actually do the same job as expensive cooling towers using freshwater have done in the more traditional setups, and that is very satisfying to think that we have harnessed a waste product to do this work and save money and precious freshwater."

Crossing to Jordan

It appears that the Jordan facility will be markedly different than the one in Qatar, with possible major changes in the way seawater is desalinated, and energy produced. The designers may choose reverse osmosis over MED, for instance and PV panels over CSP. The greenhouse condensing setup will change, since a double membrane roof appears unnecessary, as does heating the greenhouse with excess heat.

The SFP team is excited to leverage what they have learned in Qatar to the effort in Jordan. Corless elaborates.

"In Jordan, we plan on a 2 hectare 'launch station' called thus because it is qualitatively different than the pilot, where we proved how components could work. The objective of the launch station is to demonstrate the technology under local conditions in Jordan, to engage a team on the ground and attract relevant stakeholders for going forward. We have the funding and now are negotiating a final agreement about the land with the Aquaba Special Economic Zone Authority. Here we will do research on more site specific conditions relative to the greenhouse operation and outdoor plantings. Our intent is to be in construction within 6-12 months."

"The typical commercial operation would be scaled at 20 hectares to start and could either be linked in modular fashion or bumped up to a large scale of 200 hectares. The biggest challenge is the funding, frankly. The technical side adds up, but payback for investors is a slower cycle, and the interdisciplinary nature of this operation means a tougher challenge in explaining its feasibility."

“We are looking forward to testing some of the qualitative findings, or suggestions, that we uncovered in Qatar, and have already visited several of the surrounding agricultural communities, the National Center for Agricultural Research, and the nearby research station in Wadi Aquaba. There is also a well-developed academic community in Jordan that we hope to avail ourselves of.”

For engineer Bill Watts less might be more and that means shaving every bit of waste out of the system.

“In Jordan, I am looking forward to getting back to basics: leaving some of the wider agenda on the shelf for the time being (algae and halophytes), and because there will be no CSP, the evaporative hedges will need to be optimized if they are to have a future for plant propagation; pumps are expensive to operate. While the hedges did do a good job of cooling CSP plant we need to see when that can become part of the program again.”

Still, in the spirit of the project he cannot resist dreaming of the wider possibilities as he speaks to me over the phone.

“We are interested in all ways to use saltwater and will continue that quest. Also, though, I am looking forward to the capacity building of the local population, employing and training people. I am interested in some of these tangential technologies: bio pest control, for instance... and other opportunities will come up. For example, because of flash floods in the wadi, the government had placed a new flood control ditch across the site and we will try to capture that resource.”

On the other end of the line I can tell that he has already started some calculations.

Will the desert become green? Can we feed the world and quench its thirst for water and energy using the resources of the sea and sun? We shall see, but it seems clear that restoring an ancient landscape to its former verdancy will require an approach like this one, of observing natural phenomena, planning for systems, testing practical solutions, and being open to innovation. ×

Wadi rum desert in sunrise, Jordan | Photo: D-minor, 2010 | Flickr cc

Ammonite pieces

Photo: Jessica Rosenkrantz

Product design
Nervous System
Design Studio

vol 4 | 2014

Product design
Nervous System

Designers:
Jessica Rosenkrantz and Jesse Louis-Rosenberg

Could you tell us about your company?

Nervous System is a generative design studio that works at the intersection of science, art, and technology. We create using a novel process that employs computer simulation to generate designs and digital fabrication to realize products. Drawing inspiration from natural phenomena, we write computer programs based on processes and patterns found in nature and use those programs to create unique and affordable art, jewelry, and housewares.

Founded in 2007, Nervous System has pioneered the application of new technologies including 3D printing, webGL, and generative systems. Nervous System releases online design applications that enable customers to co-create products in an effort to make design more accessible. These tools allow for endless design variation and customization.

To grow our digital designs, we write generative programs. Unlike conventional design methods, our technique doesn't result in one finite form. Rather, we develop computational systems that can generate infinite distinct, yet related, forms. These systems are interactive, responding both to changes in specific variables and to physical inputs. There is no definitive final product; rather, the potential for infinite designs means each piece can be unique.

Jessica Rosenkrantz and Jesse Louis-Rosenberg

Photo: Ken Richardson

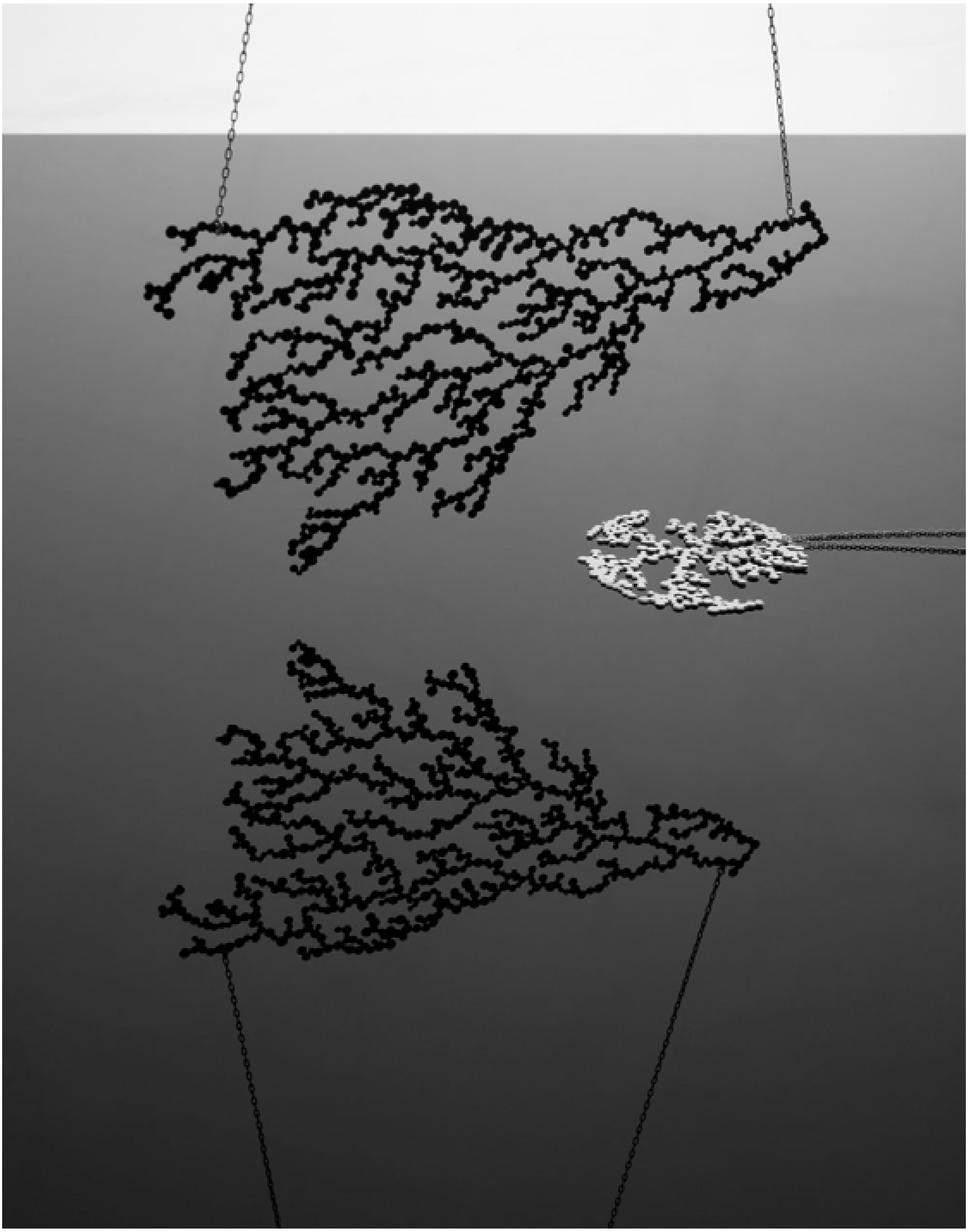
We use simulation techniques not simply to mimic natural forms, but to extend and bend these techniques to new ends. We first seek to understand the natural processes that form the world around us, and we then re-purpose these processes into design tools, applying them in ways that are unlikely or even physically impossible in nature. The resultant forms are realized through digital fabrication techniques such as 3D printing, laser cutting, and CNC routing. We release our work online as a series of interactive applications that people can use to create their own customized products.

How are you inspired by nature? Are you inspired by form, pattern, function, process, or systems in nature?

Our work at Nervous System explores processes which cause structure and pattern to emerge in nature. Our projects center around adapting the logic of these processes into computational tools; we do this by translating scientific theories and models of pattern formation into algorithms for design.

Our research focuses on the emergence of pattern and form in biological, physical, chemical, and social processes. Our designs evoke natural mechanisms such as cell division, coral aggregation, and leaf venation.

Nature provides an example for thinking about design in a new way. Rather than creating specific objects through a top-down process, we



Dendrite jewelry

Photo: Sarah St Clair Renard

create adaptive systems that work from the bottom-up generating an infinite, customized series of solutions matched for specific circumstances.

What kind of techniques do you use for your work? Can you talk more about the algorithms you use?

Our studio's projects are cross-disciplinary mashups that draw from diverse fields. We use techniques originally developed for scientific simulations, artificial intelligence, computer graphics, structural analysis, game development, architectural design, etc.

The basis of creating complex physical objects is the fundamentals of working with and representing geometry. Different projects require completely different ways of understanding shape. We use a lot of different techniques from computational geometry and graphics to represent space and form for each project.

We also work with simulations of natural phenomena that are often represented with partial differential equations. There is a vast and ever expanding array of algorithms to work these types of equations depending on the exact nature of the problem. Some projects are more particle or agent based, with individual points acting independently.

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

We draw inspiration from varied sources. We enjoy making our own direct observations of nature through hiking, scuba diving and macro photography. We spend a lot of time reading scientific papers on topics relating to natural pattern formation and simulation. Additionally, we are motivated by the latest developments in computer graphics and digital fabrication.

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

Right now we are working on a number of projects. One of them focuses on the differential growth of surfaces and was inspired by L. Mahadevan's research into the development of leaves and flowers. It is a thin shell simulation that models surfaces growing at variable rates. Complex, ruffled forms emerge from simple initial surfaces as they grow preferentially along their edges.

Another project is an online application for creating customized, cellular bookcases that combines 3d-printable connectors with plywood to create DIY furniture.

A third project called Kinematics is a system for 4D printing that creates complex, foldable forms composed of articulated modules. The system combines computational geometry techniques with rigid body physics and customization. Practically, it allows us to take large objects and compress them down for 3D printing through simulation. It also enables the production of intricately patterned wearables that conform flexibly to the body. ×

https://n-e-r-v-o-u-s.com

Tetra kinematics 175-n

Photo: Nervous System

Filament gold necklace | Photo: Nervous System

Product design
Nervous System

Designers:
Jessica Rosenkrantz and Jesse Louis-Rosenberg

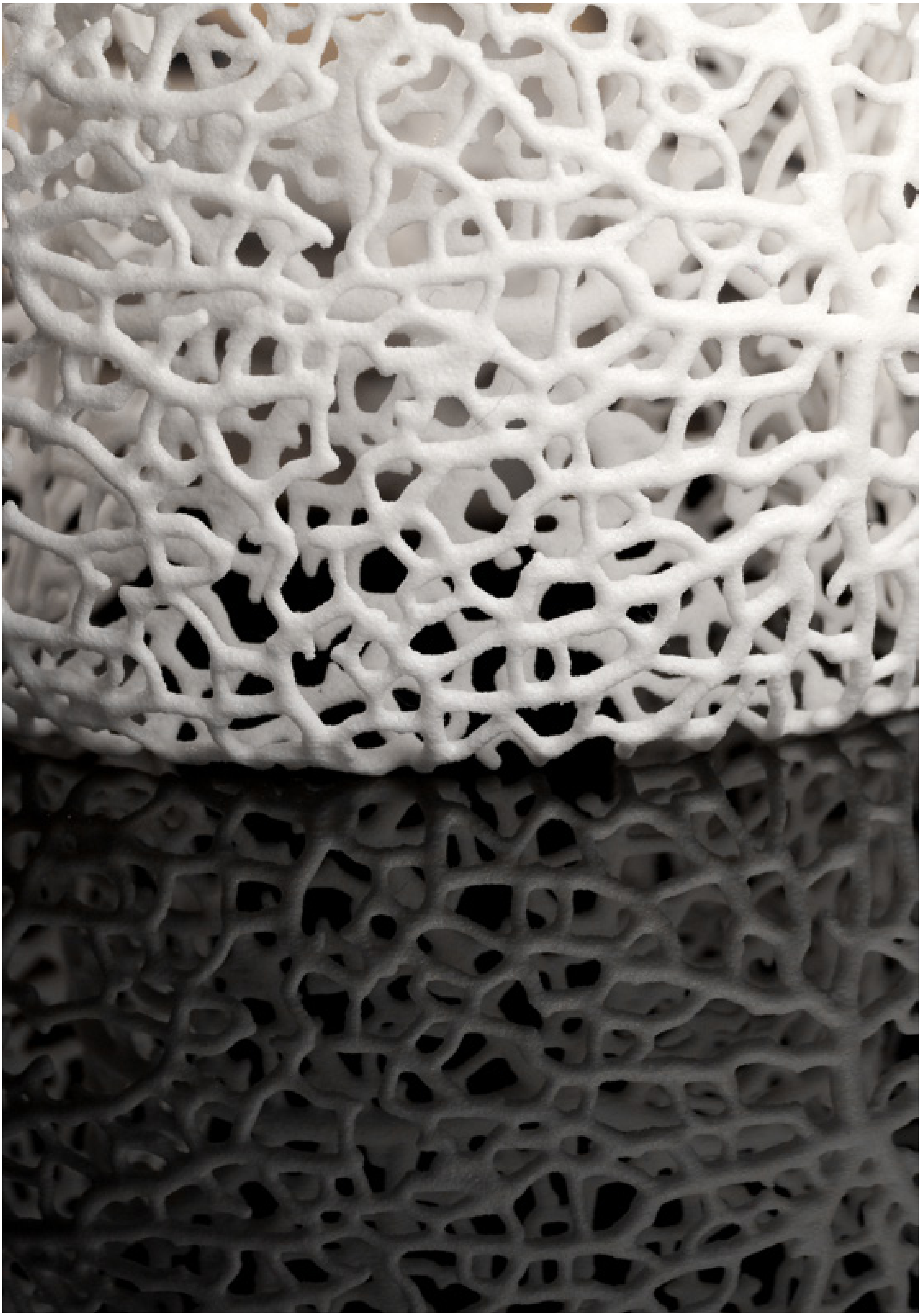
Bamboo cuff | Photo: Nervous System

Cell Cycle Exo Bangle | Photo: Nervous System

Folium | Photo: Nervous System

Laplacian Growth #1 | Photo: Nervous System

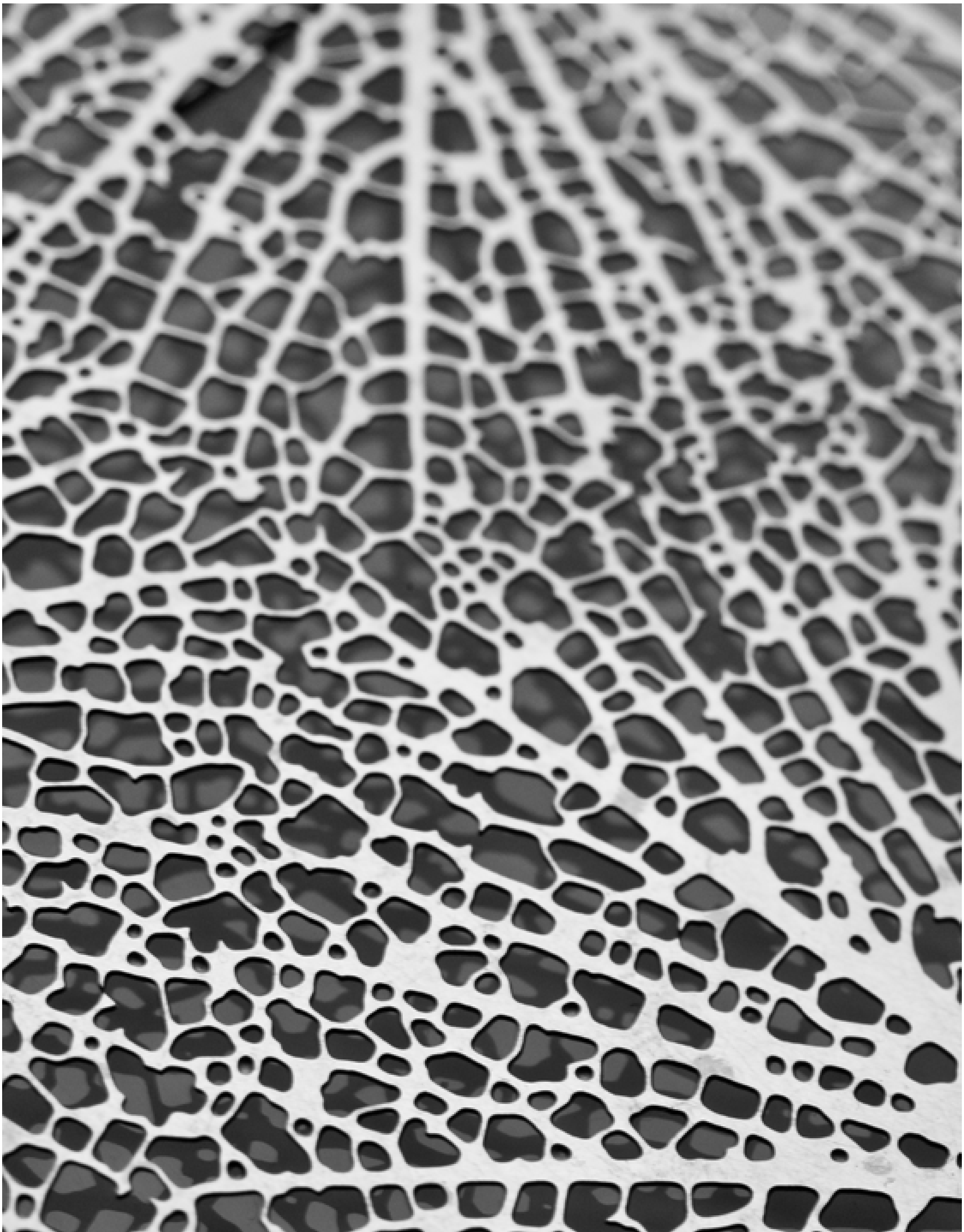
Seed Lamp | Photo: Nervous System



Hyphae | Rhizome Cuff | Photo: Nervous System

Pollen Lamp (close up) | Photo: Nervous System

Arboreal Lamp (detail) | Photo: Nervous System

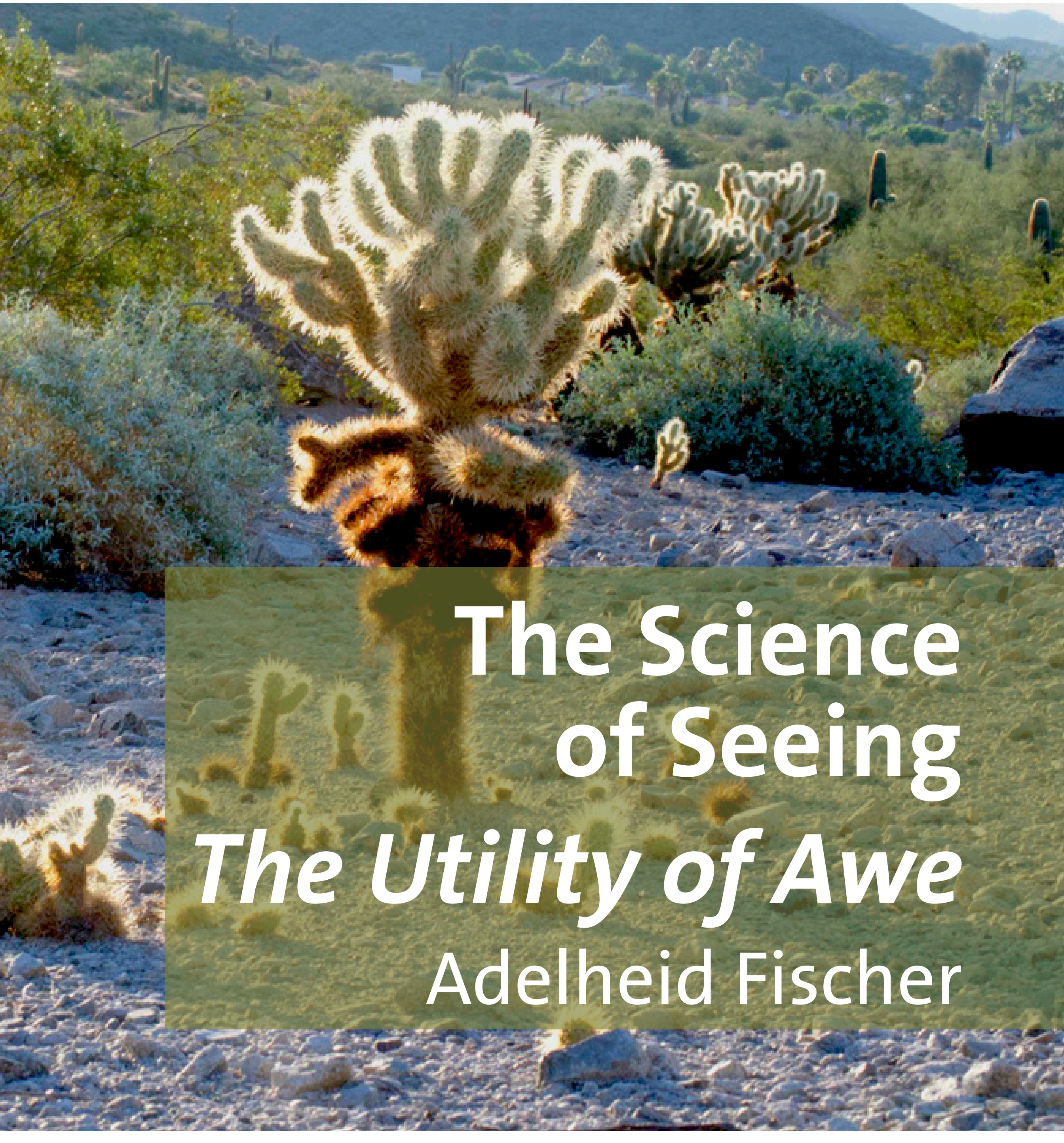


Xylem | Roots Brooch - stainless steel | Photo: Nervous System

Reaction cup and plate - porcelain | Photo: Nervous System

A “devil’s garden” of cholla cactus in the Sonoran Desert

Photo: Prasad Boradkar, 2014



The Science of Seeing
The Utility of Awe

Adelheid Fischer

The Utility of Awe

Welcome to the seventh in a series of essays entitled "The Science of Seeing."

"The more we learn about the mystery, the more we will admire it. Mystery and magic never really go away."

From *Survival of the Beautiful* by David Rothenberg

Early one morning this past summer I woke to the eastern horizon banked high with blue-gray clouds. They doused everything with a dull ashen light, draining colors and flattening textures so that the desert mountain behind my house took on the pewter tones of a landscape photograph from the 19th century. I pulled a camp chair down into a low point in the garden where I usually sip my first cup of coffee among totems of saguaro cactus and the wild-flung stems of creosote bush. The day opened soft and cool, more like Seattle than blistering Phoenix. Just as I leaned back to savor the unexpected reprieve from the heat, the sun slowly began to clear the cloud wall behind me. As if on a dimmer switch, the light brightened by degrees, a glow spreading to the crowns of the cactus and then widening until it spotlighted the ridges a quarter-mile distant. Many plants in the desert reflect sunlight as a way of dodging the intensity of its focus. They bristle with translucent spines. Some encapsulate seeds in miniature balls of plush white hairs. Others buff their surfaces with a layer of wax or resin. The strike of light on each needle, each leaf, each pod can sometimes cause the place to spangle, as if the plants were hung with chips of polished glass. I was stunned. I had expected an ordinary day, a routine cup of morning coffee. Instead, I suddenly found myself far from a familiar shore, swimming in a spilled cargo of winking stars.

This is awe and wonder, to be caught unawares by something big, like beauty, that sneaks up from behind, cups your elbow and steers you into a place you hadn't expected to go. "Wonder is anything taken for granted...suddenly filling with mystery," writes David James Duncan in his book *My Story as Told by Water*. "Wonder is anything closed, suddenly opening."

Academic psychologists know relatively little about awe—and even less about the things that provoke it, like beauty. Until recently, most studies have focused on the six classic emotions: anger, disgust, fear, sadness, happiness and surprise. I was astonished to learn that "the field of emotion research is almost silent with respect to awe," despite the fact that "awe is central to the experience of religion, politics, nature, and

The desert sun lights up the resinous leaves and plush white seed balls of creosote bush

Photo: Prasad Boradkar, 2014

The curled forms of a fairy duster's empty seedpods gleam in the light | Photo: Prasad Boradkar, 2014

The spines on the stem of a hedgehog cactus reflect sunlight, helping to keep plant tissues from overheating
Photo: Prasad Boradkar, 2014

art. Fleeting and rare, experiences of awe can change the course of a life in profound and permanent ways," write psychologists Dacher Keltner of the University of California, Berkeley, and his colleague Jonathan Haidt of the University of Virginia in a pioneering 2003 paper.

The reasons for this oversight are complicated. I suspect that "serious" researchers have avoided the subject because awe often is perceived as a kind of emotional inebriation, a little sloppy, soft-headed and embarrassing like the sentimental uncle who launches into a tipsy riff each year at the Thanksgiving table.

But there are other, more practical reasons why the subject of awe has escaped scholarly notice. Studying it is challenging on many fronts. As far as we know, animals don't experience awe, so researchers cannot learn from analogues in the lab. Moreover, the experience of awe relies on two essential triggers: serendipity and a scope of confounding size. Awe's episodic, ephemeral nature makes it difficult to conjure on the spot. Keltner describes it as a "Zen-like challenge": an attempt to measure something "which might transcend measurement, planning what can only be unexpected, capturing what is beyond description." Awe, he explains, is an encounter with something far larger than the customary confines of the self or one's ordinary frame of reference. It "requires vast objects—vistas, encounters with famous people, charismatic leaders, 1,000-foot-tall skyscrapers, cathedrals, supernatural events—that don't fit well in the fluorescent-lighted 9' x 12' space of a lab room."

The results of ingenious new research suggests that the experience of awe not only has the potential for personal transformation but also may be critical to societal well-being. It may even have played an evolutionary role in the survival of our species. The emotion promotes a lessening of what Keltner calls "the press of self-interest." In one early experiment, Keltner and his colleague Lani Shiota asked participants to recall a peak experience while out in nature such as listening to the breaking waves of the Pacific Ocean or walking through the dappled light of a forest of big trees. Study subjects commonly experienced feelings of diminishment, relaying such observations as "I felt small or insignificant." They also became less preoccupied with the self, volunteering such comments as "I was unaware of my day-to-day concerns." At the same time, they registered a sense of expansiveness and connection. "I felt the presence of something greater than myself," some reported or "I felt connected with the world around me."

Subsequent research, such as a 2012 study by a trio of researchers from Stanford University and the University of Minnesota, supports the finding that the experience of awe makes us less self-absorbed and more social, more open to connection. Some of the study's participants, for example, were exposed to awe-eliciting video clips or asked to read or write about experiences of awe. Those who viewed snippets of encounters with whales or massive waterfalls reported responses that were dramatically different from, say, those who simply watched footage of happy people waving flags through a rain of confetti at a city parade. In follow-up surveys of the two groups, the awe-exposed participants felt as if they had more time, were less impatient, were more willing to volunteer to help other people, valued experiences more than material goods and reported a bigger bump in life satisfaction.

The desert's diffraction of the sun into many points of light is mirrored in the mottled pattern of a roadrunner's feathers

| Photo: Prasad Boradkar, 2014

From these and other studies, Keltner and his colleagues conclude that awe has the capacity for creating greater openness, generosity, a willingness to connect, to help others, to collaborate. Writer Duncan summed up the positive influence of awe on human behavior like this: “I believe some people live in a state of constant wonder,” he declared. “I believe they’re the best people on Earth.”

On late Saturday afternoons in mid-winter, I like to hike into the interior of a desert mountain behind my house to a place called Pima Canyon. One south-facing slope hosts a particularly fine example of what’s known as a devil’s garden. These places are so-named for the spiny cholla cactus that tend to congregate in dense stands. Chollas are infamous for their sausage-shaped joints that can be easily dislodged from the plant but not from the fingers or ankles of hikers who become impaled when accidentally brushing up against them. Dead joints the color of dark chocolate adhere along the length of their stalks which can grow to five feet tall. Live plant parts sprout in bristled masses from the crowns of the cactus like matted braids of bleached-blond dreadlocks. In his book *When the Rains Come*, the biologist and desert writer John Alcock observes that the thatch of spines that covers each plant joint is so good at reflecting sunlight that the outer skins of chollas heat up to only fourteen degrees F above ambient air temperatures in the desert’s searing heat whereas the cuticles of less spiny cactus can soar to forty degrees F. In laboratory tests, scientists made an even more startling discovery: when they slowly turned up the heat, cholla cactus made biochemical adjustments that enabled them to survive 138 degrees F.

I love these elite thermal athletes, but not just for their extraordinary capacities. In winter the low angle of the setting sun runs through the devil’s garden like a wildfire, illuminating each blond spine until the whole hillside glows. Someday, I would like to take a couple neuroscientists into the field, have them string up my head with electrodes and and watch their monitor burst into flame when the sunset takes a match to the hillside—and to my heart. “Happens every time,” I’ll tell them. This is your brain on awe.

For those of us who study and practice biomimicry, awe is regarded as a fringe benefit, albeit a much-valued pleasure. New insights from the academic literature in psychology, however, might offer another, far more serious perspective. I’ll wager that the experience of awe drew us to the discipline of biomimicry in the first place. Each one of us could likely point to our own treasured organisms that, like the cholla cactus, inspire with their ingenuity and seduce with their beauty, organisms that we visit time and again in the wild to restore a sense of magnificence to our lives.

I might go one step further, however, to say that the experience of awe not only makes us revisit nature time and again but that it also helps us persist in our search for the secrets to survival and puts us in a frame of mind to make the most of what we find. Positive emotions such as awe actually create the conditions conducive to innovation. I believe this for the reasons that Keltner and his colleagues have proposed: that awe has the capacity for creating greater openness, generosity, a willingness to connect, to help others, to collaborate.

Biomimicry is labor in the trade of wonder. For me, the paycheck is to stand in the midst of an extended family of cholla cactus and feel a throb of gratitude as they ignite with the sunset, burn and then rise again from the ashes of a long winter's night. What astounds even more is this: that at any point in time, we could have taken a wrong exit into a dead end on the long highway of evolution. And yet here we are together in the world, lit with joy and sunlight on an ordinary afternoon in winter. It could have been otherwise—but it wasn't. "Believe in what lasts," writes David Rothenberg in the *Survival of the Beautiful*, "knowing that evolution has kept these beautiful forms alive because they started out being possible and ended up being actual—not because they had to be, but because they ended up surviving through a mix of randomness and opportunity that likely would not be repeated if we were to roll time back a few million years and start again. So is there nothing especially good about what life strategies and results we have got? They are important because they are there. And we are there too." ×

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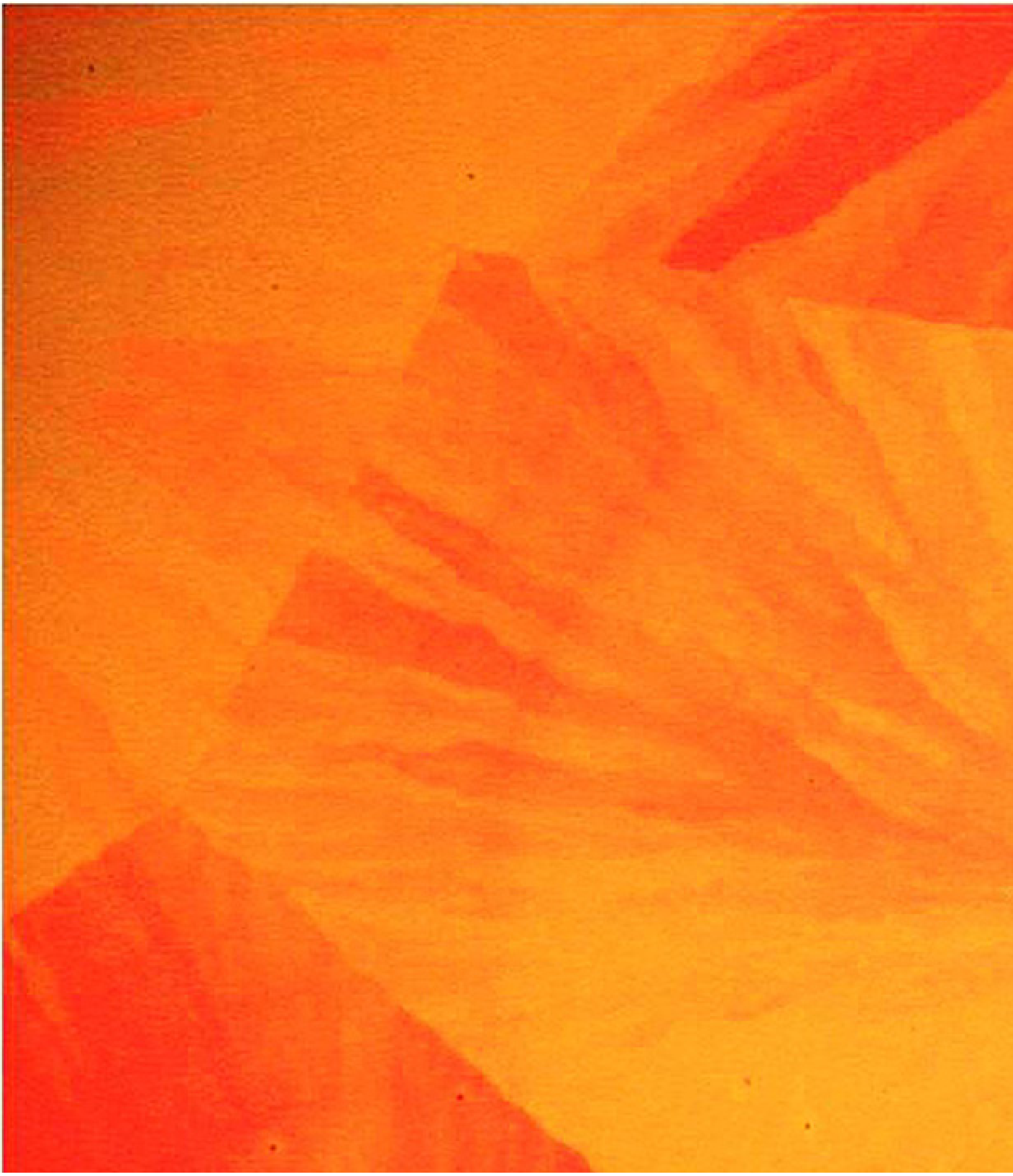


Spherulites

Photo: Anna Hailey (graduate student), Marsha Loth (University of Kentucky), John Anthony (University of Kentucky), Yueh-Lin Loo *01 (faculty) | 2014 Princeton University Art of Science Competition

Portfolio

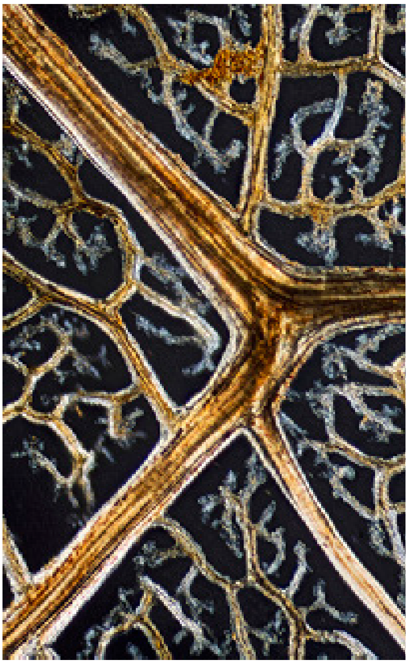
2014 Princeton University Art of Science Exhibition

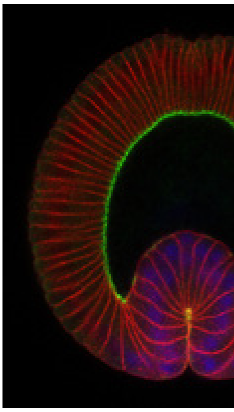
In this portfolio we show you a selection of the 2014 Princeton University *Art of Science* Competition entries. All images are courtesy of Princeton University. To view all entries please see http://artofsci.princeton.edu

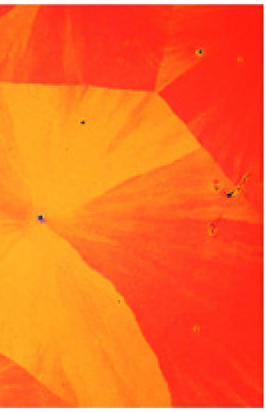
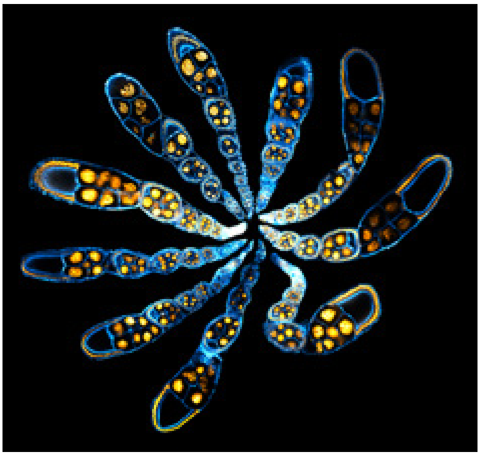
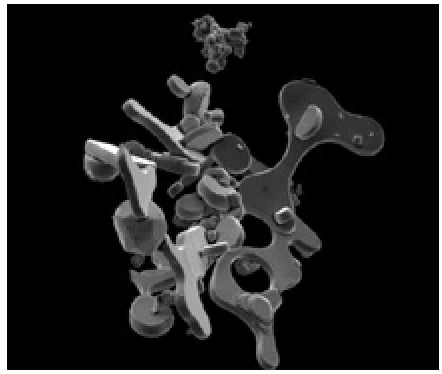
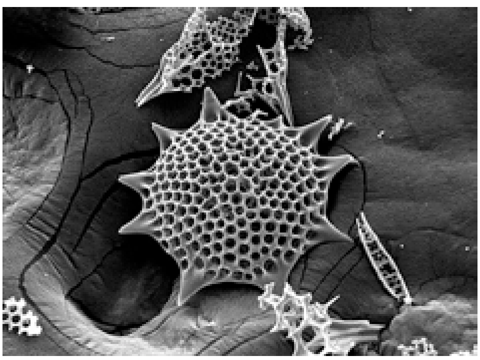
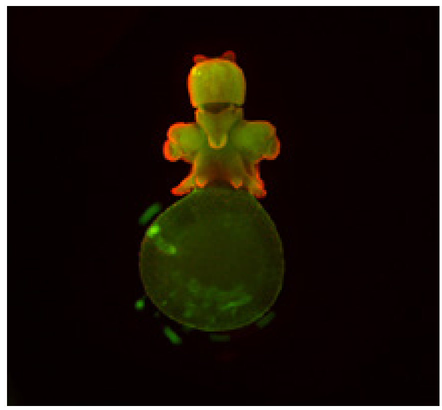
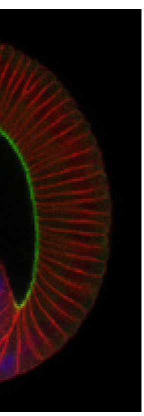
The Princeton University *Art of Science* exhibition explores the interplay between science and art. The images are not art for art's sake. Rather, they are produced during the course of scientific research. Entries are chosen for their aesthetic excellence as well as scientific or technical interest.

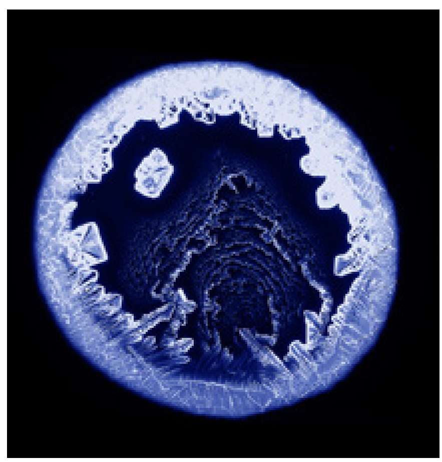
Art of Science spurs debate among artists about the nature of art, opens scientists to new ways of "seeing" their own research, and serves as a democratic window through which the general public can appreciate both art and science — two fields that for different reasons can feel threatening to the non-expert. *Art of Science* imagery has universal appeal, across cultures, languages, and age groups.

Powerful imaging tools can now capture our world in ways never before contemplated and unintentionally produce aesthetically interesting visual artifacts. When viewed through the lens of art, these images can further one's concept of what it means to be human, enhance our appreciation of the natural world, and enrich our cultural heritage by expanding the definition of what we call art and who we call artists. Ultimately, the aim of the AoS enterprise is to create a new symbiosis of the two fields long considered irreconcilable ever since C.P. Snow's pronouncement in the 1950s of the great cultural divide that exists between science and the humanities. ×



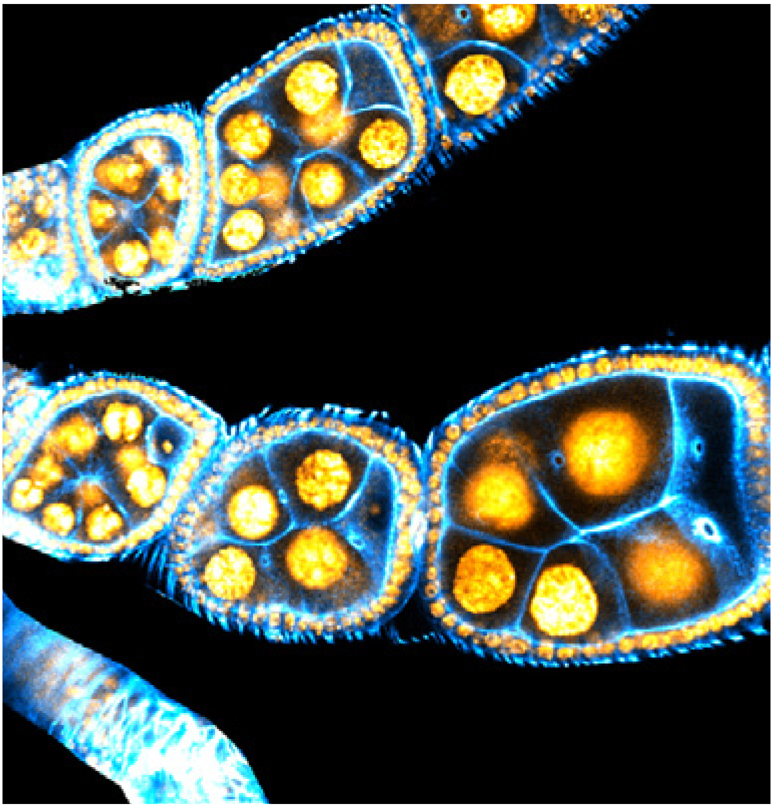


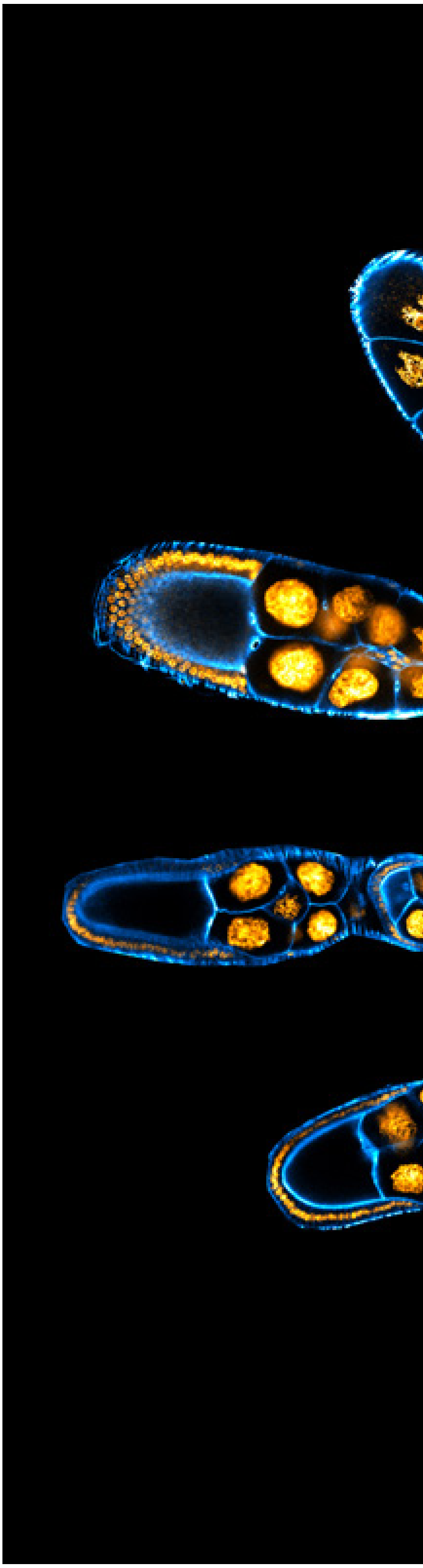









This page: Fruit fly factory (with detail) | Yogesh Goyal (graduate student), Bomyi Lim (graduate student), Miriam Osterfield (post-doc), Stas Shvartsman (faculty)

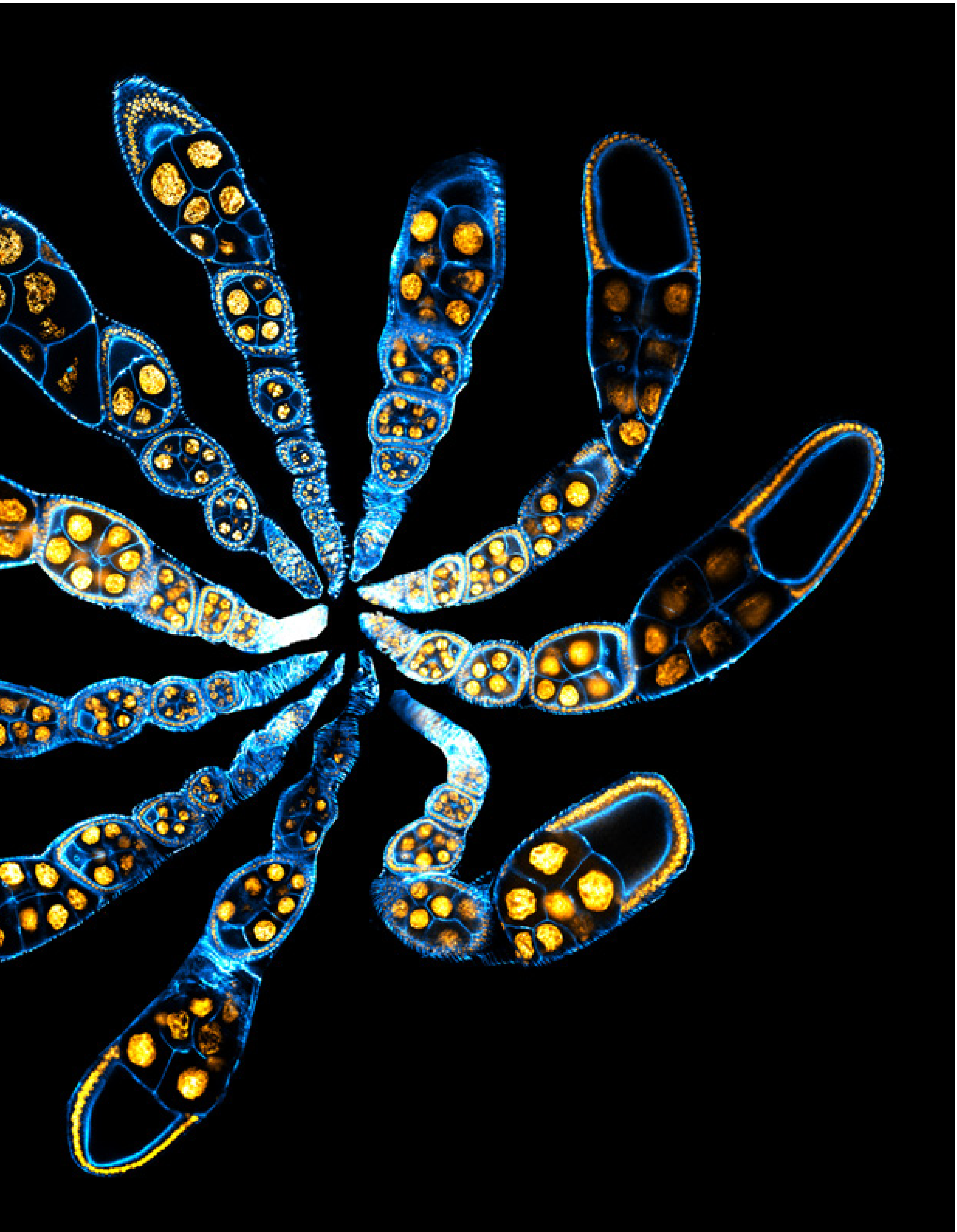
Each ovary of the female fruit fly houses multiple ovarioles or "assembly lines" in which individual egg chambers develop into fully formed fly eggs. Each egg chamber consists of 16 large germline cells (one of which is the future egg cell), surrounded by a thin sheet of smaller cells. In this picture, cross-sections of ten ovarioles from different female fruit flies are arranged with stem cells and early stage egg chambers at the center, and the more mature chambers at the periphery. The nucleus of each cell is stained yellow/orange. The cell membranes are stained blue.

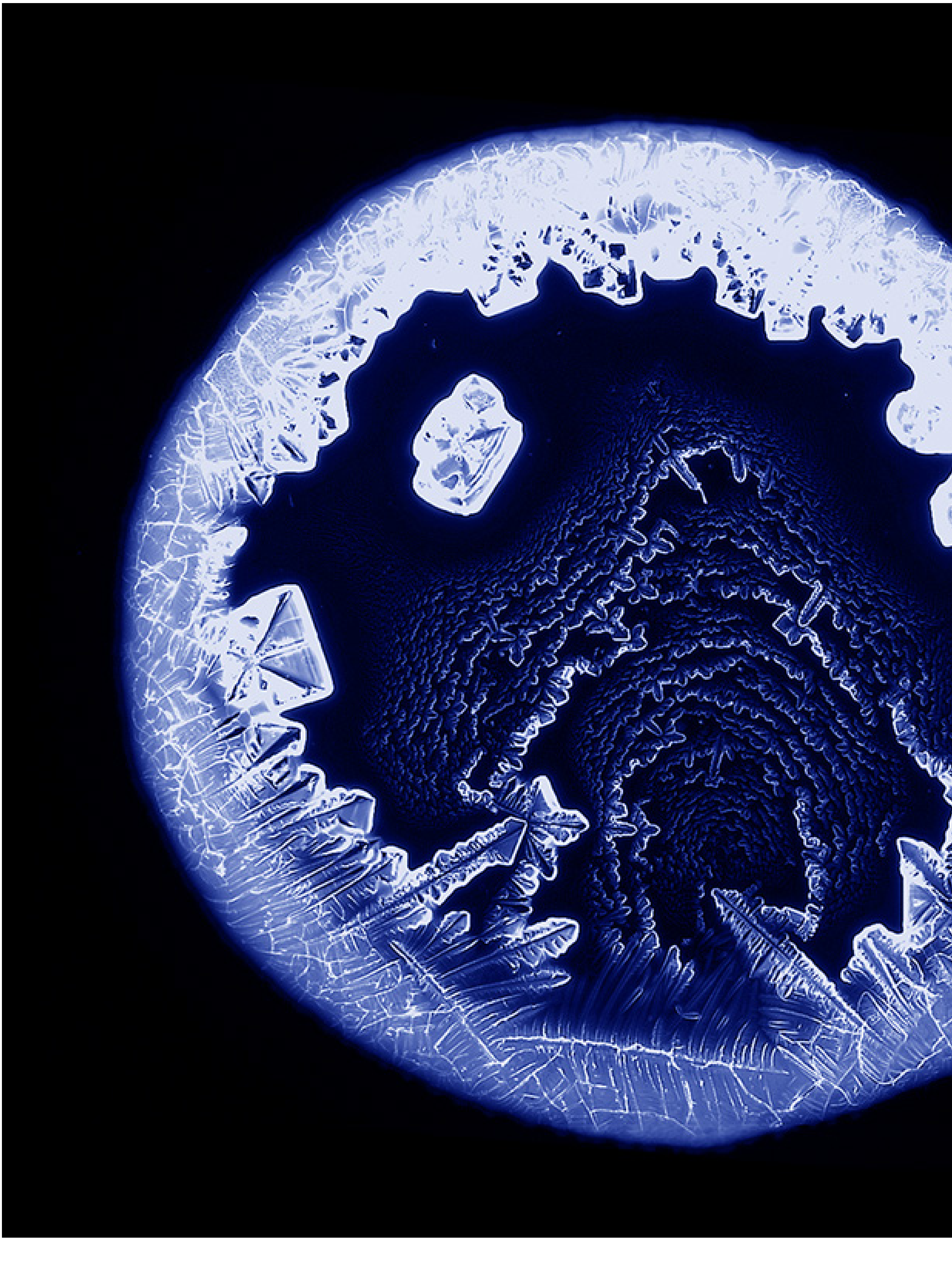


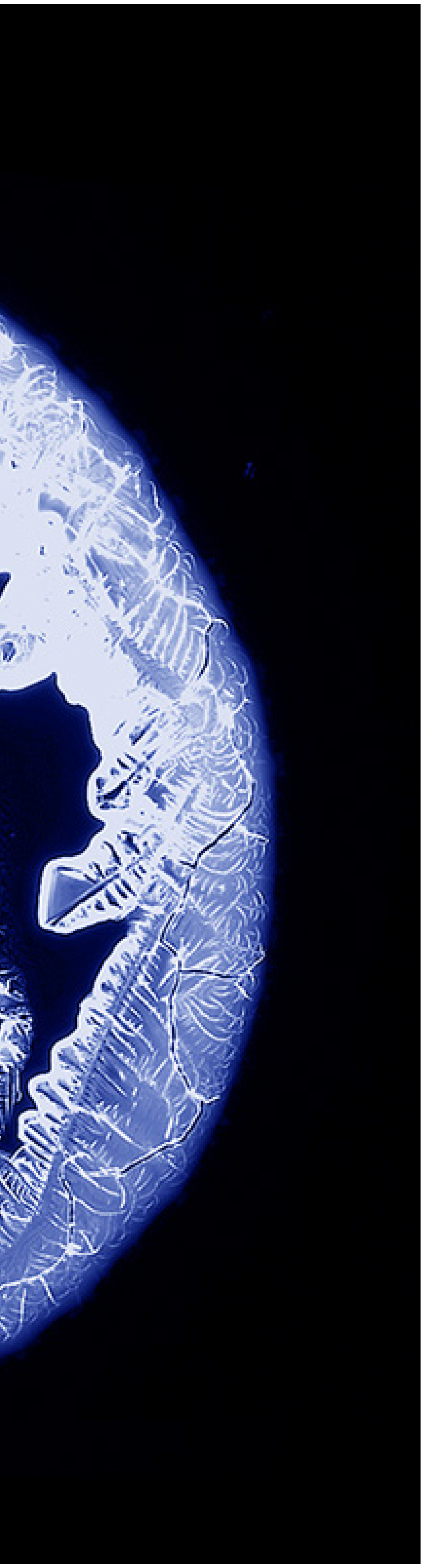


Previous page: Watermarks | Sara Sadri (postdoctoral researcher)

Water can erode rock, carve through cliffs, and sculpt sand. Water moving back and forth on the Atlantic coast created this intricate pattern. As a hydrologist, I am fascinated by the natural phenomena of our beautiful planet. The way water in this picture found its way back to the ocean reminded me of a peacock's tail spreading under the sun or a woman's hair blowing in the wind.

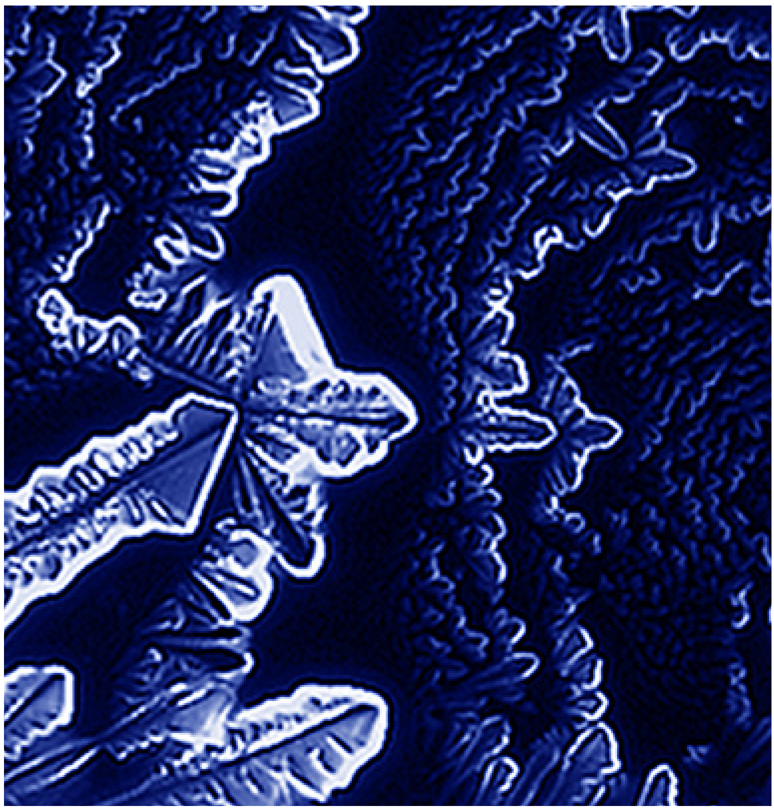






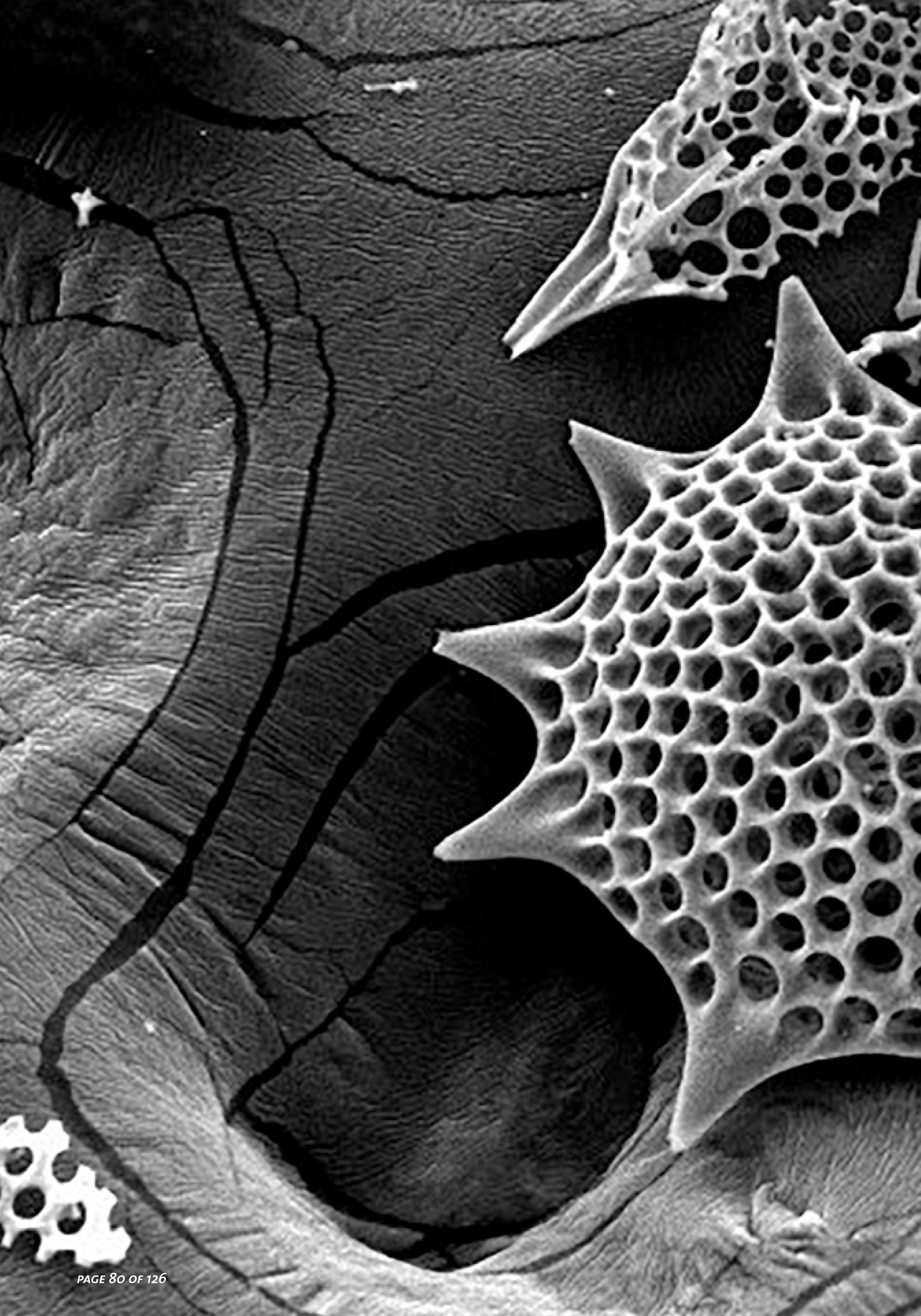
This page: A cave of crystals (with detail) | Hyoungsoo Kim (postdoctoral researcher), François Boulogne (postdoctoral researcher), Howard A. Stone (faculty)

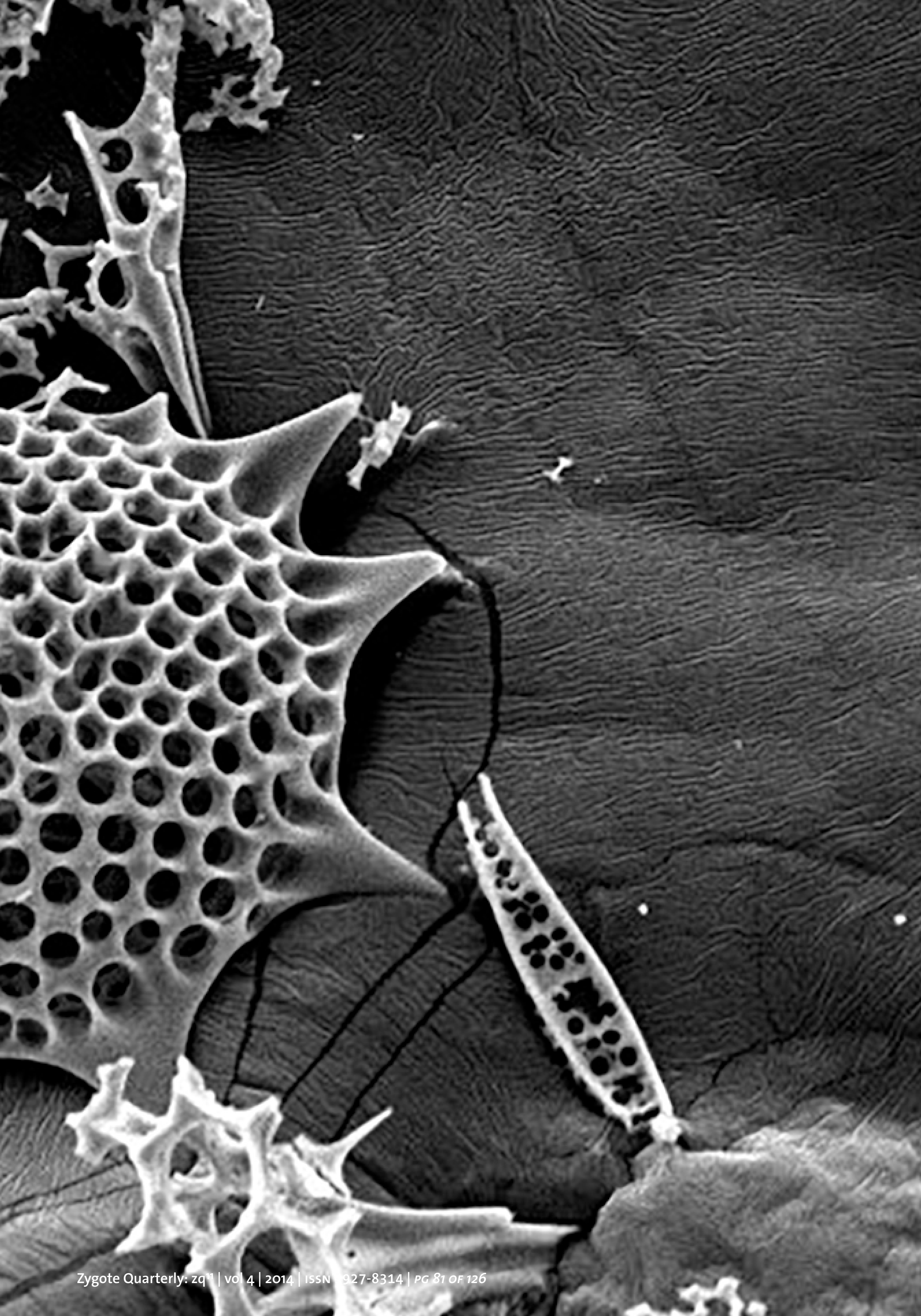
Watch any liquid – from tap water to the richest coffee – evaporate off a surface and you will see it leave a unique, ghostly mark. Here, we deposited a dilute solution of bovine serum albumin – a protein from cow's blood. As the solution droplet evaporated, the protein crystallized and left a delicate pattern similar to that seen in snowflakes, which we call "dendritic crystallization." As time passed, more and more moisture evaporated, ultimately revealing a crystal cave that represents, to us, the need to explore even deeper in our quest for scientific discovery.

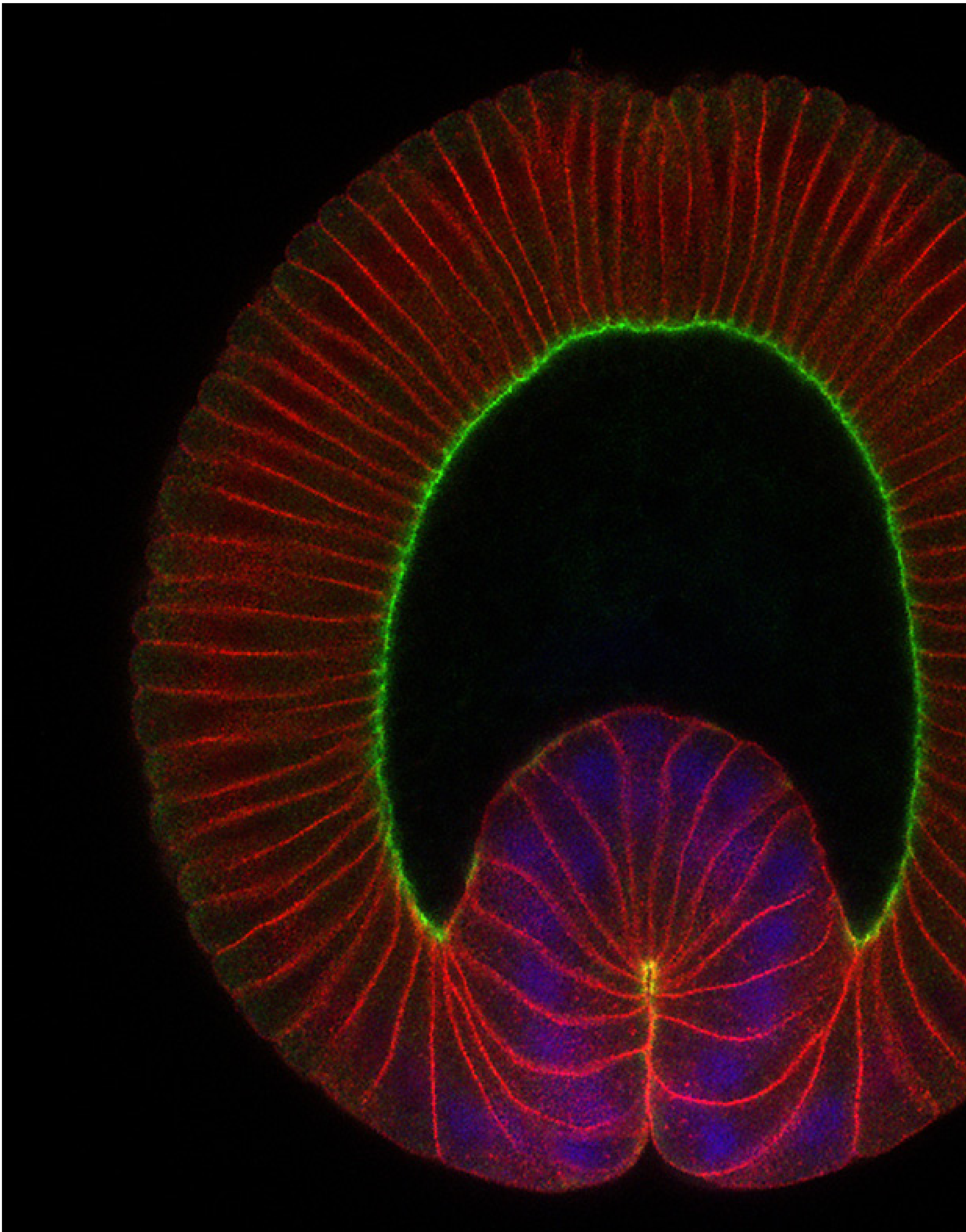


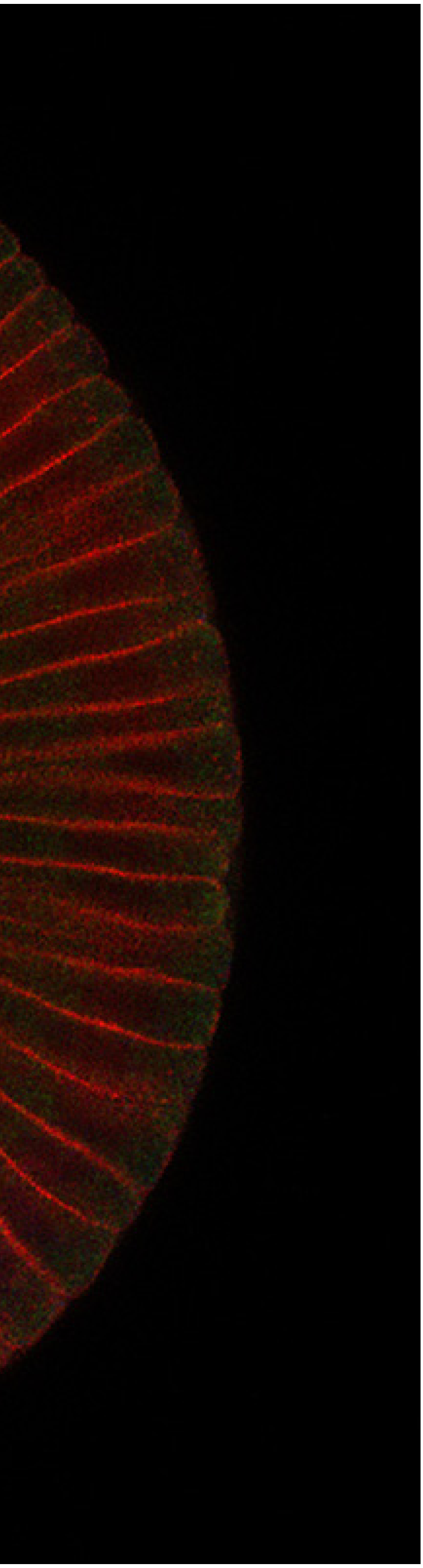
Next page: Star light, star bright | Marisa Sanders (graduate student)

Sometimes the scum of the Earth is brimming with beauty. The gelatinous brown coating often seen on sticks or rocks near bodies of water is composed of plant-like organisms known as diatoms. Invisible to the naked eye, they are a favorite subject among microscopists and come in a variety of shapes – ovals, stars, triangles, and more. I used a scanning electron microscope to image these diatoms at 350x magnification. SEM is a type of electron microscope that produces images by scanning a sample with a focused beam of electrons.



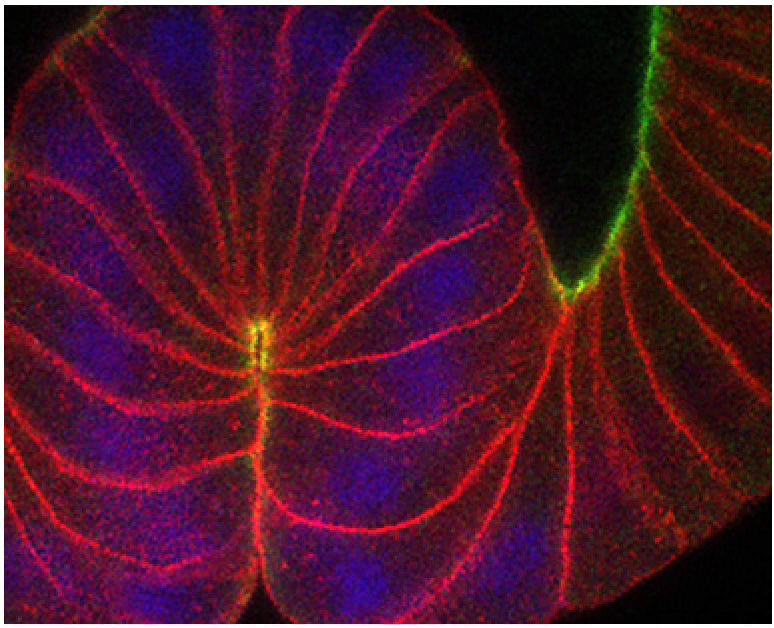






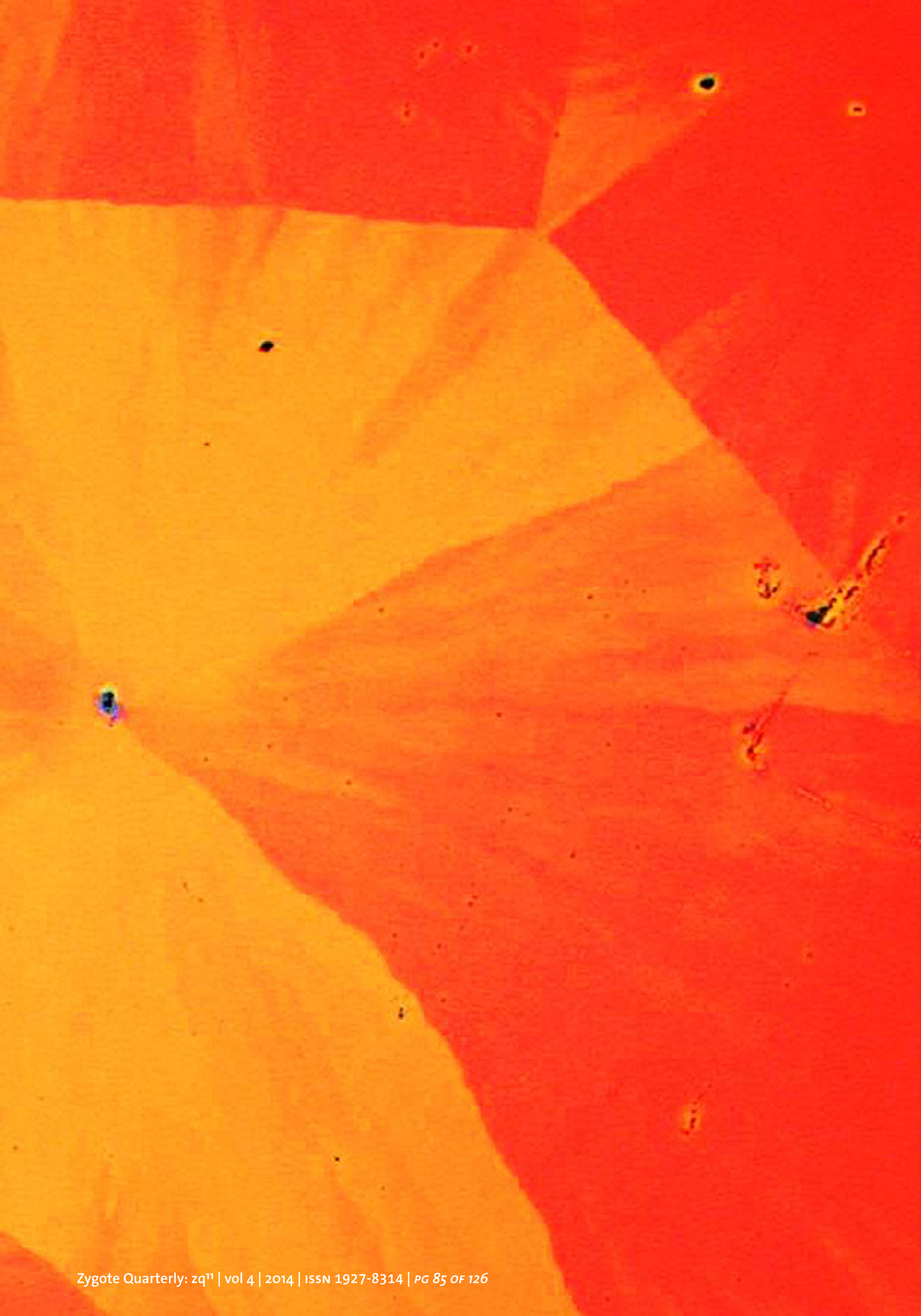
This page: Not birth, marriage, or death (with detail) | Michael Swan (graduate student), Eric Wieschaus (faculty)

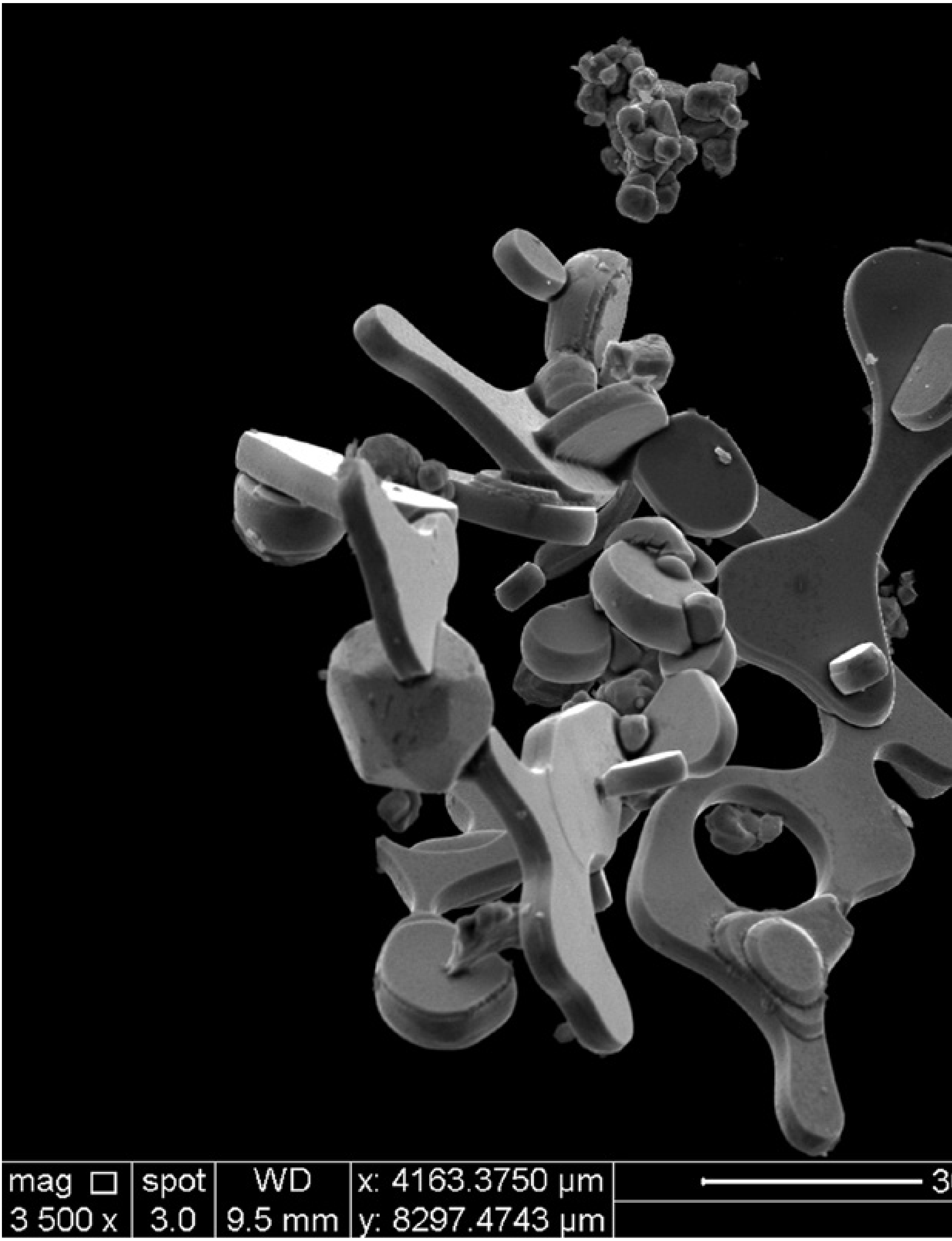
The title of this image paraphrases Lewis Wolpert's declaration: "It is not birth, marriage, or death, but gastrulation, which is truly the most important time in your life." 'Gastrulation' is the process by which, through coordinated cell shape changes and movements, an embryo takes form. This image shows a transverse view through a gastrulating fruit fly embryo. The transcription factor twist (the blue omega shape) demarcates the "invaginating mesoderm." Mesodermal cells will eventually form tissues like musculature and the heart. Differences in cell shape are highlighted by a plasma membrane marker (red). The embryo – which is barely visible to the human eye – was heat fixed, processed for immunofluorescence, and then dissected by hand under a stereomicroscope. The embryo is roughly 150 microns in diameter.



Next page: Spherulites | Anna Hailey (graduate student), Marsha Loth (University of Kentucky), John Anthony (University of Kentucky), Yueh-Lin Loo (faculty)

Compared to traditional inorganic semiconductors like silicon, organic materials that conduct electricity are lightweight, easily processed, flexible, and inexpensive. With the help of a microscope, we can see spherulites (spherical crystals) in an especially promising semiconductor material called - are you ready for this? - 5,11-bis(triethylsilylethynyl)anthradithiophene (TES ADT). In the Loo Lab we have found that exposing this material to a special chemical vapor induces the growth of spherulites.

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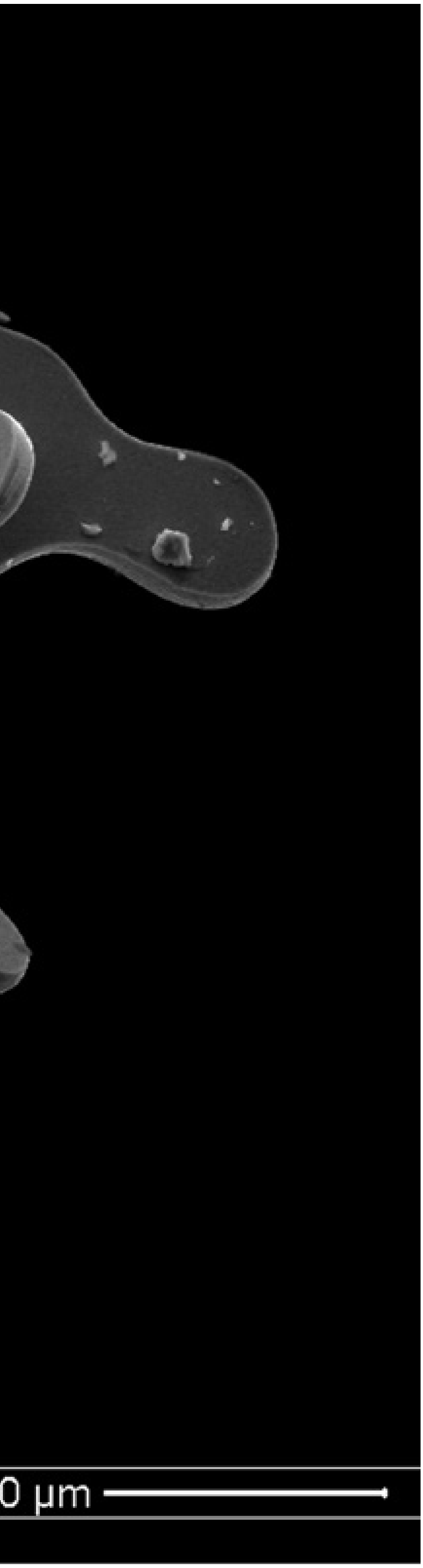
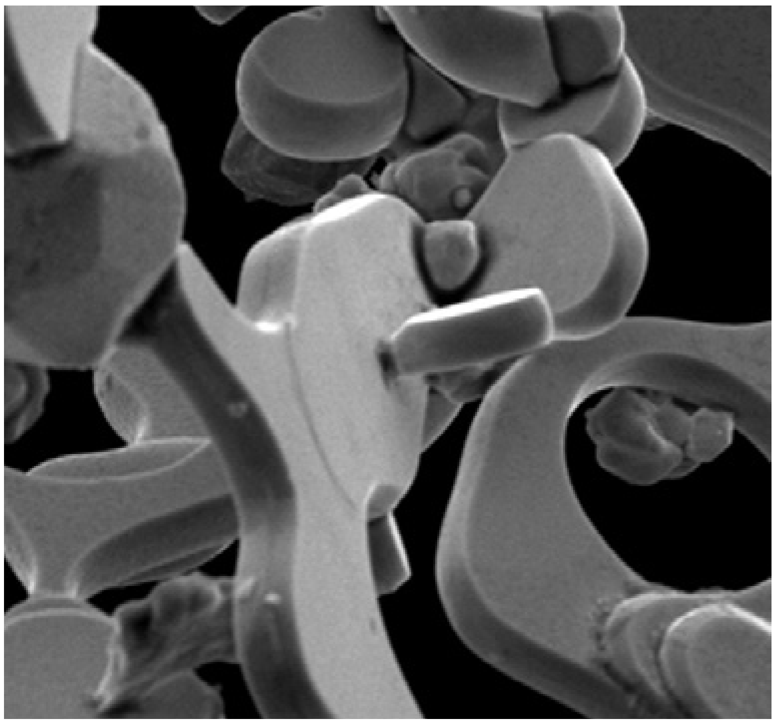


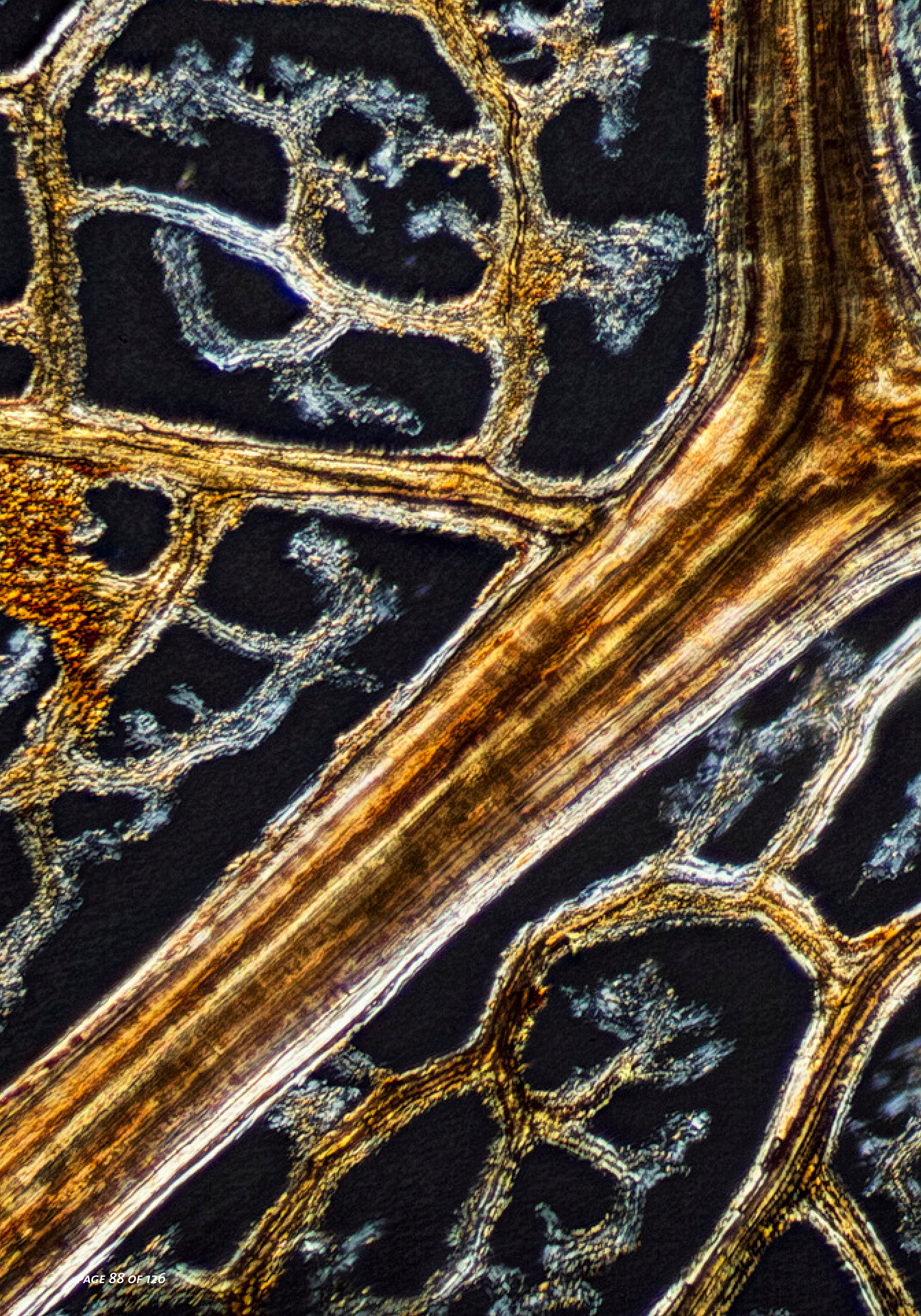
This page: Where's Snoopy? (with detail) | Mazhar Ali (graduate student), Leslie Schoop (graduate student), Rebecca Smaha (undergraduate '14), Quinn Gibson (graduate student), Zach Detweiler (graduate student)

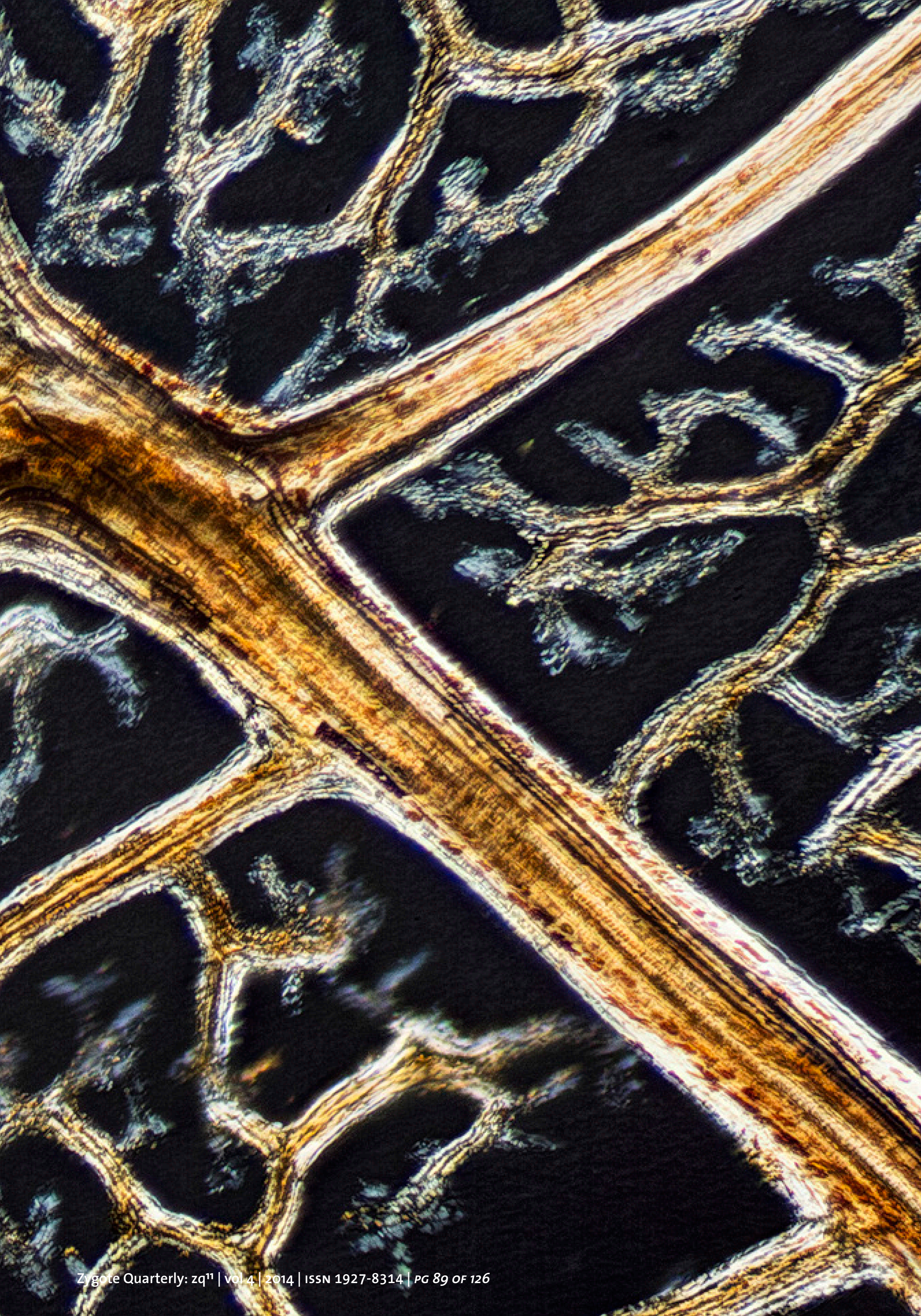
When found in nature, sodium iridium oxide crystals form honeycomb-like plates. But the crystals we see here have rounded edges and holes. We're not sure why. It may be that fast-track growth in the lab (where it takes days rather than millennia for a crystal to form) allows the individual hexagonal cells to stack with a slight rotational offset, resulting in these curious shapes. If you were to visit our lab this is exactly what you would see looking through a Scanning Electron Microscope. Can you find Snoopy?

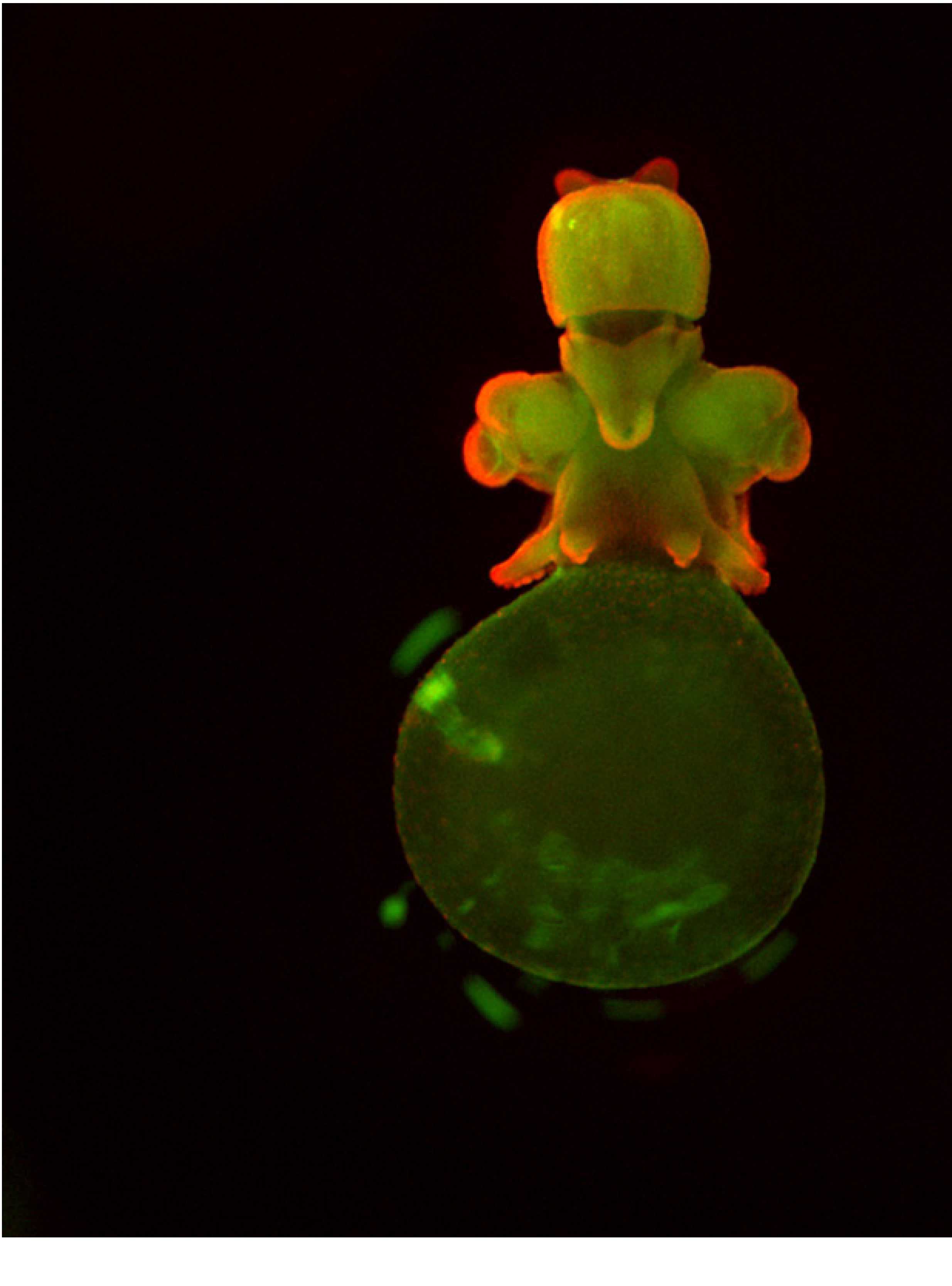


Next page: Leaf | Nathan P. Myhrvold (graduate alumnus *83)

With the naked eye, one can see the veins spreading from the stem to the tips of a leaf. Amazingly, even under high magnification, as shown here, the vein hierarchy looks qualitatively the same: each large vein branches off into secondary, tertiary, and quaternary veins that support the cells of the plant. In mathematical terms, the structure is fractal. This image was taken using dark-field microscopy, a technique that can produce higher-resolution photomicrographs than bright-field microscopy but sometimes alters the colors of pigmented objects from their true hues.





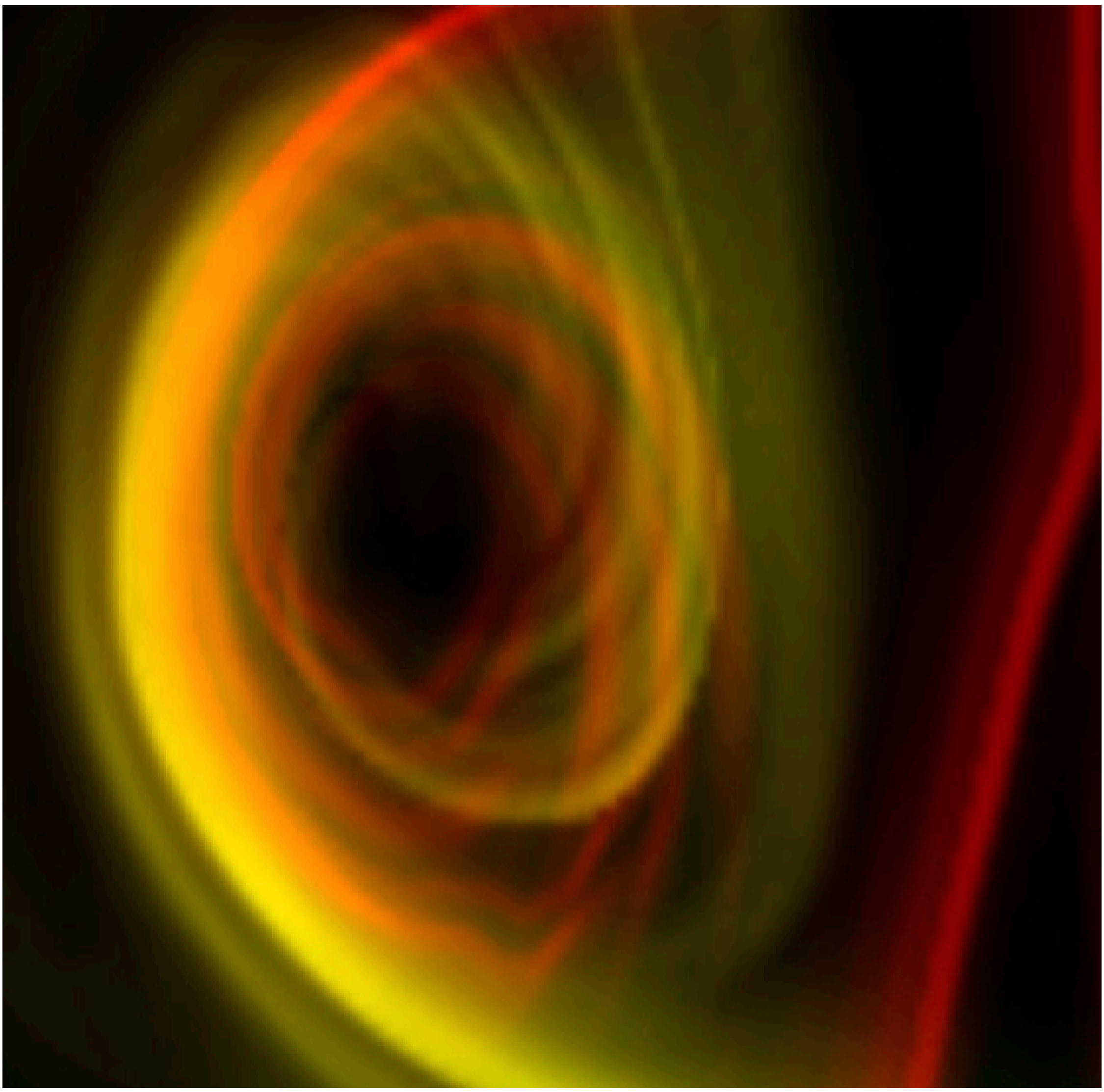


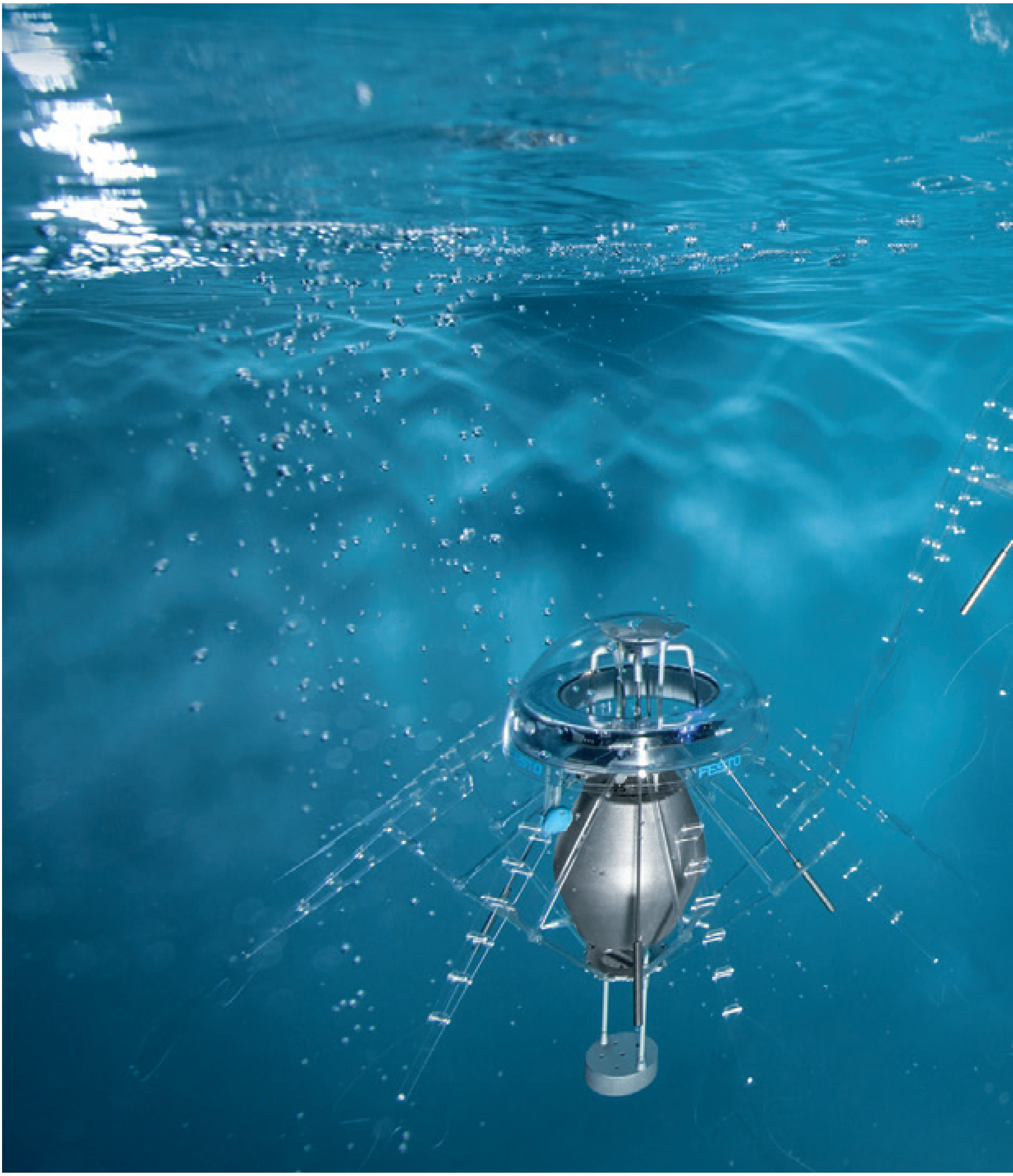
This page: Baby kraken (with detail) | Celeste M. Nelson

Even sea monsters start as babies. Squids begin their lives as embryos in eggs, and take two to three weeks to hatch. This image of a squid embryo was taken using a fluorescence microscope, a common method for imaging embryos with remarkable detail. In this image, we see the baby squid's eyes, four of its arms (check out the tiny suction cups!), and the large yolk sac that provides nutrients to the growing embryo -- which is smaller than the size of a pea.

This page: Ring of fire (with detail) | Clara O'Farrell (undergraduate alumna, Class of 2008)

Vortex rings – regions where a liquid or gas spins in a closed loop around an imaginary axis – are abundant in nature, for example in a river rapids or a stormy sky. But they are hard to see unless revealed by suspended particles, much as smoke particles reveal the structure of a smoke ring. We generated this vortex ring in a water tank seeded with tracer particles in order to visualize the flow of the vortex with a technique called particle image velocimetry (PIV). The red and yellow colorations reveal "Lagrangian coherent structures" - separate and distinct regions of the vortex. Unlike most circular vortex rings, this one is elliptical, which is why the vortex deforms as it travels.





Collective behaviour: the AquaJellies show how autonomous actions of individual systems can result in an overall system
Photo: Festo AG & Co. KG

World
Interview with
The Bionic Learning Network of Festo

Author:
Dr.-Ing. Heinrich Frontzek
Head of Corporate Communication and Bionic Learning Network

Festo AG is a global player and an independent family-owned company with its headquarters in Esslingen am Neckar, Germany. The company supplies pneumatic and electrical automation technology to 300,000 customers of factory and process automation in over 200 industries. Our products and services are available in 176 countries. With about 16,700 employees in 61 companies worldwide, Festo achieved a turnover of around €2.28 billion in 2013. Each year over 7% of this turnover is invested in research and development. In this learning company, 1.5% of turnover is invested in basic and further training. Yet training services are not only provided for Festo's own staff – Festo Didactic GmbH also supplies basic and further training programmes in the field of automation technology for customers, students and trainees.

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

The field of biomimetics/bio-inspired design is huge and spans from robotics to material sciences, from architecture to medicine.

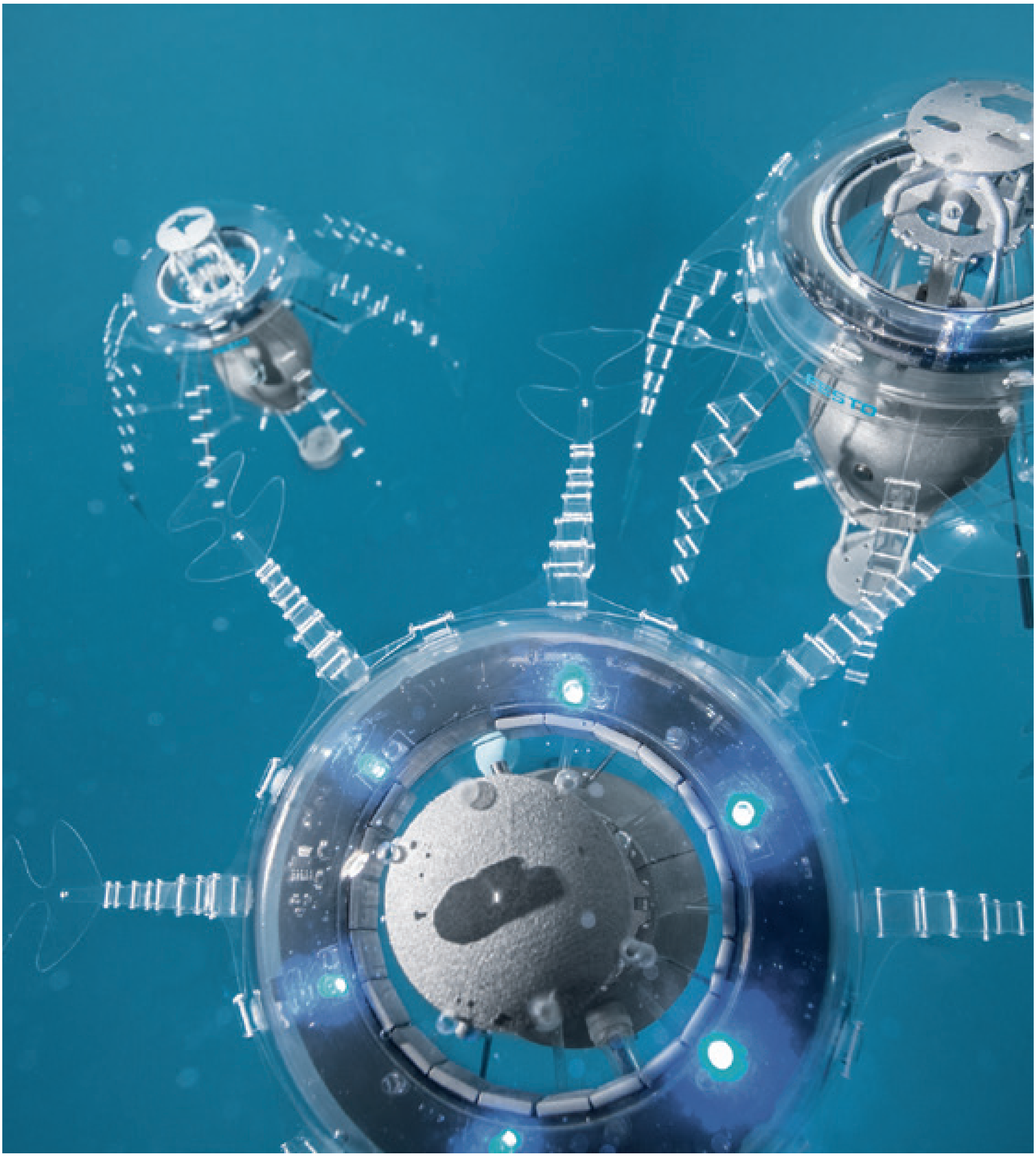
The Bionic Learning Network of Festo, however, has a defined focus. We do not want to copy nature, we want to learn from nature, understand the underlying principles, and transfer these principles into innovations for factory and process automation of the future. In the course of evolution, nature has developed a wide variety of optimization strategies for adapting to the environment. These strategies, like energy efficiency through lightweight construction, function integration or energy recovery, or the ability to learn and to communicate, have been optimized over millions of years. Within the Bionic Learning Network we focus on exactly those strategies and transfer them to the technical world. In this sense biomimetics/bio-inspired design has a huge potential to make the production of the future more energy-efficient and sustainable as well as more intuitive for the human user.

What do you see as the biggest challenges?

Each project of the Bionic Learning Network is based on a new natural role model and thus faces new challenges. First, we have to understand the role model and analyze the underlying principle (of energy-recovery, for example), in detail. Next, the principle has to be transferred to the technical world. This process is not easy since boundary conditions of the natural and the technical world rarely match. Thus, building a technical prototype is an iterative process. A first demonstrator is built and tested, compared to the natural role model, this prototype helps to better understand the role model and the new knowledge is then transferred to the technical world again to improve the prototype.

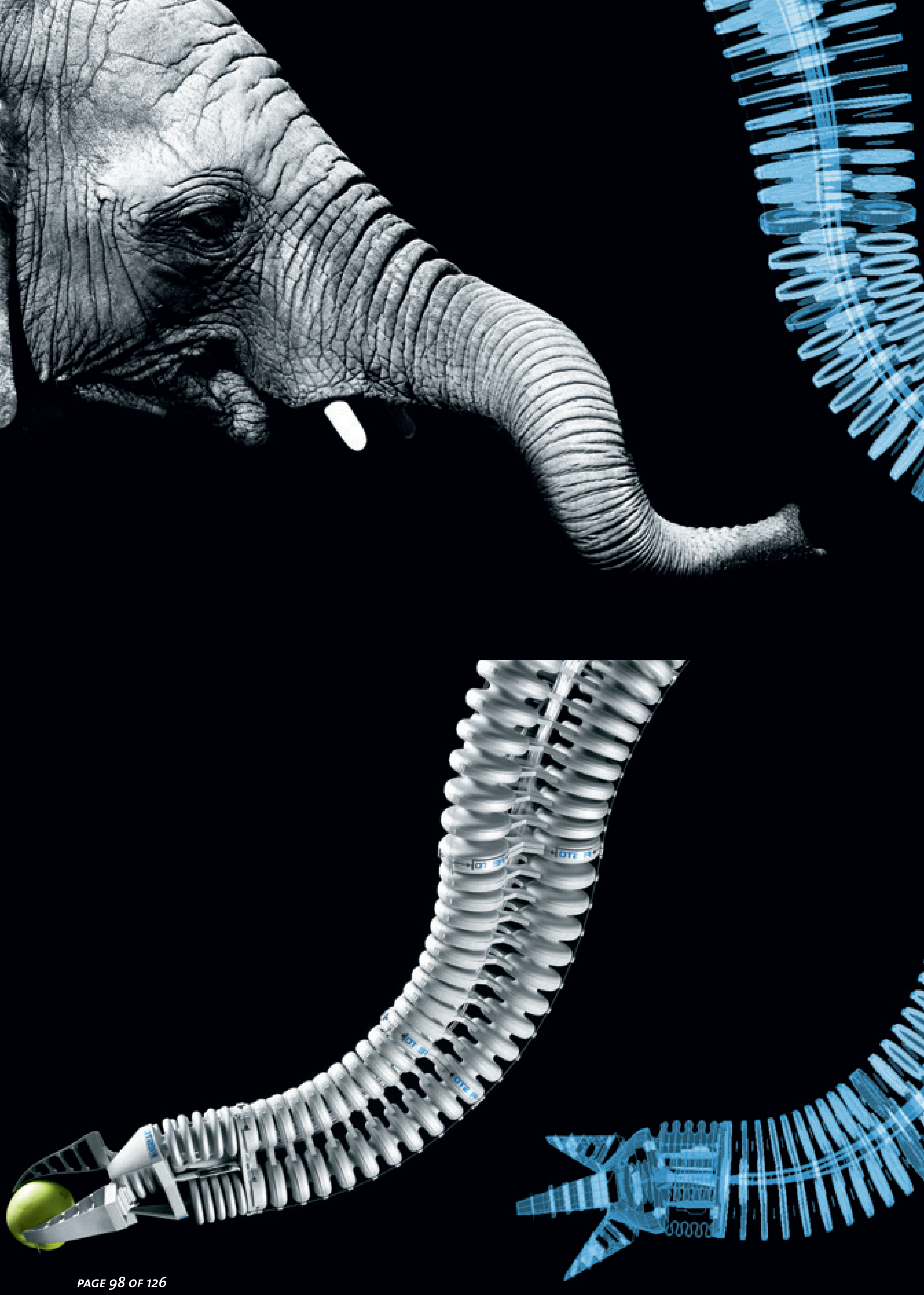
Finally, to yield a functioning prototype it is necessary to optimize an overall biomechatronic concept. However, it is also necessary to reduce its complexity, since it is never possible to copy nature in full details. These are just some challenges project managers of the of the Bionic Learning Network face.

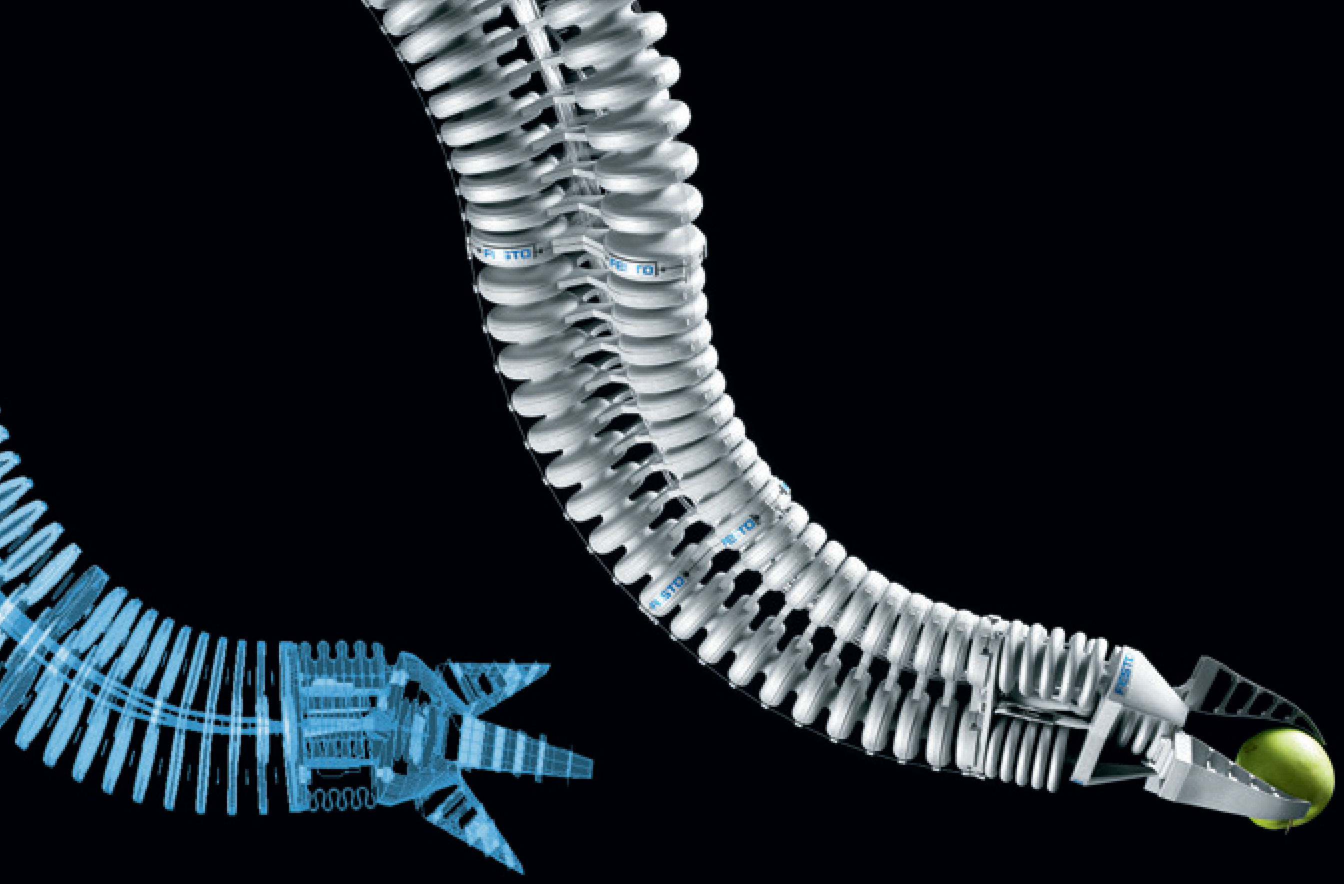
To illustrate this process, here is an example from one of our recent projects, the BionicKangaroo: First we had to understand why the kangaroo can increase its speed without increasing its energy consumption. This is because it stores some energy from one jump and transfers it to the next jump. Most of this energy is stored in

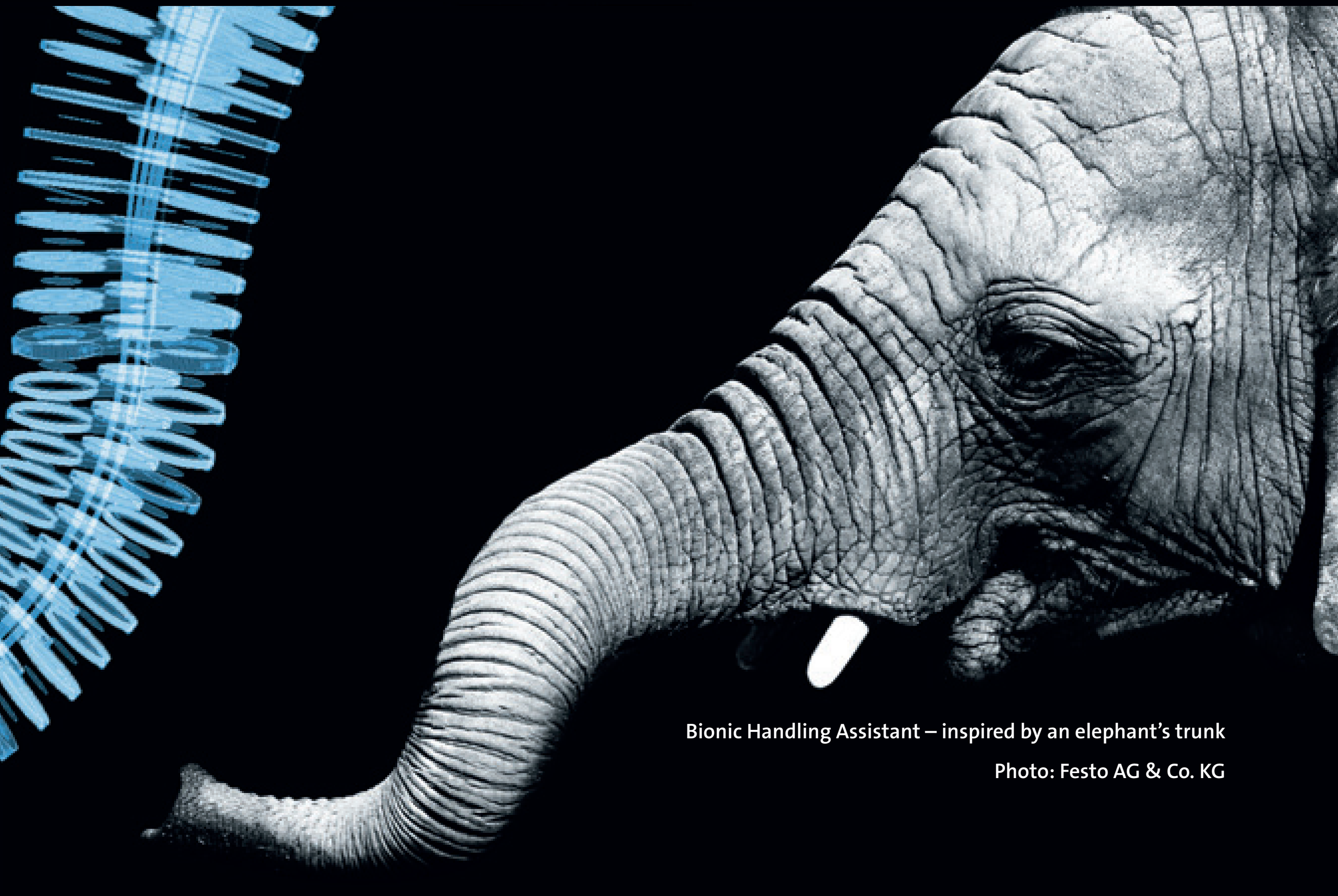


Natural role model: the peristaltic thrust propulsion of the AquaJelly has a strong resemblance to the natural movements of the jellyfish

Photo: Festo AG & Co. KG







Bionic Handling Assistant – inspired by an elephant's trunk

Photo: Festo AG & Co. KG

Author:
Dr.-Ing. Heinrich Frontzek
Head of Corporate Communication and Bionic Learning Network

the Achilles tendon. For the technical prototype the natural Achilles tendon was replaced by a rubber band, which also stores jumping-energy from one jump and transfers it to the next. For stable jumping, however, we had to develop a complex overall system. Pneumatic actuators delivered the energy for dynamic jumping. Electrical drives in the hip and tail were used for very precise movements to gain stable jumping. The whole system is guided by complex control algorithms to keep the balance while jumping. The sensor data and the actuator output have to be calculated on board within milliseconds.

Besides developing the kinematics and the control algorithms, one big challenge was lightweight construction. Impact forces and jumping distance directly scale with the weight of the demonstrator. Thus we combined laser-sintering technologies with carbon fibres to build a lightweight demonstrator.

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

Bionics provides new approaches to product development. Applied science, which derives findings from nature and transfers this knowledge to technology, is a field for the future.

Festo bionic engineers are concerned with understanding the workings of nature in order to transfer them to technical applications. This will make automated movement patterns even more efficient and productive. A particularly impressive innovation from the Bionic Learning Network is the Bionic Handling Assistant, which is modelled on the elephant's trunk.

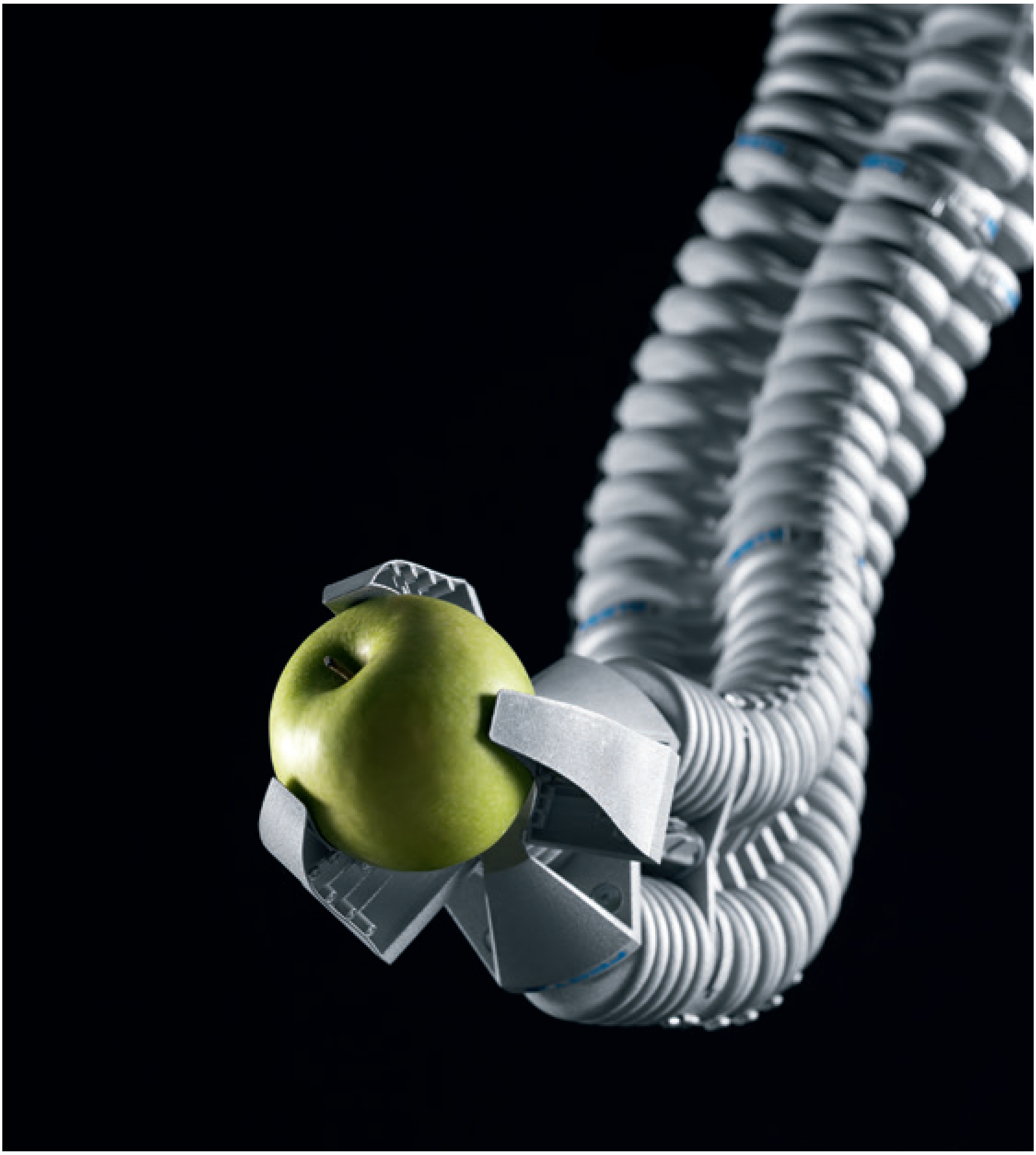
The Bionic Handling Assistant is light, freely moving and safe even for direct human-machine contact. That is why the assistance system won the German Future Award in 2010. The system also acts as a multi-technology platform for the simultaneous development of mechanics, electronics and software for machines and handling solutions, with the addition of new operational concepts such as voice control and image recognition.

Creative minds are in demand! Within the Bionic Learning Network we get inspired by nature and learn from nature's vast pool of intelligent solutions. Lightweight construction, function integration and energy-efficiency are only a couple of examples where technology can be improved by these lessons from nature.

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

Targeted innovation plays a key role at Festo. Research, development and technology provide us with the basis for the development of 100 new products each year. Festo has registered 2,900 patents worldwide. We invest over 7% of our annual revenue in research and development.

Good ideas are fertile ground for new innovations; these are the basis of our research and development sector. Festo secures the competitive advantage for itself and its customers with the new product development system. The focus of applied research is on the areas of simulation technology, mechatronics, systems engineering and future technologies. This extends to microsystems, piezo technology and sensors, as well as wireless technology,



Light, freely moving and yielding – the Bionic Handling Assistant is safe even for direct human machine contact
Photo: Festo AG & Co. KG

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BionicOpter – Inspired by dragonfly flight

Photo: Festo AG & Co. KG

handling technology, robotics and control technology, and nano and surface technology.

Project managers, knowledge and technology managers and researchers, designers and developers work in international teams, since Festo brings its products to market throughout the world. Vision and knowledge make way for new technologies and processes along with innovative solutions, systems and services.

Besides these R + D activities our future concepts offer our customers new features by means of Bionics, such as an adaptive gripper that can handle fragile goods carefully and easily. Bionic design, therefore, is a lot more than an outstanding aesthetic experience. Nevertheless, we want to inspire youth for technology with our Bionic Learning Network.

What is your best definition of what you do?

Our main business is automation technology. Festo AG is a leading global player in the field of pneumatic and electrical automation technology for the factory and process automation. We are also a well-know partner for industrial training and consulting around the world.

As a global manufacturer of pneumatic and electric automation technology, the core business of Festo is helping to shape the production and working environments of the future and offering its customers innovative solutions for the production systems of tomorrow and beyond. For almost 20 years, Festo has also been working in the field of bionics - the application of natural phenomena to the world of technology.

As a technological leader and a learning company, Festo has set itself the objective of creating an impetus through bionic projects to stimulate innovations and generate enthusiasm for technology. The Bionic Learning Network of Festo was founded in 2006, and since then a process of lively and open exchange has established itself between Festo and well-known universities, institutes and development companies. The future-oriented fields in which this year's Bionic Learning Network research activities are being conducted include energy recovery, self-organisation, adaptive systems and new kinds of drive concepts and positioning systems. There is an emphasis on taking a holistic approach as a means of developing the production technology of the future, with great importance being attached to fundamental technologies for networked systems and the interaction of humans and machines. This year's projects, the BionicKangaroo, eMotionSpheres, DualWingGenerator and MultiChoiceGripper, once again demonstrate ways in which nature can be combined with technology.

By what criteria should we judge the work?

Each project of the Bionic Learning Network is unique. We always combine the newest knowledge from biology with the newest materials and technologies and build a functioning prototype. In this sense the innovativeness is the criteria to judge the work on.

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What are you working on right now?

Top secret! We are going to present our next year's bionic projects for the first time to the public at the Hannover Messe 2015.

Why and how did you get started, and discuss the philosophy, design process and organizing of the Bionic Learning Network?

Festo has been investing considerable effort in the subject of bionics since the start of the 90s. With the Bionic Learning Network, an association between Festo and renowned universities, institutions and development companies, Festo promotes ideas and innovations which transcend its core areas of automation and didactics and which represent developments for the future. The Bionic Learning Network is closely linked with the innovation processes within our learning company and constitutes part of our commitment in the field of technical education and training. The core team consists of engineers and designers, biologists and students from Festo. It works closely with specialists from other departments as well as external partners from all over the world. This open, interdisciplinary teamwork offers new perspectives and inspiration for industrial applications.

Here are the objectives of the Bionic Learning Network:

To motivate, inspire and enthuse and to kick-start innovation – as a technological leader and as a learning company, Festo is pursuing a set of clear objectives with the Bionic Learning Network:

To establish networks and to motivate people from different sectors to develop their ideas with Festo

To keep track of current trends in research and development and to test new technologies and manufacturing methods

To encourage greater creativity in solution processes and to drive preliminary product development through prototyping

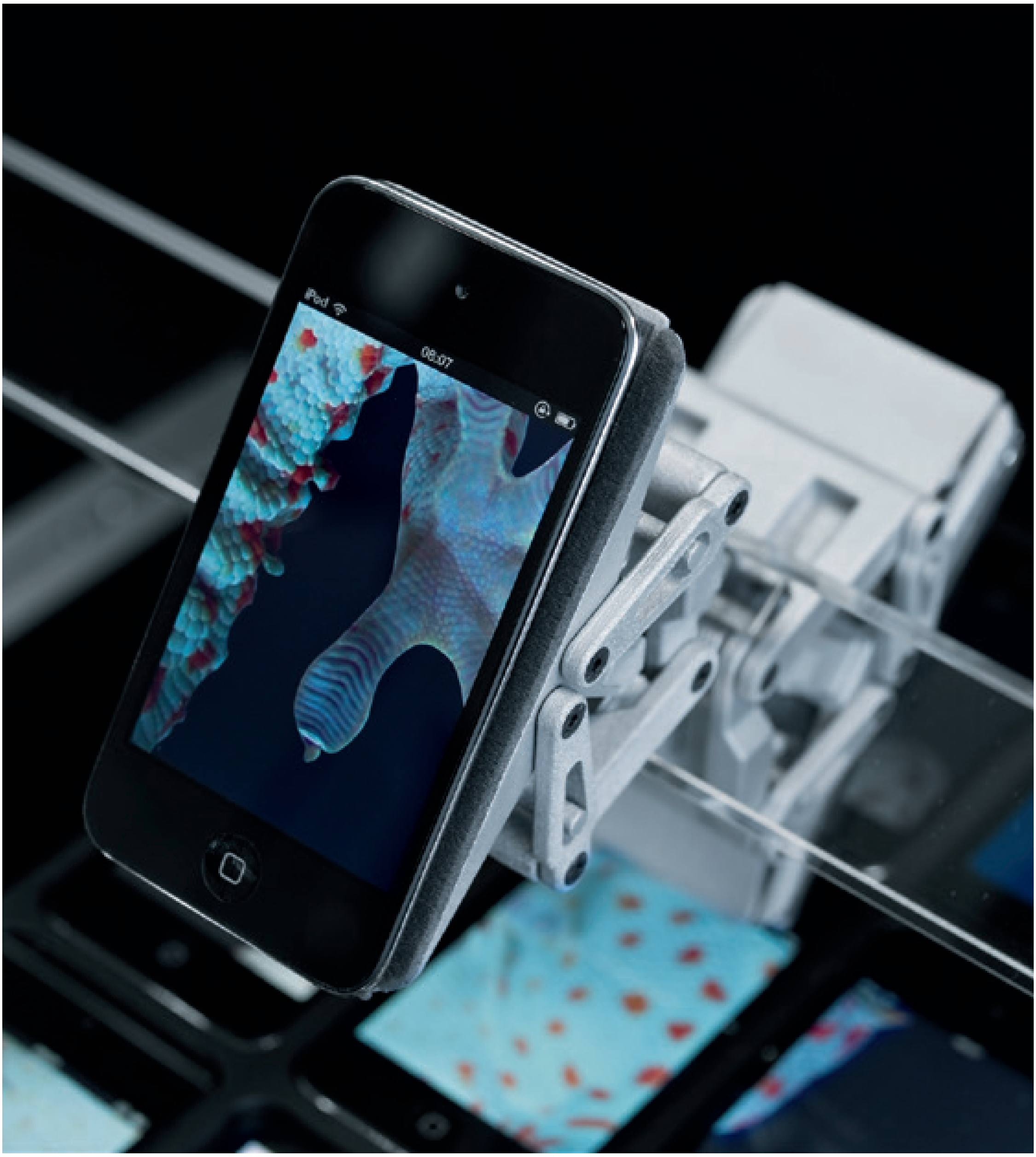
To discuss possible solutions with customers and partners and obtain customer feedback in relation to issues surrounding innovation

To demonstrate the solution expertise of Festo in a way that will inspire young people to take an interest in technology and help us to discover new talent

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

We presented the BionicKangaroo at the Hannover Messe this year and this Bionic Learning Project was impressive. With the BionicKangaroo, Festo has technologically reproduced the unique way a kangaroo moves. Like its natural model, it can recover the energy when jumping, store it and efficiently use it for the next jump. On the artificial kangaroo, Festo intelligently combines pneumatic and electrical drive technology to produce a highly dynamic system.

The consistent lightweight construction facilitates the unique jumping behaviour. The



NanoForceGripper – energy-efficient grasping based on the model of the gecko

Photo: Festo AG & Co. KG

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Head of Corporate Communication and Bionic Learning Network

system is controlled by gestures. Festo paid particular attention to the mobile energy supply on the artificial kangaroo. For this purpose, the team even developed two different concepts – one with an integrated compressor and one with a mobile high-pressure storage device. As a result, the artificial animal weighs just seven kilograms with a height of around one metre, and it can jump up to 40 centimetres high and up to a distance of 80 centimetres.

What is your favorite biomimetic work of all time?

The SmartBird is one of our favourite bionic projects. It was one of the toughest projects and required a long time of preparation, research and work. We started 2009 and the SmartBird was shown for the first time at the Hanover Fair 2011. Our goal was to develop a flight model that is capable of taking off autonomously and rising in the air by means of its flapping wings alone, without the aid of other devices to provide lift. And we succeeded: SmartBird flies and glides through the air. It was amazing to see the SmartBird fly and that we achieved our goal.

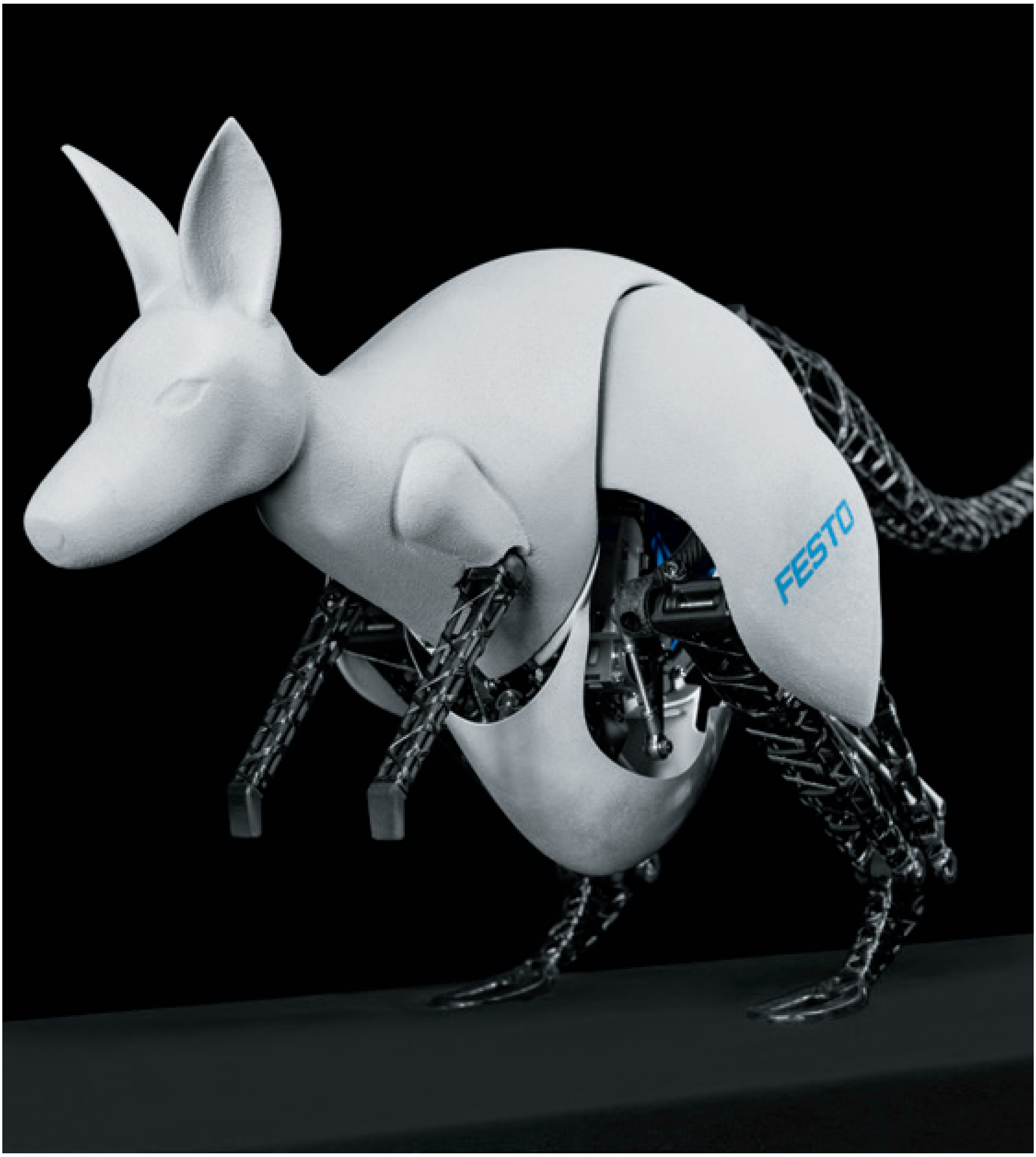
What was the biggest technical challenge in getting the SmartBird to fly from an engineering/ design perspective?

SmartBird is only able to fly because of its elaborate lightweight design. Birds have an impressive lightweight skeleton and furthermore almost hollow bones. The principle of lightweight design was transferred to the SmartBird. It has a wing span of 2 m and still only weights 450 g. Because of this it is able to fly for 20min with only one cell phone battery.

Besides lightweight construction the next biggest challenge was function integration. Analysis of birds showed that the wings do not only flap up and down but that they twist as well to yield an optimal angle of attack while flapping. This way the wings generate forward and upward thrust at the same time. This active torsion effect was also implemented in the SmartBird kinematics and is precisely controlled by the onboard electronics. To understand the effect of active torsion, to transfer it to the technical kinematics and to control the precise timing of the torsion correctly was crucial to allow the SmartBird to fly.

What form changes did you explore in the wing design that were essential to success? How did you experiment with flexibility in the wings for instance?

Flexibility in the wing design was analyzed in detail when developing the DualWingGenerator. Here we invented adaptive wings combining knowledge from fish fins (called Fin Ray Effect®) and from birds (active torsion). Combining findings from these two animals lead to the development of an adaptive wing which is used to flap up and down in an airflow. The airflow moves the wings up and down, this movement is then used to generate electricity. The Fin Ray Effect® makes the shape of the wing passively adapt to the wind conditions. Together they yield an efficient system converting wind energy into electrical energy.



BionicKangaroo – energy-efficient jump kinematics based on a natural model

Photo: Festo AG & Co. KG

Optimal layout: function integration in the tightest space | Photo: Festo AG & Co. KG

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Can you tell us more about the NanoForce Gripper and some of the challenges from an engineering/ design perspective?

With the NanoForceGripper, engineers from the Bionic Learning Network of Festo have developed a gripper whose adhesive components are modelled on the foot structure of a gecko. They cling reliably and permanently to the surfaces of the object to be gripped thanks to tiny, intermolecular forces of attraction called van der Waals forces. A key component of the gripper is the Gecko® Nanoplast® tape on its underside with 29,000 gripping elements per cm².

The project of the NanoForceGripper was developed under the top-down process. Engineers were confronted with the challenge to pick and place objects with a smooth surface without leaving any scratches or stains on the surface. This is not achieved easily with the technology at hand. However, the Gecko can climb up windows easily and even in an energy-efficient way without leaving any stains or scratches. First the underlying principle of the Gecko foot had to be analyzed and understood. The underlying structure then had to be reconstructed with materials at hand. The Gecko® Nanoplast® tape was developed. Due to this tape the NanoForceGripper can hold objects without needing any energy at all, which is unique in the technical world. This tape therefore is a strong adhesive, but the goal was to pick and place objects, and thus to release them again after holding them. Thus we had to go back to the natural role model, the Gecko, and analyze how it attaches and especially detaches its foot from a smooth surface. Analysis showed that he peels off his foot from the surface. By this he peels off the adhesive structure hair by hair and thus only has to overcome the minimal forces of the van der Waals forces instead of the whole adhesive force of the whole foot (up to 10 kg of adhesive power per Gecko foot). This principle of peeling of the adhesive material from the surface was transferred to the technical world as well. This mechanism transferred the adhesive tape into an energy-efficient gripper able to pick and place objects efficiently.

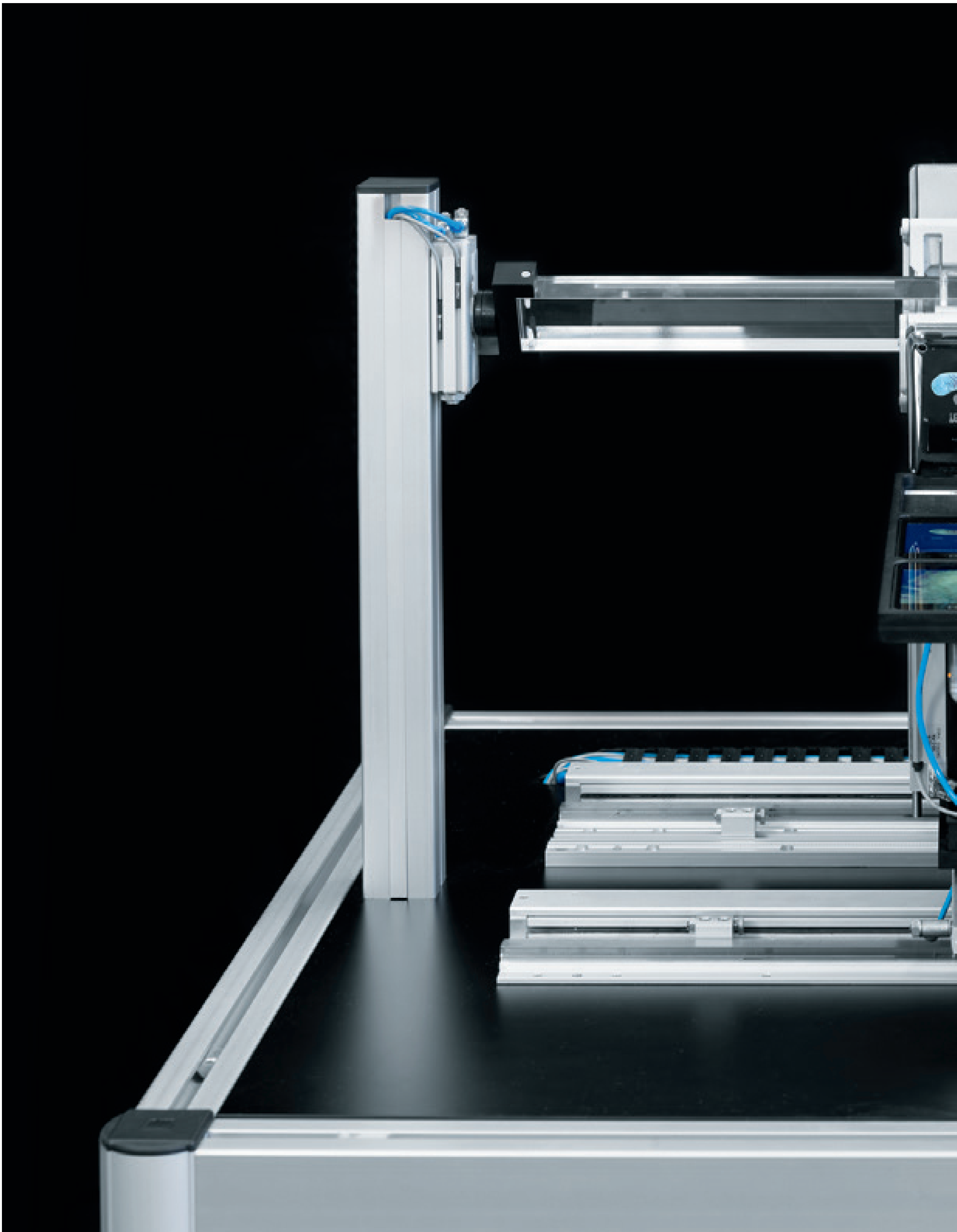
Energy-free holding and energy-efficient gripping are an innovation for grippers that work with a push-push mechanism. In particular, this type of energy-free holding of objects was not previously possible. The NanoForceGripper can grip especially delicate objects with smooth surfaces such as glasses or displays without almost any energy. The new technology complements the existing pneumatic gripping technology which can be used as needed and as appropriate to the application.

Can you talk about the collective behavior of the AquaJelly? Should we imagine a flocking-type algorithm?

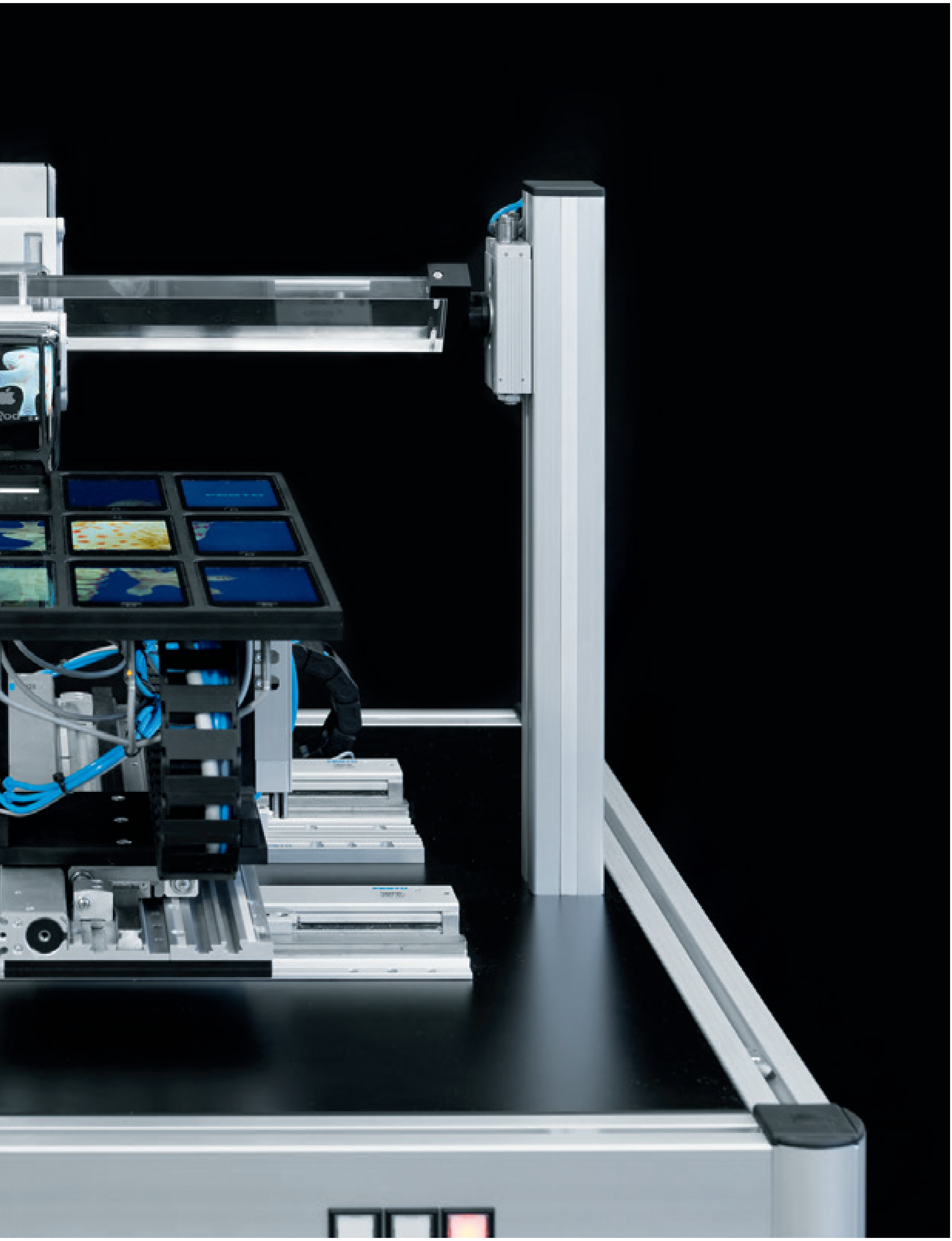
Festo's AquaJellies are artificial, autonomous jellyfishes with electric drive and an intelligent, adaptive mechanical system. The autonomous jellyfishes, which are equipped with communicative capabilities, embody innovative developments in the areas of system capabilities, energy efficiency, communication and lightweight construction. Each jellyfish decides autonomously what action to take next – depending on the state of the battery charge, on the orientation of the propulsion system, but also on the proximity of another jellyfish. The overall behaviour of the AquaJellies is

The gecko at the focus of the researchers' attention: secure adhesion to any smooth surface

Image: Festo AG & Co. KG

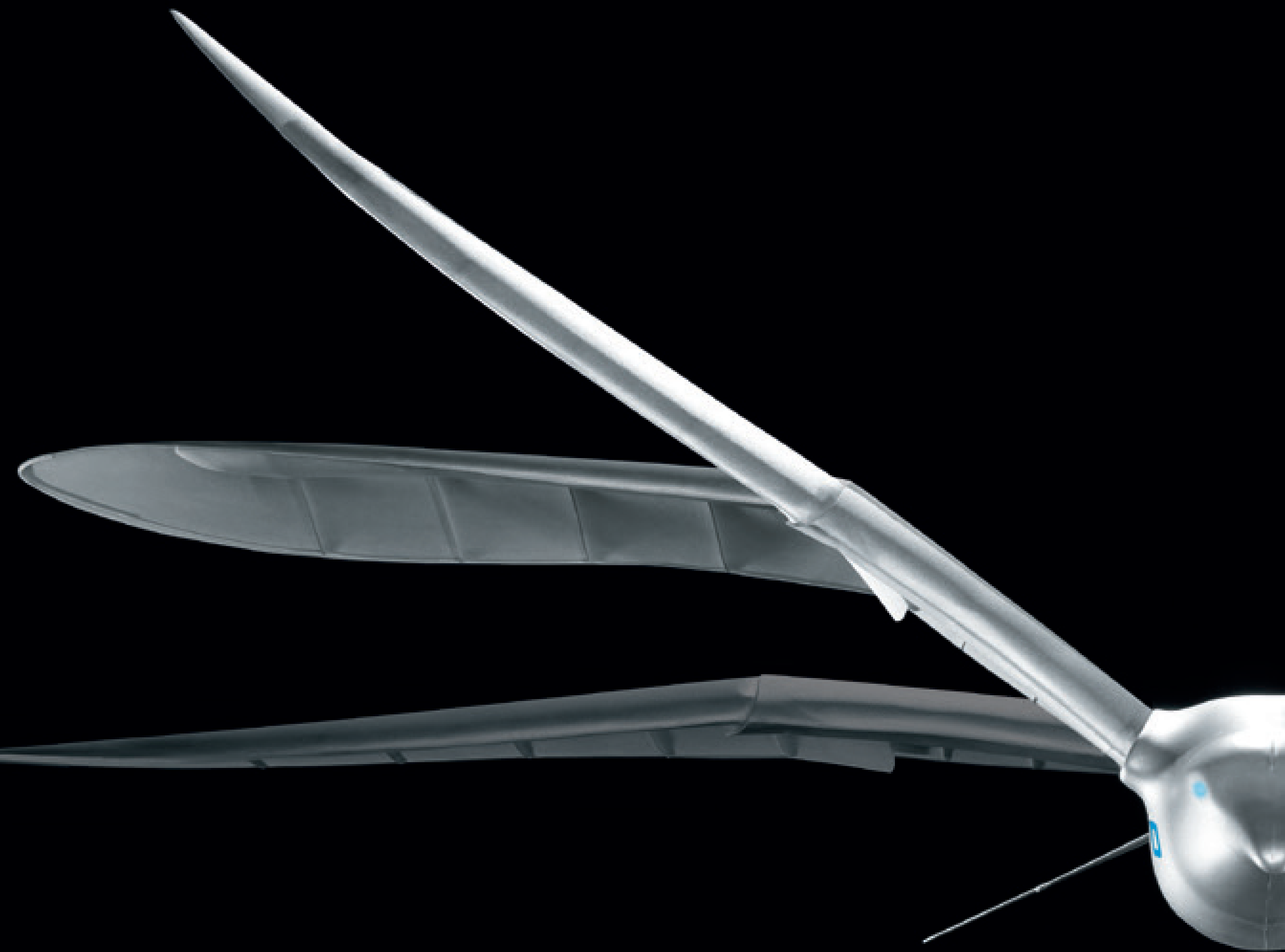


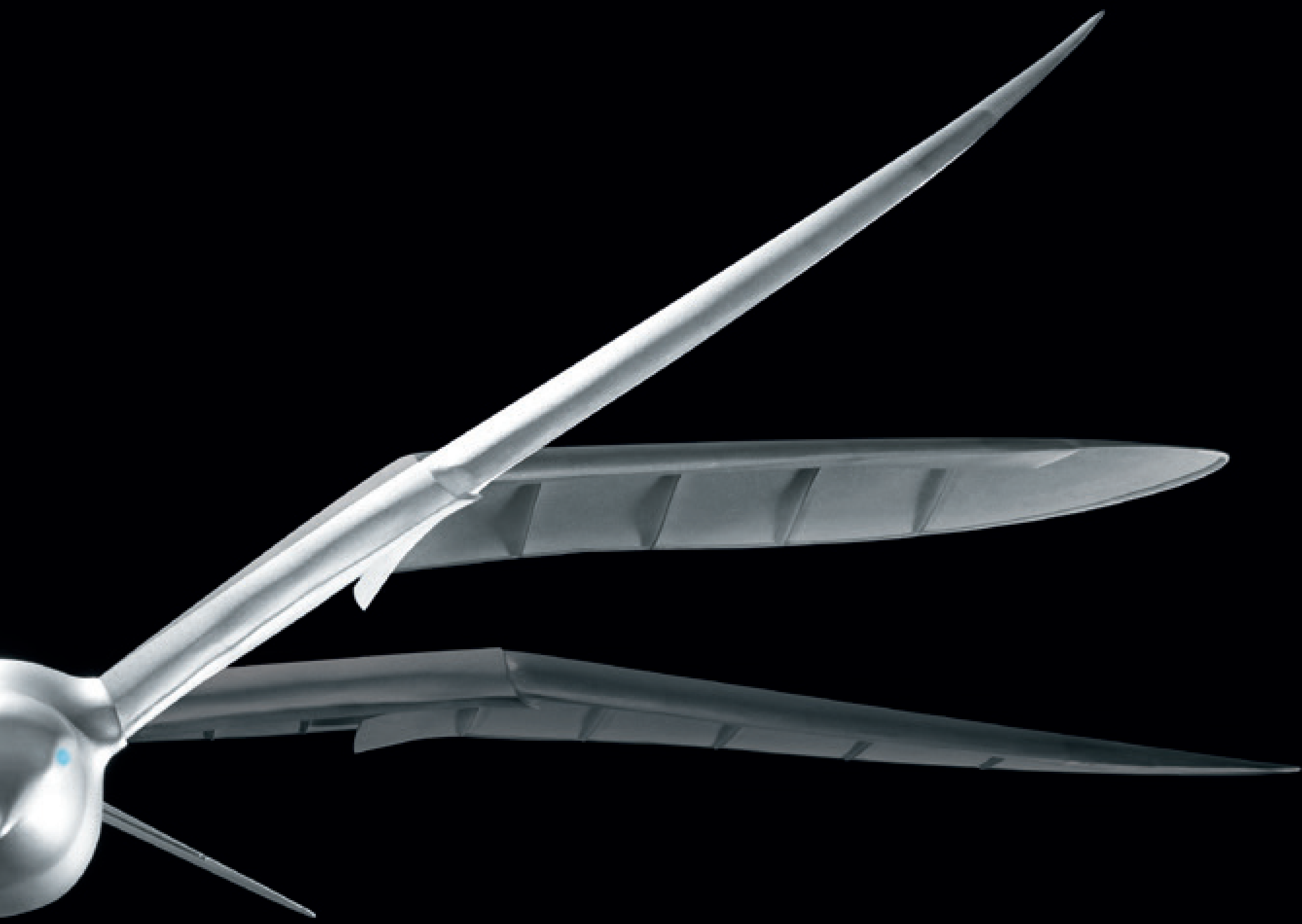
A new gripping concept for smooth, sensitive surfaces | Photo: Festo AG & Co. KG



emergent. This means, in other words: without predetermined control of the overall system. Nevertheless, from the simple actions of the individual alone, a collective behaviour displayed by the overall group emerges. This makes the AquaJellies a starting point and inspiration for other developments; among other things, studies of collective behaviour patterns. If this principle is transferred to the field of automation, several autonomous, decentralised systems could be networked for a specific purpose and together solve a bigger task. ×

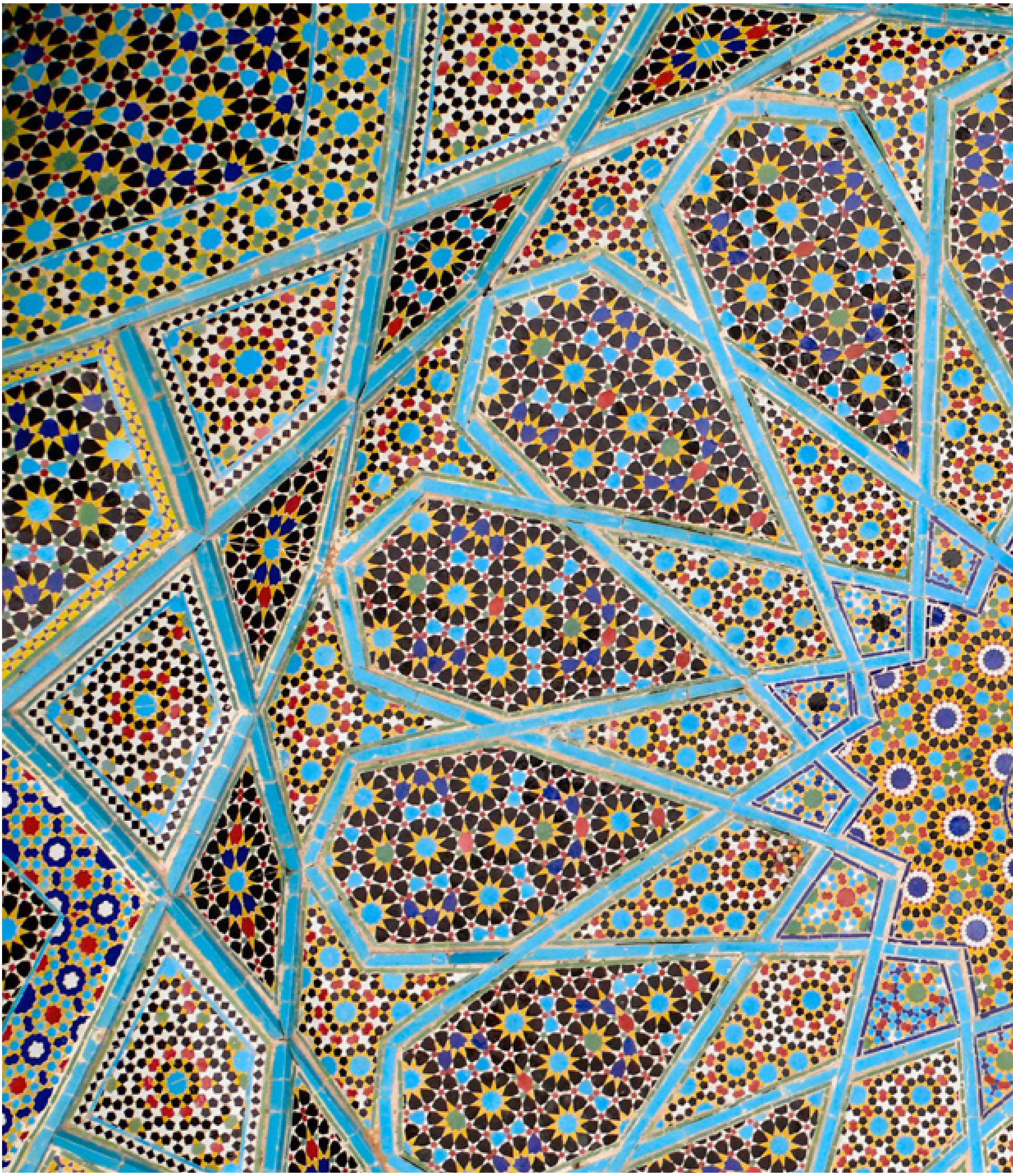
SmartBird – Aerodynamic lightweight design with active torsion
Photo: Festo AG & Co. KG





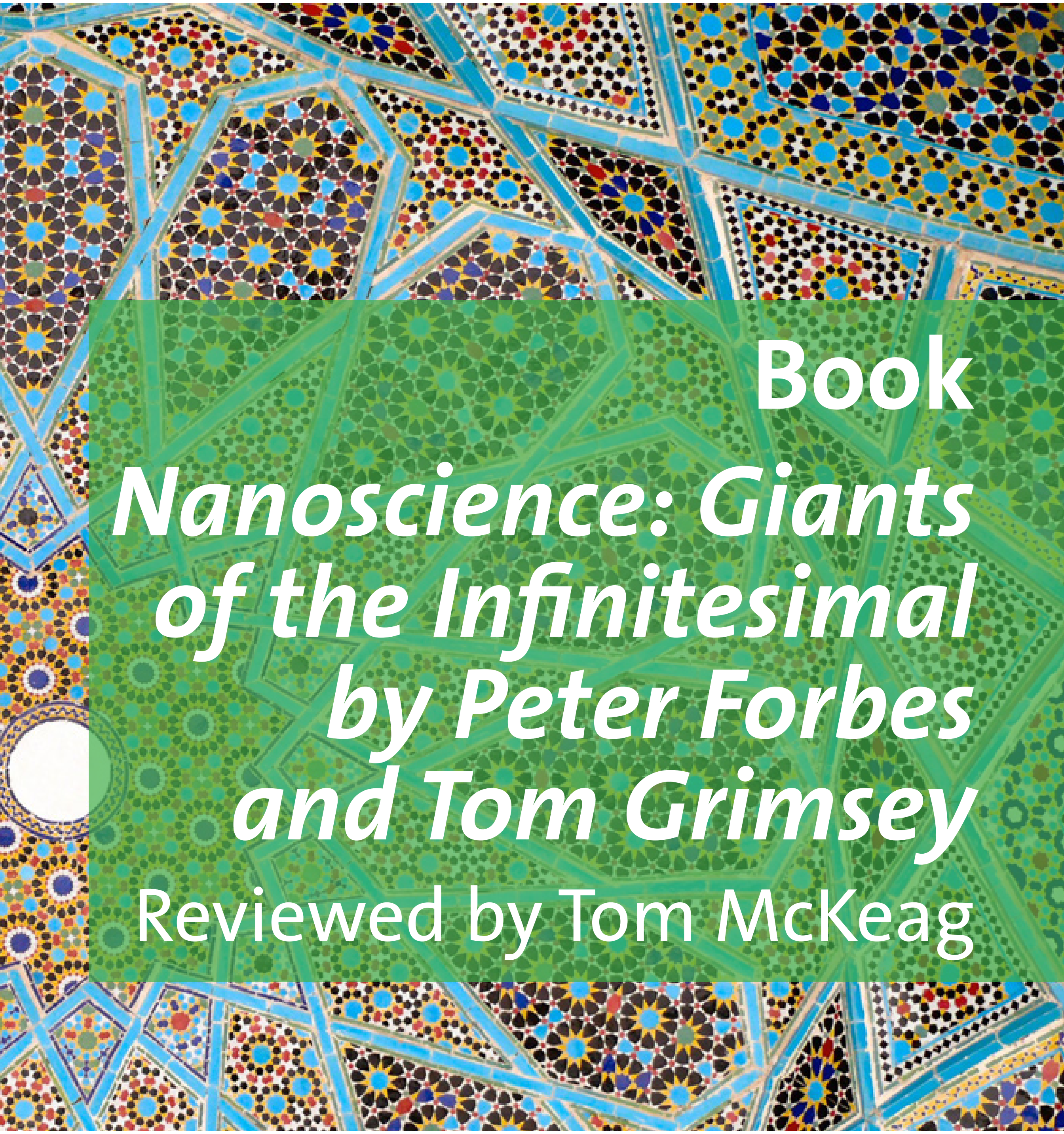
Precisely twisted: Active torsion during the upward wing stroke

Photo: Festo AG & Co. KG



Complex Mosaic patterns at ceiling of the Tomb of Hafez in Shiraz

Photo: Pentocelo, 2008 | Flickr cc



Book
Nanoscience: Giants of the Infinitesimal by Peter Forbes and Tom Grimsey
Reviewed by Tom McKeag

vol 4 | 2014

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Reviewer:
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In a wide-ranging, informative and approachable book, authors Forbes and Grimsey do the public a great service by writing clearly about a subject that can easily elude the average citizen. Not the average citizen? Then this book might still teach you a thing or two about the fast-changing world of nanoscience.

Nanoscience, is limited only by the scale of things being investigated, so while the objects of its study may be small, the range of phenomena is almost limitless. The authors manage to give readers a sense of this range without overwhelming them.

The book is a mix of story telling, thumbnail biographies, and thematic explanations of some of the important realms in nanoscience with a few serendipitous chapters added at the end. The bio-inspired practitioner will recognize some familiar territory here with references to the lotus effect, geckos, close-packing and structural color. Indeed this publication echoes many items from Mr. Forbes' previous book *The Gecko's Foot*, one of the better general surveys of the field of bio-inspired design. Much of what nature does so beautifully it does at the very small scale so it is not surprising that there is a great deal of overlap between this book and the world of BID.

Along the way, *Nanoscience* informs without losing some of the sense of discovery, wonder and connection to our everyday world that these developments hold. For example, in describing the discovery of graphene, the authors weave several stories of discovery together as a way of setting the stage for the explanation of the material itself and why it is so important. It doesn't hurt that one of the discoverers of graphene, Nobel Prize winner Andre Geim, is such an interesting person. Geim once gained notoriety by winning the Ig Nobel prize for levitating a frog with a superconducting magnet and was quoted in his Nobel Prize lecture as saying "Better to be wrong than boring!"

Self organization, super strong materials, alternate fuels and optics are all dealt with in turn, but this is a popular science book and the reader seeking the straight path and depth of a textbook should look elsewhere. Each chapter is typically a mix of different allied topics. Chapter six, *Petrol from Air*, for example, discusses artificial photosynthesis, but also algae-derived fuel and desalination. Here the authors succinctly dispatch with an explanation of photosynthesis, for instance, to a degree sufficient to appreciate the technological progress being made in synthesizing it.

Window Apartments Crown Prince | Topkapi Palace, Istanbul, Turkey | Photo: Serhinho, 2007 | Wikimedia Commons

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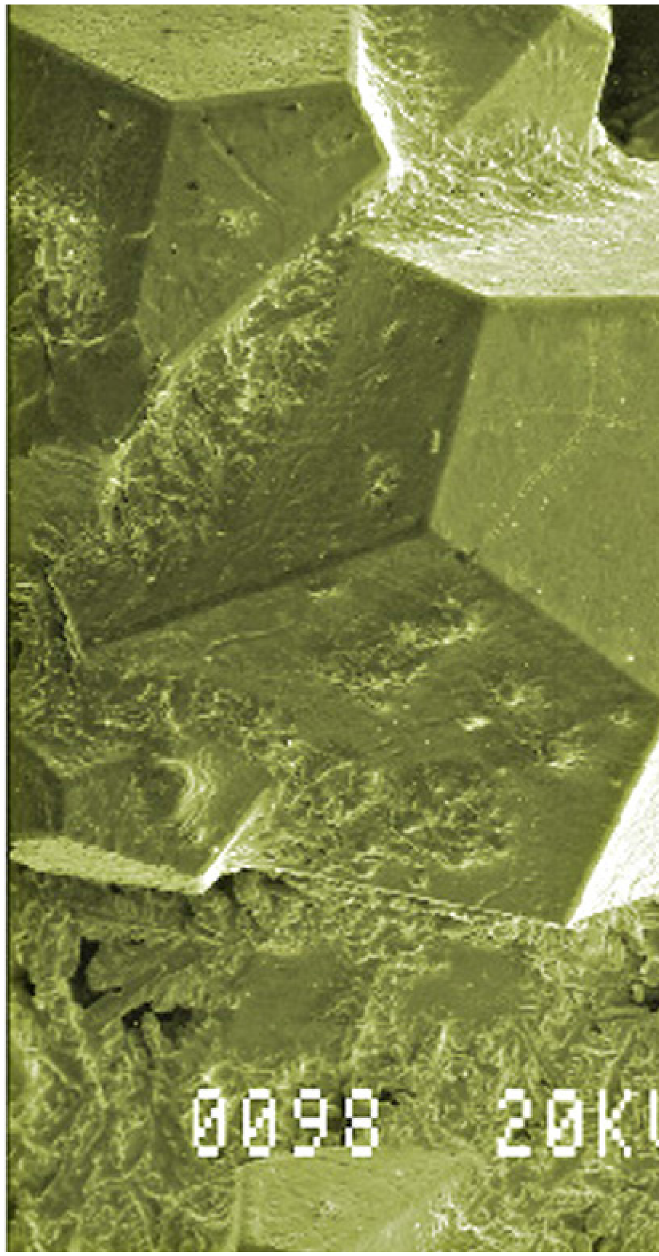
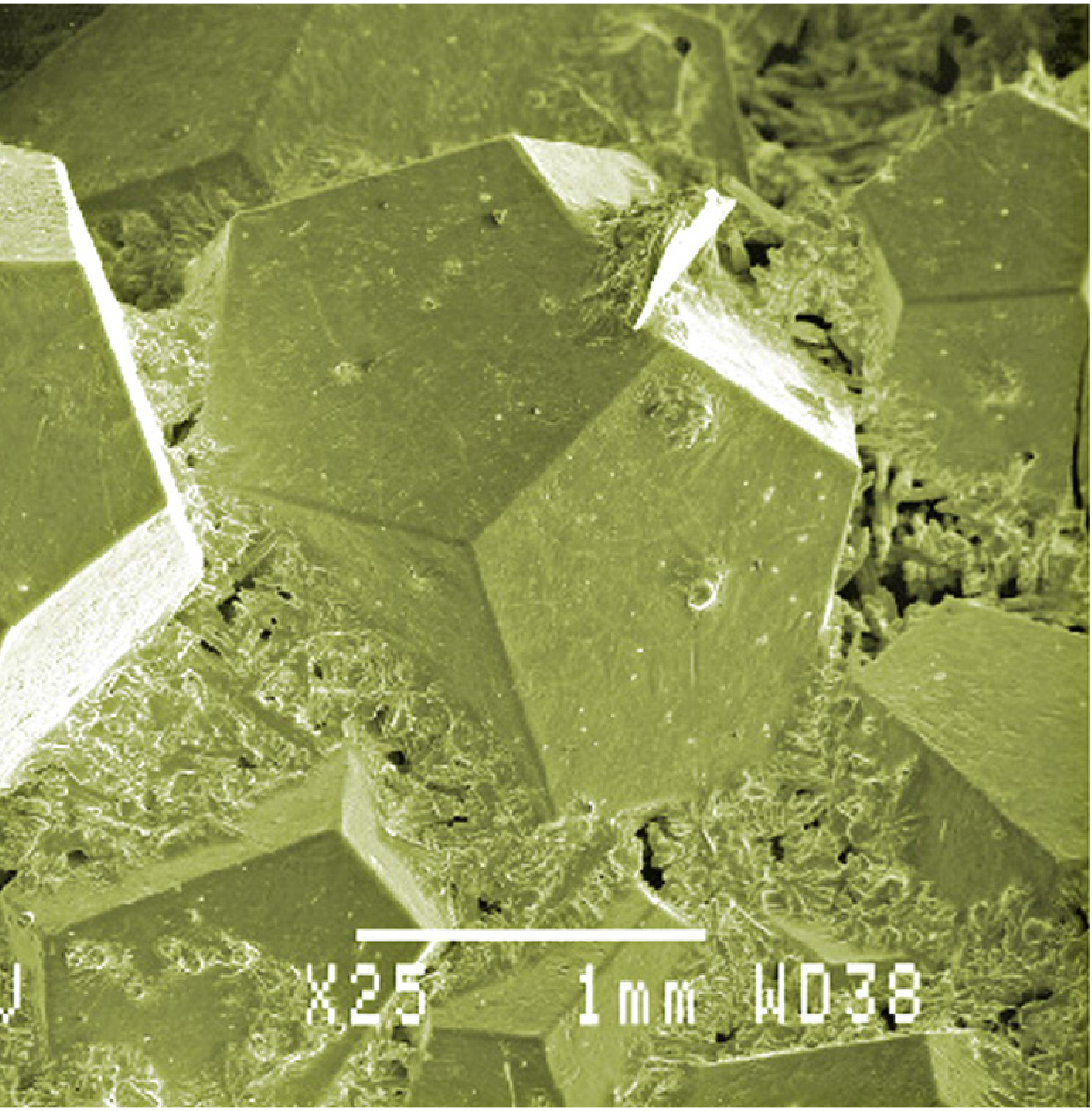
It is mildly disappointing that the graphics within the book do not match the clarity of the text. While there are many images in the book, some seem a bit gratuitous in their size, some simple computer renderings of molecules taking up whole pages, for example. At other places an explanatory diagram rather than a generic photograph of the topic might have made a big difference for comprehension.

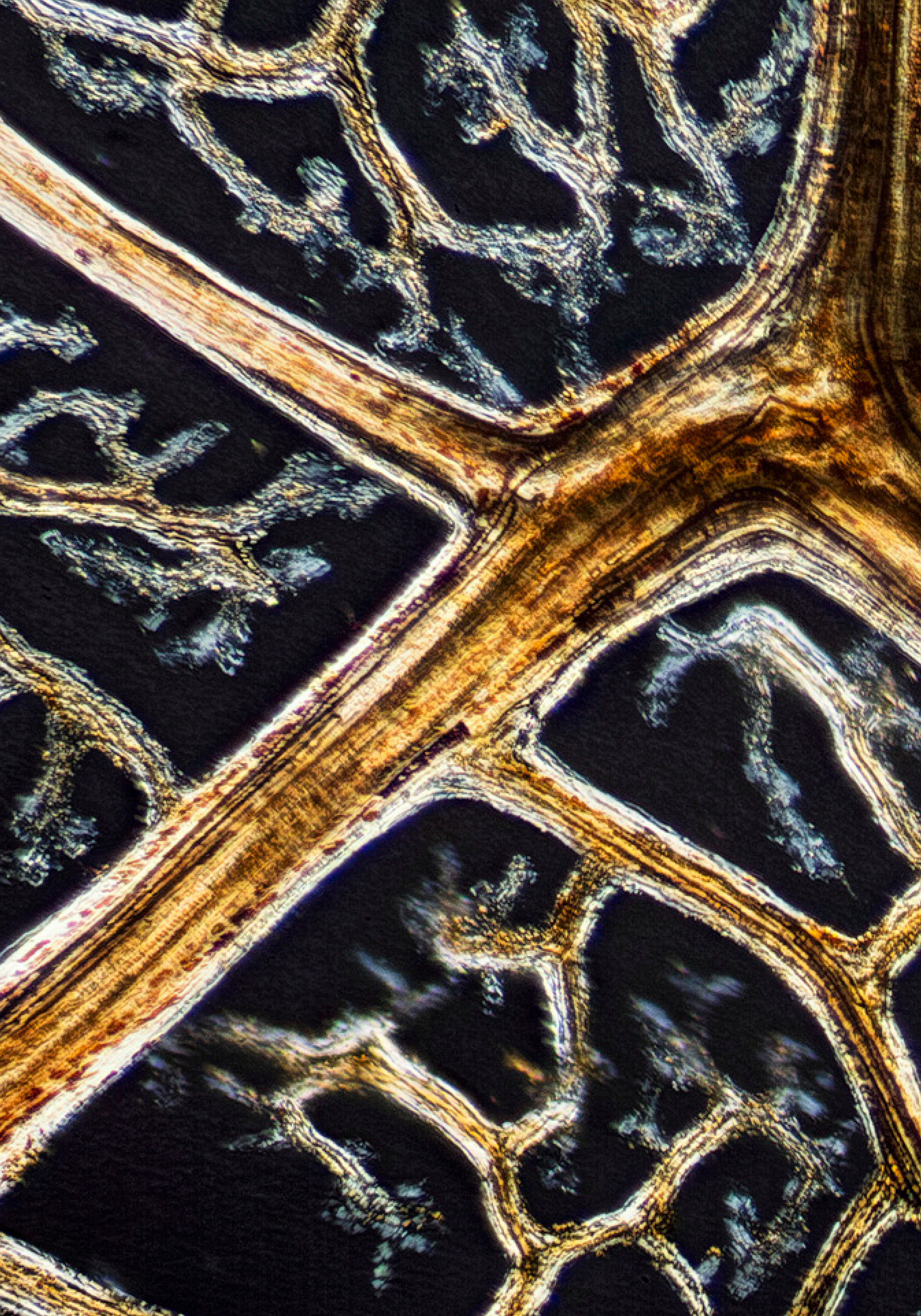
While the book is sometimes unwieldy in its organization, it makes up for it in its wide polling of researchers and clear explanations of basic science. To be fair, oftentimes the domains that are its subject do not fit neatly into any typology. Moreover, the realm of innovation is comprised often of the disparate. How should one, for example, describe quasicrystals, metal alloy-like materials with distinct, nesting molecular structures? With important implications for material advances in durability, hydrogen storage capacity, and light trapping, quasicrystals exhibit exceptional properties in hardness, low-friction and insulation. To explain them, the authors range from the personal career story of their disbelieved champion, Daniel Shechtman, to a downed meteorite in Siberia and then the Topkapi Palace in Istanbul, where tile patterns reveal an intriguing connection between ancient Arab geometers and today's scientists. Yes, it is a bit of a scenic drive around the park, if you will, but worth the ride.

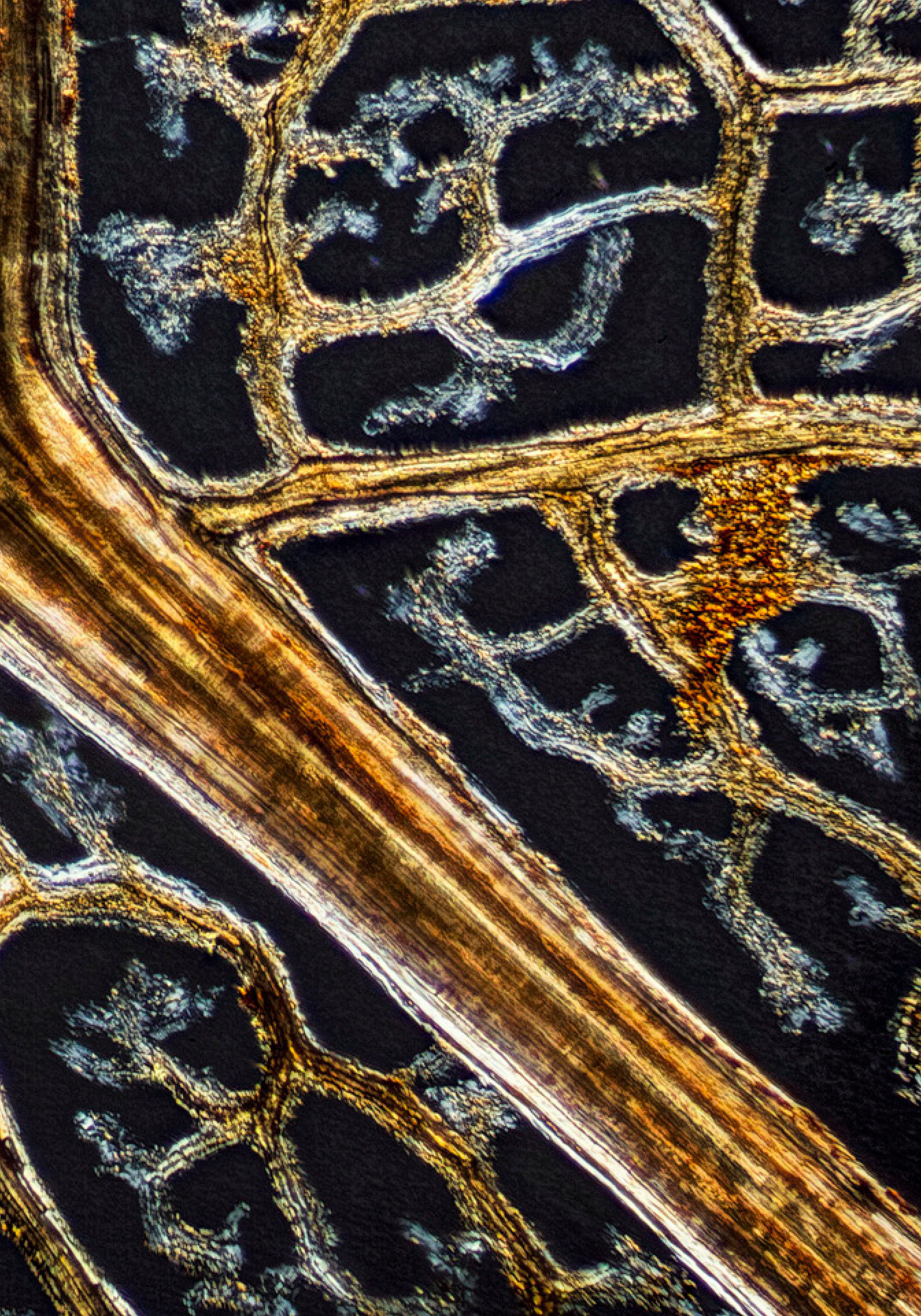
For the literate layman and BID practitioner wanting an introduction to this field this is a good acquisition, and despite its popular style, even the above average citizen might still find him or herself referring to it again and again. ×





Nano Quasi Crystals
Photo: Aranda\Lasch, 2006 | Flickr cc



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