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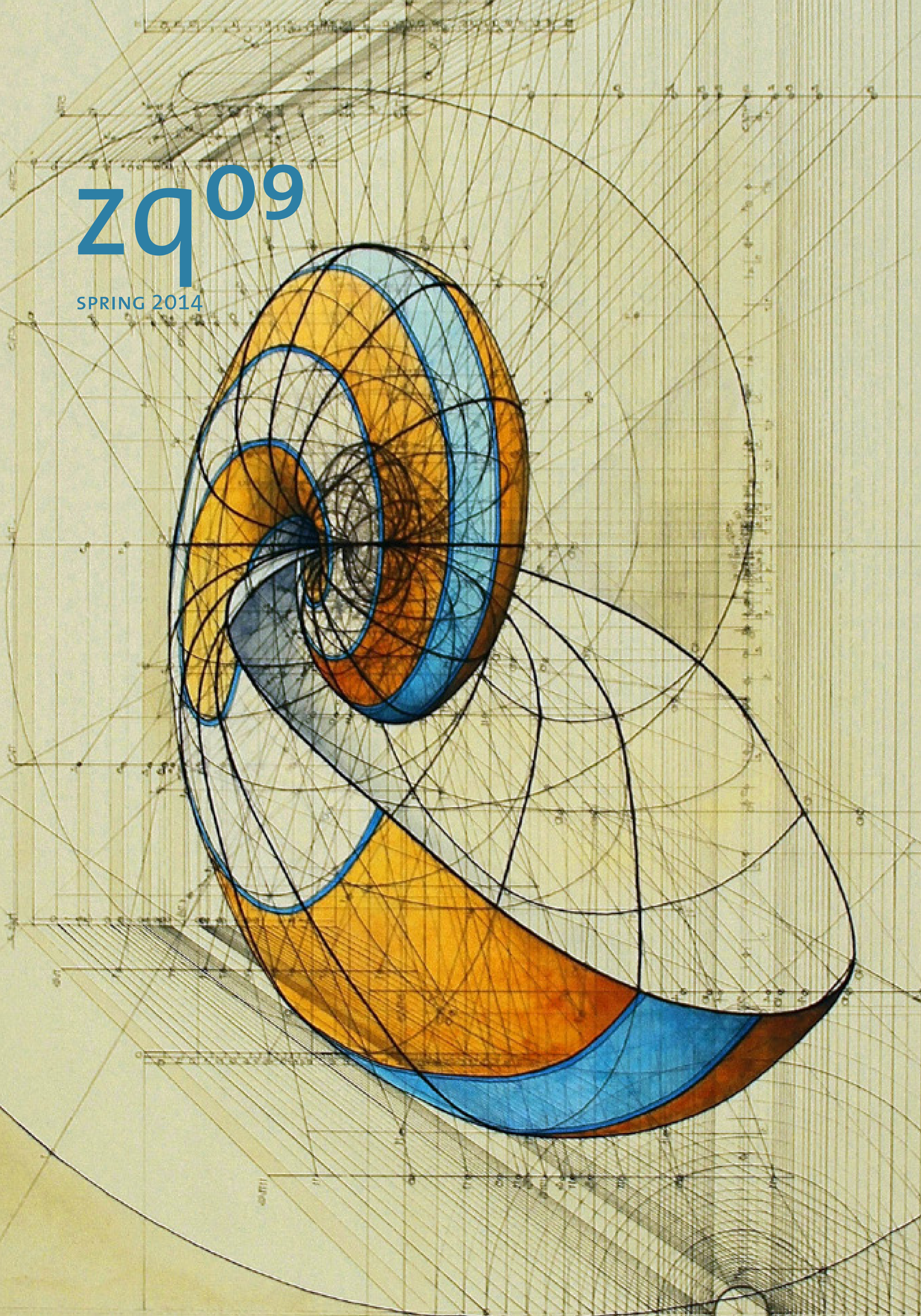

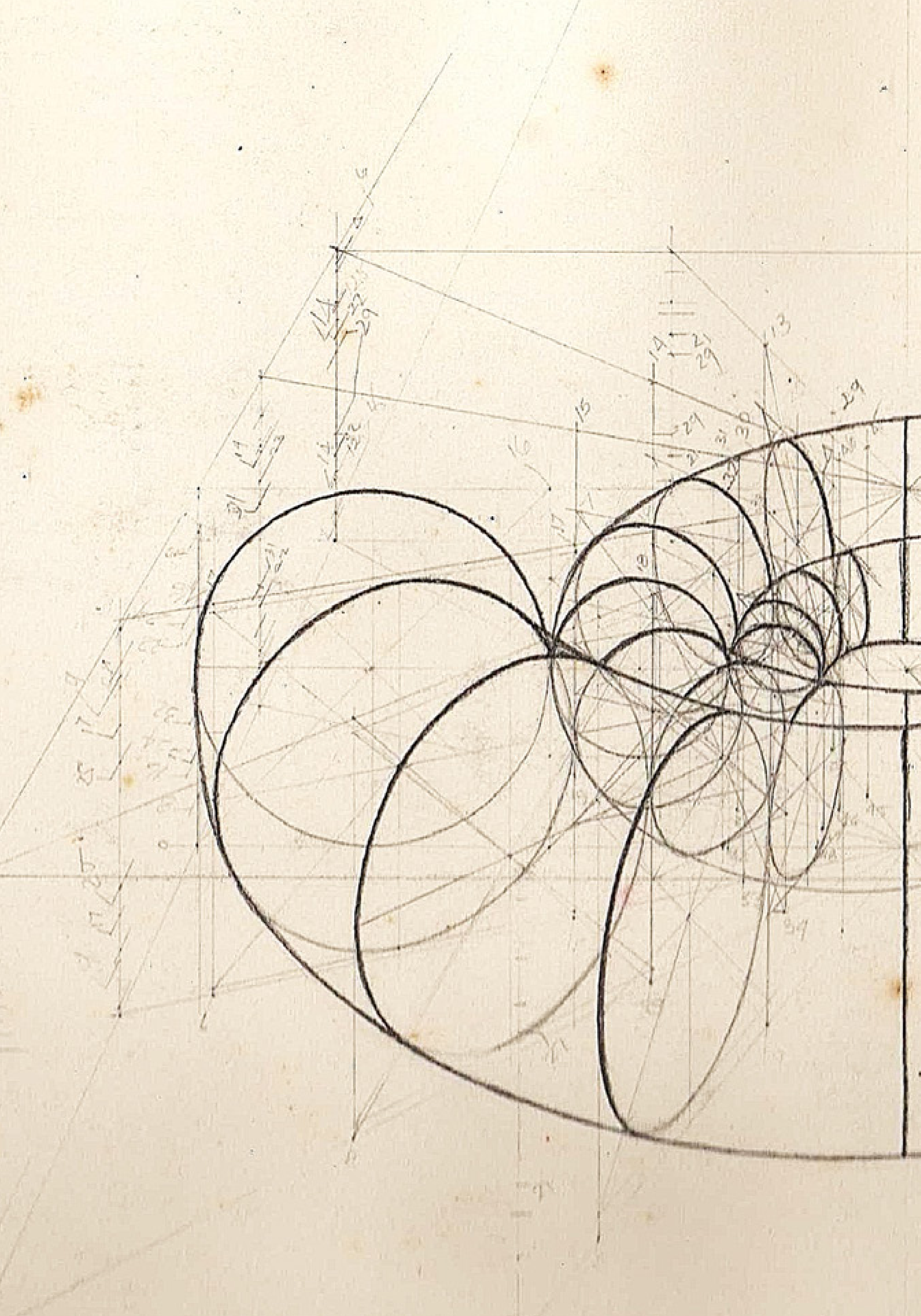

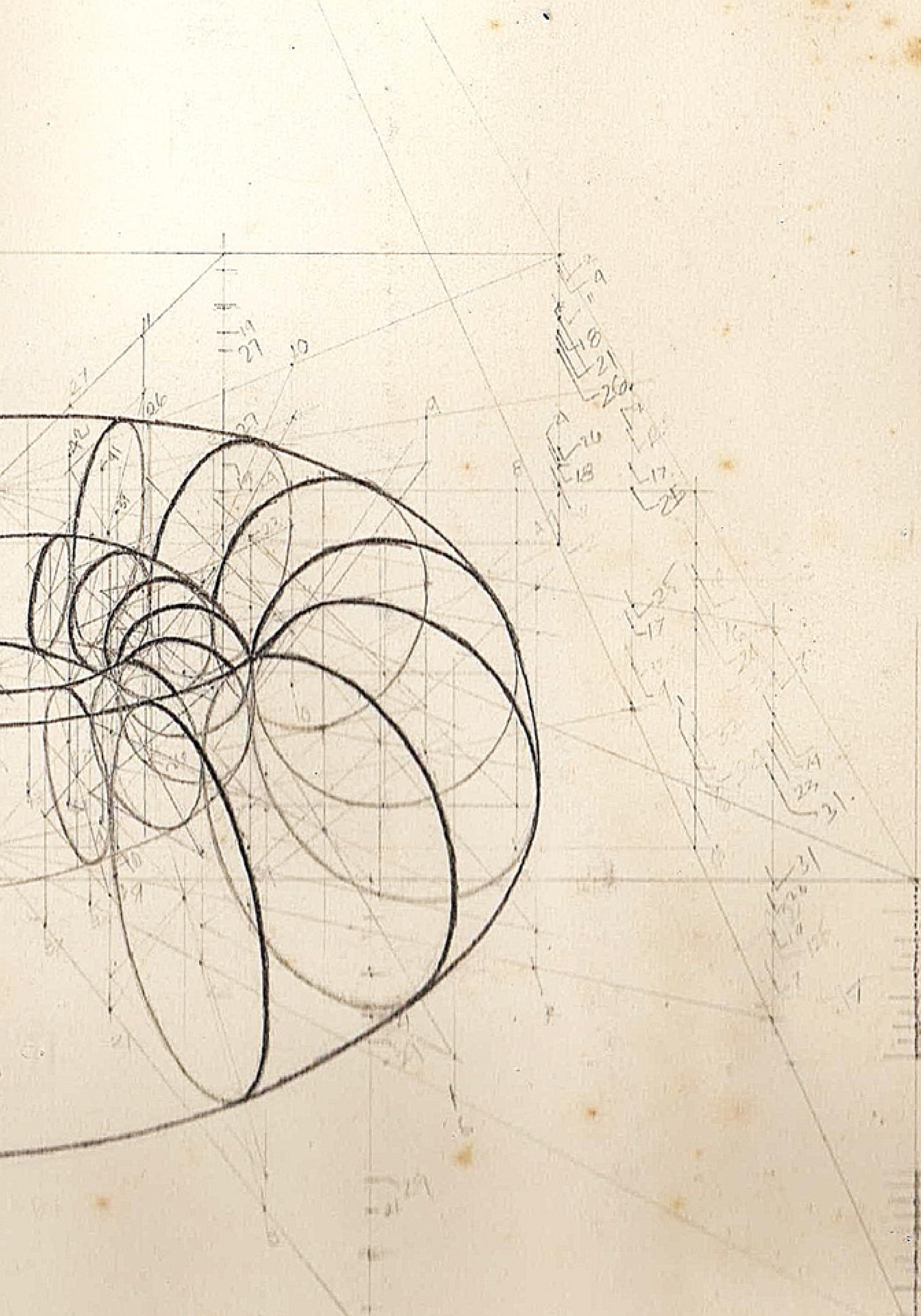

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Purple shell

Photo: BotheredByBees, 2007 | Flickr cc

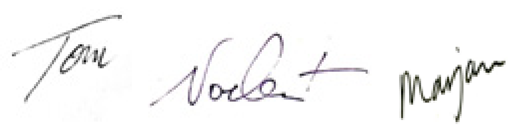
In this issue we interview Brian Olson and Randy Palermo who have a story to tell about how to tell science stories. They share a method that they think is very useful. All stories, they write, can be reduced to the sequential words “and”, “but” and “therefore”. Moreover, explaining a field like bio-inspired design should include the *sine qua non*, the essential ingredient, of the discipline, without which nothing makes sense.

In our opinion, nothing makes sense in bio-inspired design without the idea of “creative interrelatedness”; that physical phenomena can be related to new design ideas, that one species can inform another, that methods applied in one realm might prove useful in another. Bio-inspired design is a method, and a discipline, but more than anything else it is a branch of innovation.

Fritjof Capra has been creatively relating ideas for decades and tells us about his latest book with Pier Luigi Luisi, *A Systems View of Life*. It joins a long list of international best sellers for Mr. Capra, and we are pleased to have his summary here.

Relationships are integral to systems and in our tools and case study sections these come to the fore in a look at hierarchical structures and in how to use engineer Curt McNamara’s System Explorer tool. In her regular column, Heidi Fischer reveals the hidden world of desert potholes in which an animal’s relationship with the season can mean life or death. Heidi has recently won the Ellen Meloy Desert Writers Award. Congratulations, Heidi!

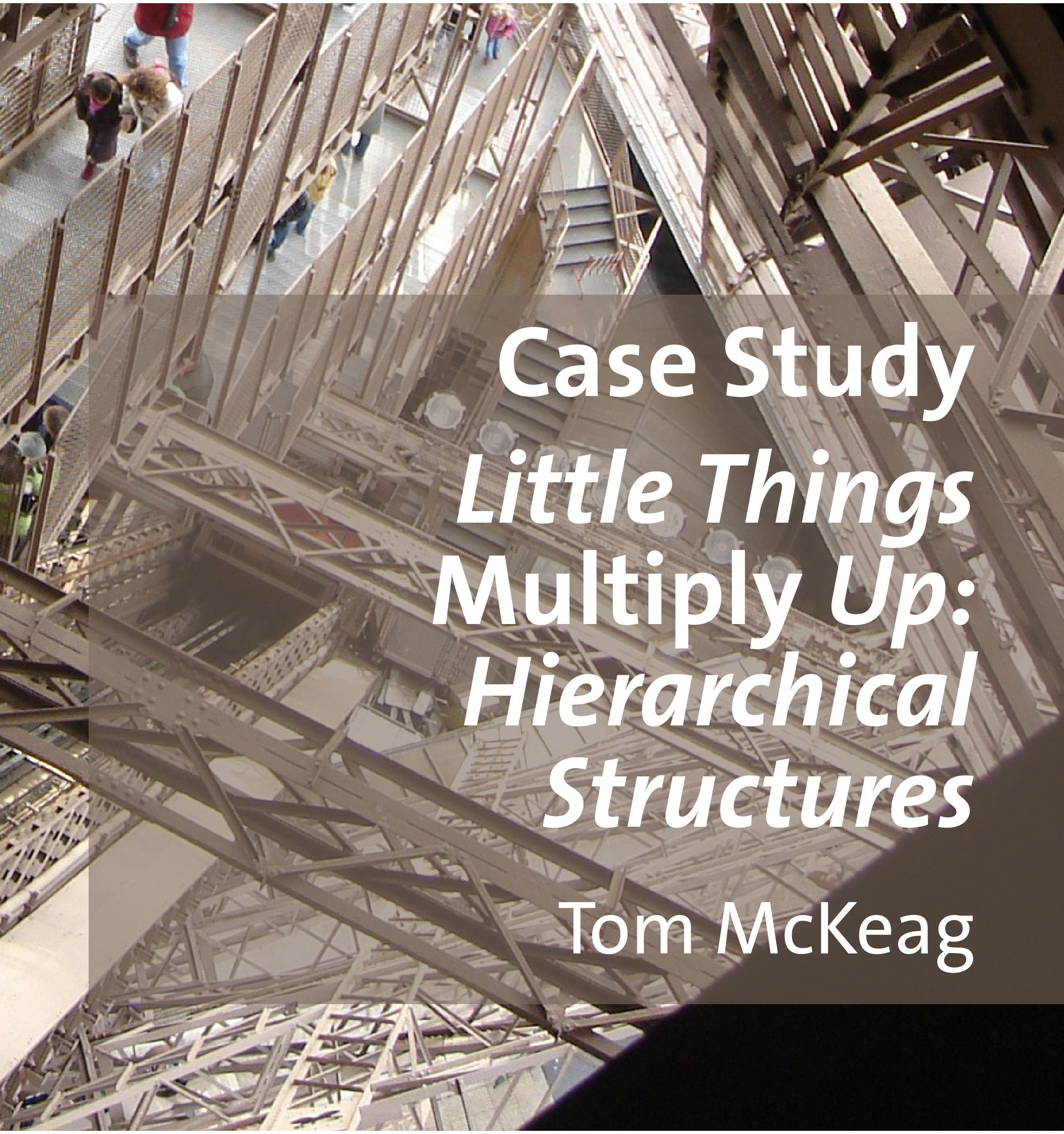
Finally, we hope you will be as delighted as we in viewing artist Rafael Araujo’s constructed drawings of natural objects. He brings an architect’s discipline to his craft and eschews any digital aids, preferring instead to make geometrically complex images with simple drawing tools. The results possess a distinct quality. ×



Tom McKeag, Norbert Hoeller, and Marjan Eggermont

Stairs Eiffel Tower

Photo: gadl, 2006 | Flickr cc



Case Study

Little Things Multiply *Up*: *Hierarchical Structures*

Tom McKeag

Little Things *Multiply* Up: Hierarchical Structures

The Concept

“As thin as a human hair” is a trite analogy we all know, and implied in that simile is the simplicity of the unseen. This simplicity, however, is a false assumption for us to make, for, as biologists know, the human hair is anything but simple when you take a closer look.

Your hair is made of protein, keratin to be exact, and like many of the wondrous strategies nature has, it is how this protein is arrayed that gives hair its performance capabilities...and allows it to be as thin as it is. Keratin is first wound in a right-handed helix, then braided in a two-part left-handed coil, then bundled and sheathed into a microfibril. This bundling is done not once but several times as the hair reaches its ultimate width of 180 micrometres (0.00067 to 0.00709 in). Even the outside coating of the hair, the cuticle, is complex and made of many overlain parts.

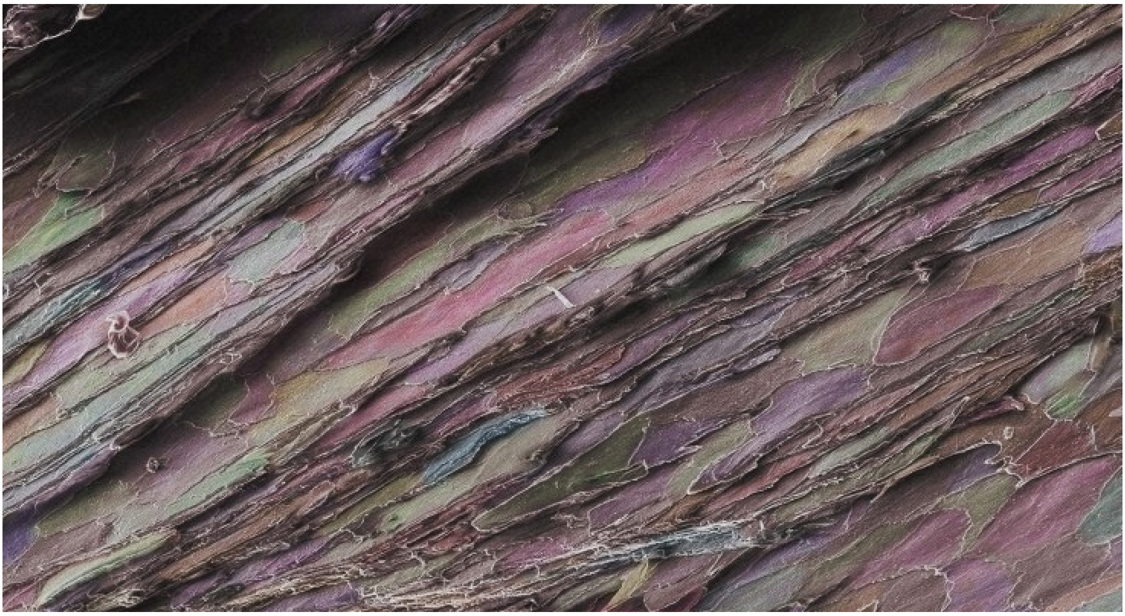
Hair, like bone, is a complicated system of interrelated parts that solves functional challenges across length scales. It is a hierarchical structure, and this type of structure has many advantages. Using structure for strength, rather than materials, saves both the material and the energy needed to make it; modularity and recombination of parts allow for a wide diversity of solutions; nested solutions across scales provide safeguards to whole system failure. Bone, for instance, is as strong as steel but as light as aluminum; all thanks to its complex, hierarchical structure that, among other things, resists cracking through at least five different strategies at as many scales.

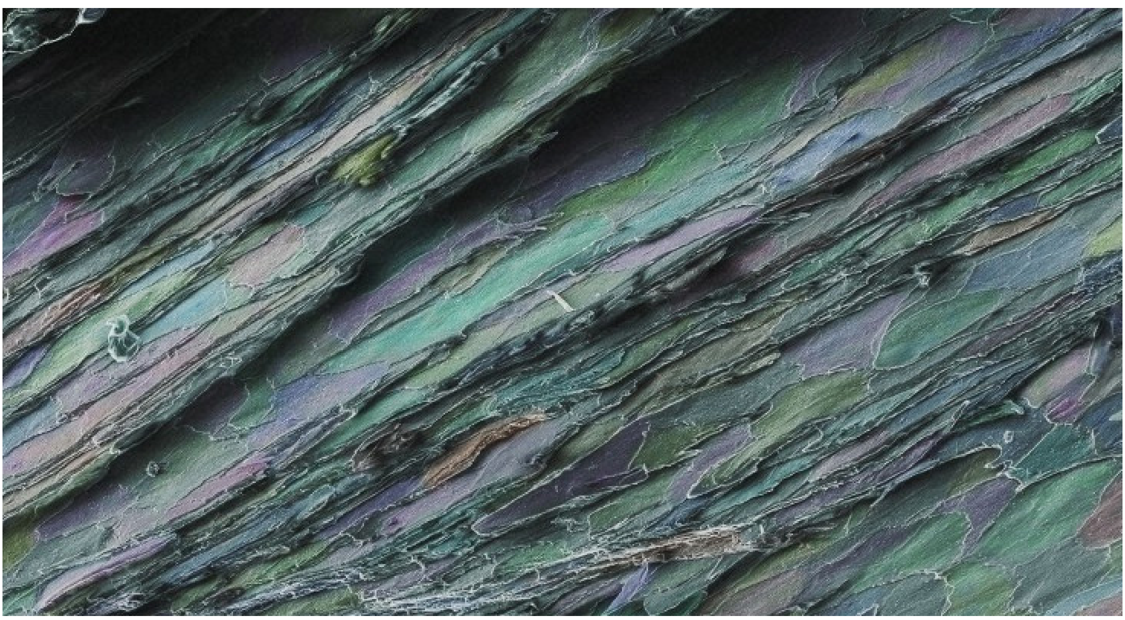
Natural hierarchical systems like wood, tendon and bamboo share some common traits that are worthy of emulation. Here are some of their key characteristics.

A few components can make a wide array of different structures because of the way in which they are recombined and arrayed. The over 70,000 different kinds of proteins found in the human body are all made from just 20 amino acids.

These components are arrayed in controlled orientations that are critical to performance. The hemoglobin molecule, a complex protein, for example, is able to carry either oxygen or carbon dioxide through the blood because of the way that its parts are arranged. Importantly, this array is tunable and triggered by the environment.

These arrays possess durable interfaces between different materials. Osteons are a basic building block of compact bone. They are hollow fibers of about 200 micron diameter made from concentric layers or lamellae of fibrils made from collagen, a protein, and hydroxyapatite, a mineral, which are combined to provide stiffness

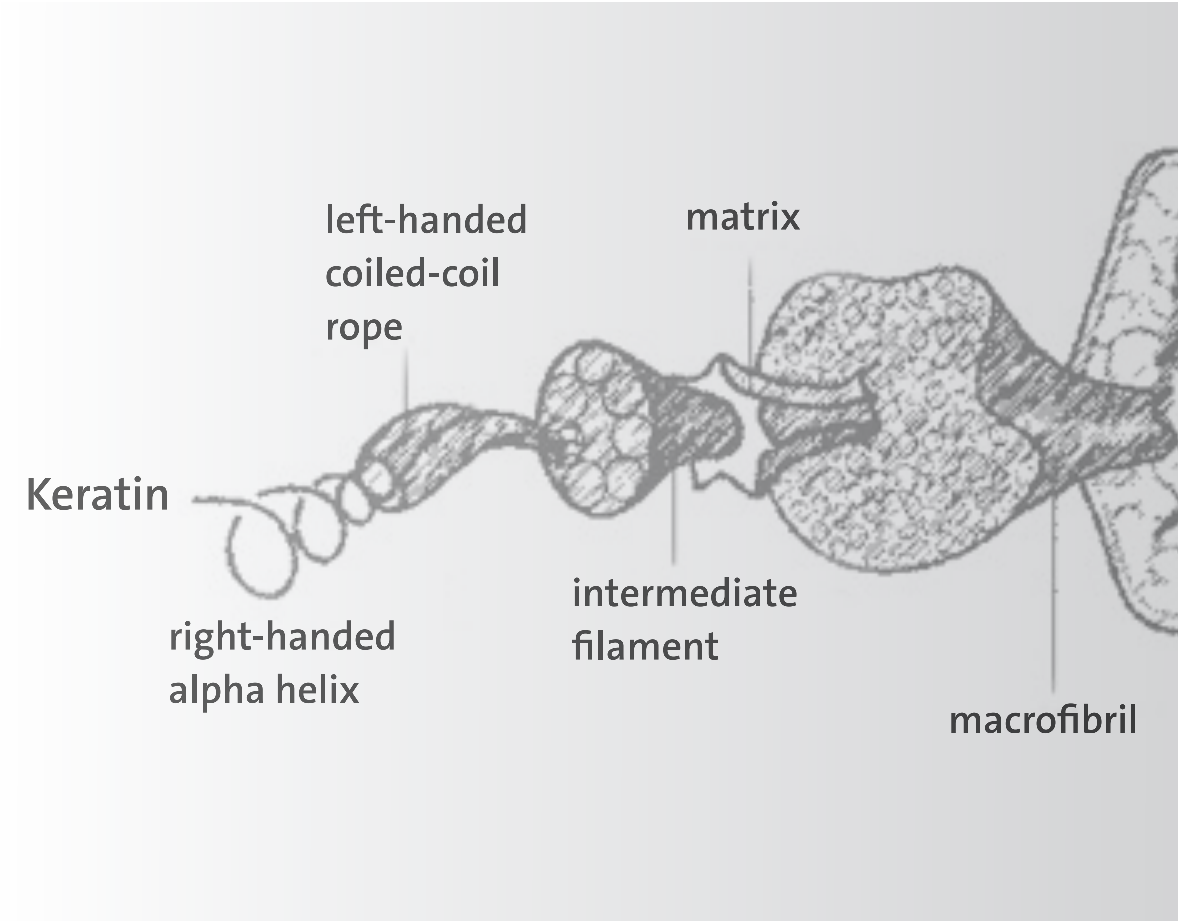




False coloured scanning electron micrograph of the keratin of a dog claw.

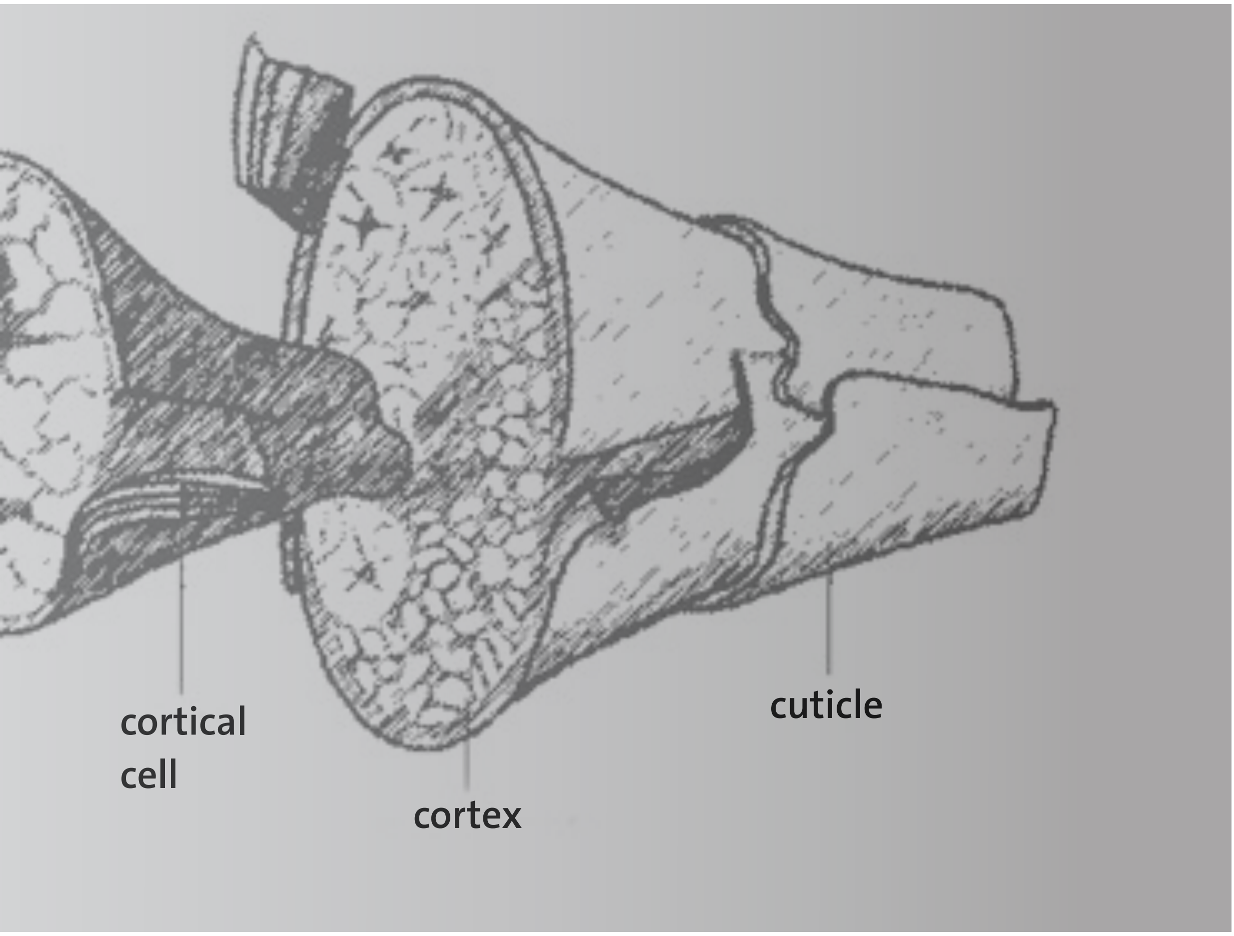
The image shows the multi-layed structure of the keratin.

Photo: Anne Weston, LRI, CRUK, Wellcome Images, 2012 | Flickr cc by-nc-nd 2.0



Schematic of Hair

Sketch based on http://www.rsc.org/ej/CS/2007/b604537p/b604537p-f2.gif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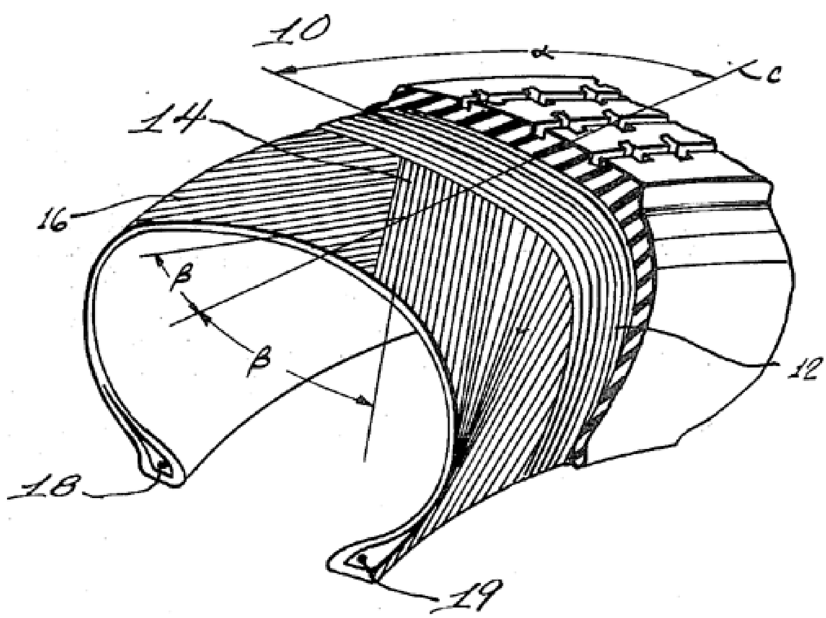


Eiffel Tower in the fog

Photo: JF Schmitz, 2012 | Flickr cc

Tire plies | Belted radial tire

Image: Alexander Duduk, 1970 | Wikimedia Commons

and durability. Between osteons relatively weak cement lines exhibit slow creep and this movement under stress imparts a degree of durability to the bone.

All of these structures demonstrate the concept of "emergence". This is where a phenomenon or characteristic, like the strength of bone, cannot be explained by a reductionist examination of its constituent parts. It is how the parts are related that produce the phenomenon. In other words, "Two and two make five" because of the power of these relationships. Put another way, "Little Things *Multiply* Up".

Hierarchical structures are common in nature, but replicating their integration of parts is not that easy to do in technology. Mankind has some notable but simple macroscopic examples, such as the cable suspension bridge, composites like the belted radial tire, and buildings like the Eiffel Tower or the geodesic dome.

Some Historical Examples

The Eiffel Tower

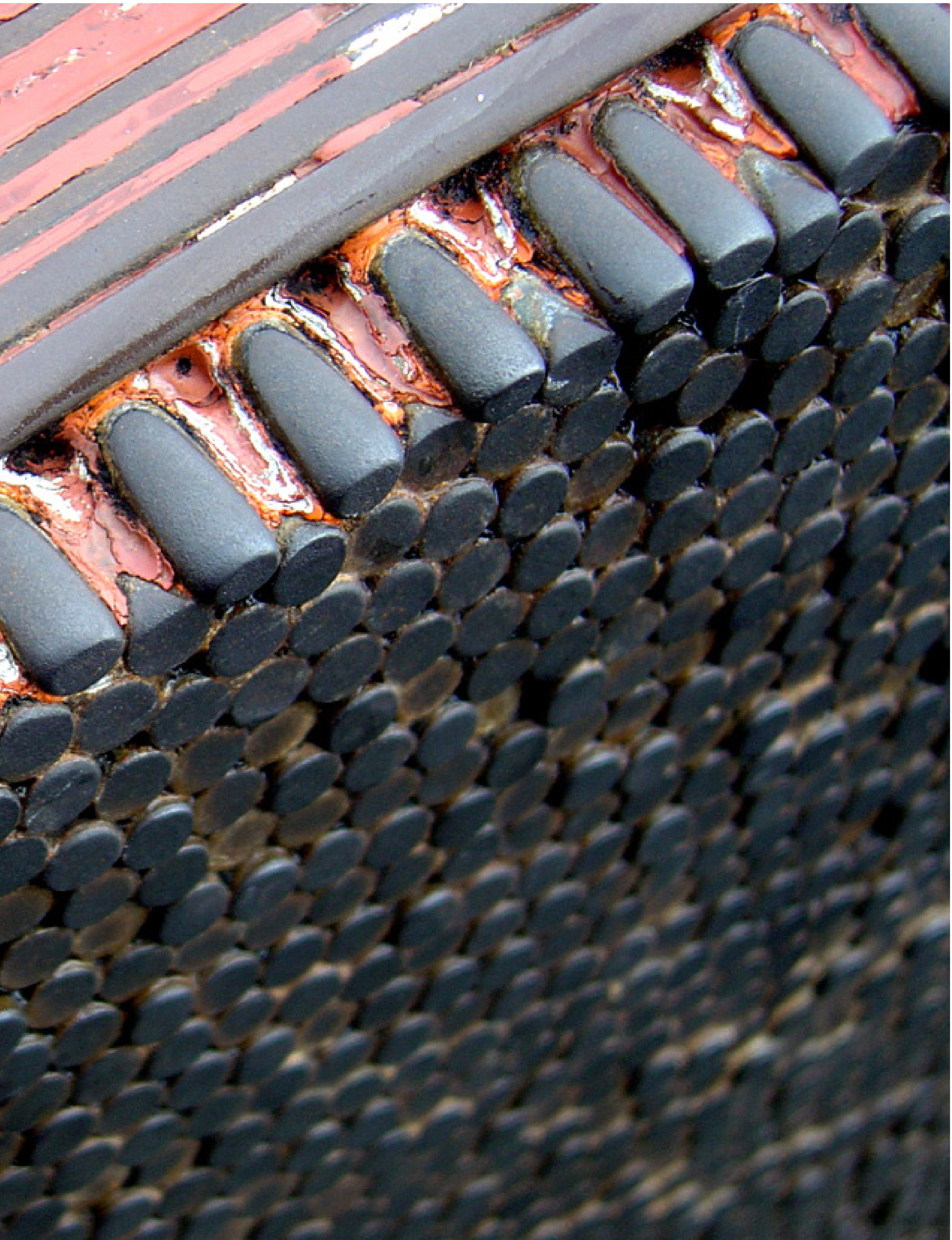
La Tour Eiffel, much maligned when it was erected in 1889, was ground-breaking in many ways, not the least of which was its modular design, which resulted in a building of a record-breaking 1,063 foot height that, should it be compacted, would fit within a 30 foot cube. Most of the building, therefore, is space and those spaces have everything to do with its strength and stability. Put another way, its relative density, the ratio of mass per unit volume to the density of the puddled iron material it is made of, is very low: 1.2×10^{-3} or 0.0012.

Four swooping latticework columns rise from the ground and are tied together by diagonals for stiffness and light weight. These columns are linked by two observation platforms and then directly to each other as they converge towards the top. The radical choice of the relatively small girders has been attributed to the desire for easy construction, but Bernard Mandelbrot of fractal fame had suggested that there might be structural advantages as well.

The building has been labeled a biomimetic structure in the recent past because of an assumed connection between the Swiss engineer, Karl Culmann, made famous by D'Arcy Wentworth Thompson for studying a human femur in designing a crane. It has been suggested that the femur directly inspired the landmark, but this does not appear to be the case. There is a connection to Culmann, however, in that Eiffel's managing engineer, Maurice Koechlin, had been a student of Culmann's at Polyteknikum Zurich and undoubtedly had absorbed Culmann's technique of form observation for structural principles. It was Koechlin, not Eiffel, who had designed the tower with fellow engineer Emile Nouguier and architect Stephen Sauvestre while getting virtually none of the credit.

The building is one of the most famous in the world but it is not for its third order hierarchy, but for the attribute that this regime gives to it: a character of both airiness and stability which is especially surprising given the standard technology of its day.

Golden Gate Bridge cables (27572 wires per cable) | Photo: Antonio de la Mano, 2005 | Flickr cc



The Golden Gate Bridge

This engineering marvel was completed in 1937, at the height of the American Depression and employed a cable suspension system to support the 1.2 mile roadway. It was the longest span that had ever been attempted. The suspension method of hanging a roadway from above, however, had been known since 1796 when James Findlay of Pennsylvania invented it using wrought iron chains. The new bridge at the mouth of the San Francisco Bay would not use iron, but steel that would be spun into stronger and stronger strands.

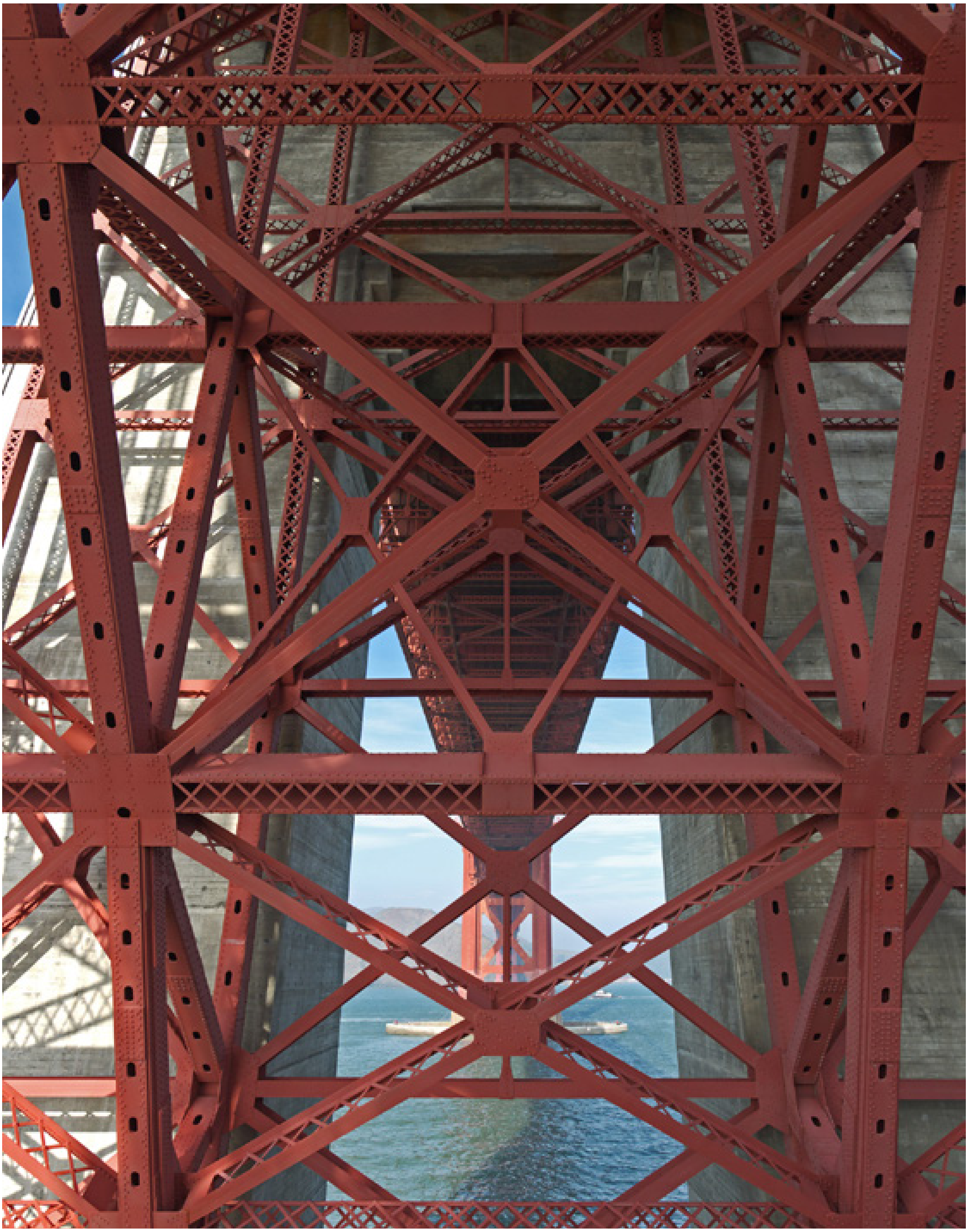
Like the human hair, the Golden Gate bridge system comprised a progression of twisting, bundling and sheathing of threads into larger and larger structures. In this case, galvanized carbon steel wire. Over 80,000 miles of 0.192 inch wire was used in the two main cables hung over the two 746 foot towers and anchored in immense concrete blocks at either end of the bridge. Each wire was wrapped in place using a loom type shuttle that ran back and forth over the course of six months: 452 wires to a bundle; 61 bundles to a cable; all sheathed in a steel jacket. Every 50 feet, cable bands and vertical suspender ropes served to hang the over 166,000 ton reinforced concrete deck.

The Geodesic Dome

R. Buckminster Fuller patented the geodesic dome in 1954, and thousands have been erected around the world since that time. Fuller was a pioneering systems thinker, so it is not surprising that his buildings, like the U.S. pavilion at the 1967 Montreal Expo, exhibit hierarchical structure; all based on the stability of the triangle. One of the reasons for the dome's utility is this minimalist design in which relatively small linear struts are fitted together in hubs to create larger triangles. These in turn form hexagons and pentagons which are combined to form a sphere.

In Montreal Fuller and architect Shoji Shadao created a 200 foot high by 250 foot diameter three-quarters sphere made entirely of steel pipes and 1,900 molded acrylic panels. This is a class 1, 16 frequency dome which means that it is based on the icosahedron, a 20-face solid based on the equilateral triangle, and the original triangle that formed the icosahedron has been further divided into smaller triangles, 16 to a side or 256 total. The more divisions in the original triangle, the smaller the chords and the more nearly the dome approaches a sphere .

In Cornwall, England, Nicholas Grimshaw and Partners designed the world's largest array of geodesic dome greenhouses in the Eden Project site in an abandoned china-clay pit in 2001. These were also steel pipe space frames covered with cladding. In this case the cladding was the lightweight ETFE (Ethylene tetrafluoroethylene), made into air-filled pillows. The frame is actually two different spheres, an inside and an outside, the former based on the icosahedron and the latter based on the doadecahedron, a 12 faced solid based on the pentagon. Michael Pawlyn, project architect, explained that the use of the ultralight cladding and the lighter weight superstructure created a cascade of savings throughout the building, such as obviating the need for a more robust foundation. He has calculated that the volume of air within the buildings is greater than the weight of the superstructure itself.



Structure of Golden Gate Bridge

Photo: Jesse Varner, 2009 | Flickr cc

Each of these three examples was an innovation at the time of its building. These edifices saved material, time and money, and because of that they were able to span longer, rise higher and enclose more space for less money and in a shorter time. Indeed, they have remained icons in both the popular and professional consciousness, and make most lists of important buildings. Still, they are static macro-scale structures from the mechanical age and, if the concepts being developed and tested in the following research are adopted, will seem as obsolete as a stone arch.

Current Research

Advances in the discovery of the very small and its processes as well as methods of manufacturing have put more complex versions of hierarchical systems within our reach. Here are two examples of laboratories that are investigating the mechanics of materials to provide those versions.

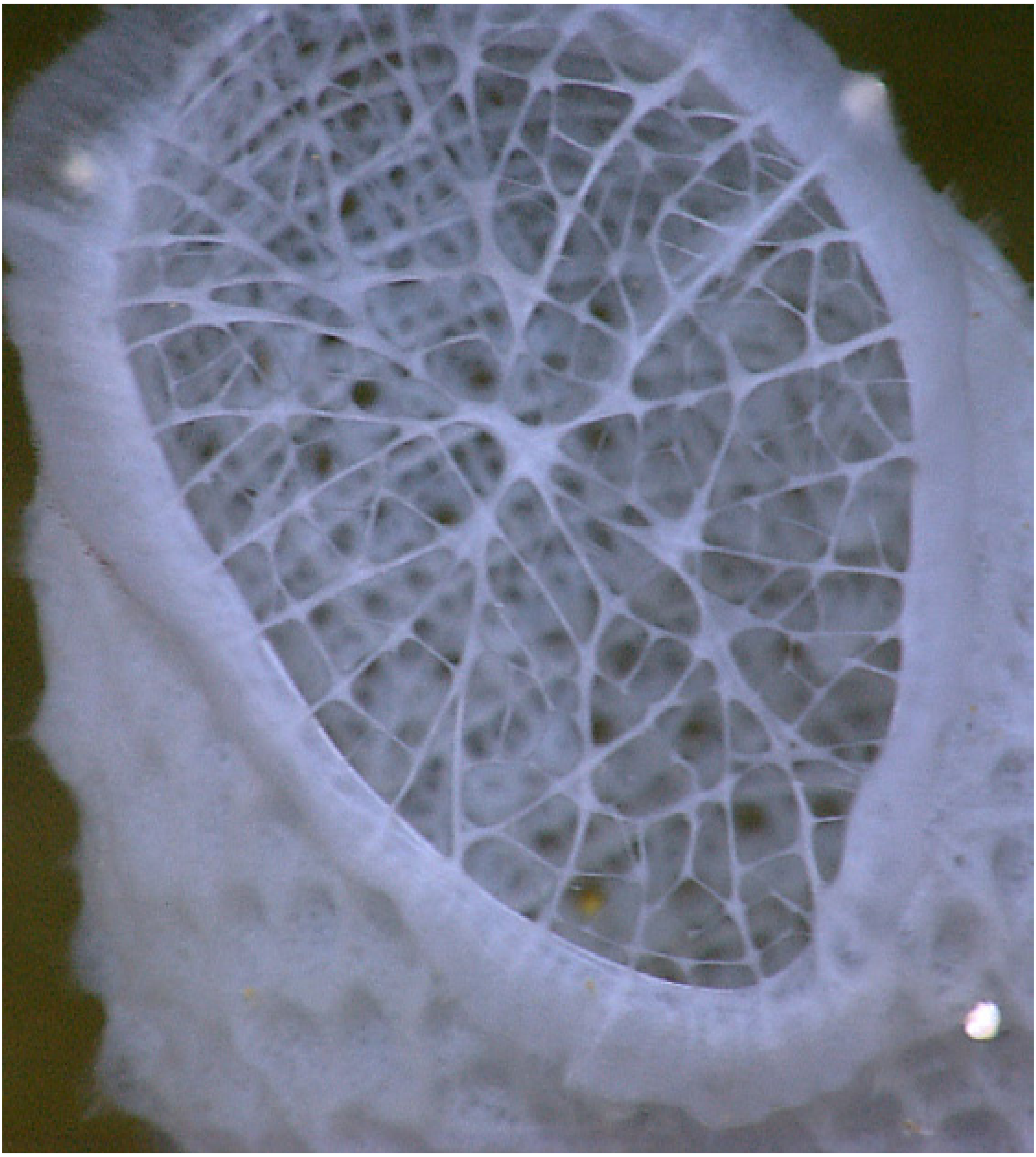
Aizenberg Lab

Dr. Joanna Aizenberg and her colleagues at Harvard studied the cylindrical endoskeleton of the marine sponge *Euplectella* (Venus' Flower Basket) in a well-cited 2005 Science article that has become a model for this type of work. These investigators noted that the Venus' Flower Basket achieved seven scale layers of structural strengthening in growing its silica skeleton. The organism precipitated silica out of seawater and formed this silica into nanospheres arranged in concentric layers and alternated with organic layers. These were bundled into rods; these rods were in turn ganged into composite beams and these beams formed into cage-like struts at the micron scale. These struts were then arrayed at the macroscale in a square lattice with diagonal cross-beams.

Fascinatingly, the method of cross bracing every other square and thereby achieving the needed reinforcement without excess weight was exactly what engineers had practiced based on structural engineering calculations. Indeed such cross bracing methods can be observed on buildings such as the former Swiss Re Tower (aka the Gherkin) now the St. Mary Axe building in London. In another optimized form, the layering of crystals and organic material in the rods was not equal. Where crack resistance was needed, towards the outside, the layers of silica were thin, and where tensile-compressive strength was needed, at the core, the layers were thicker.

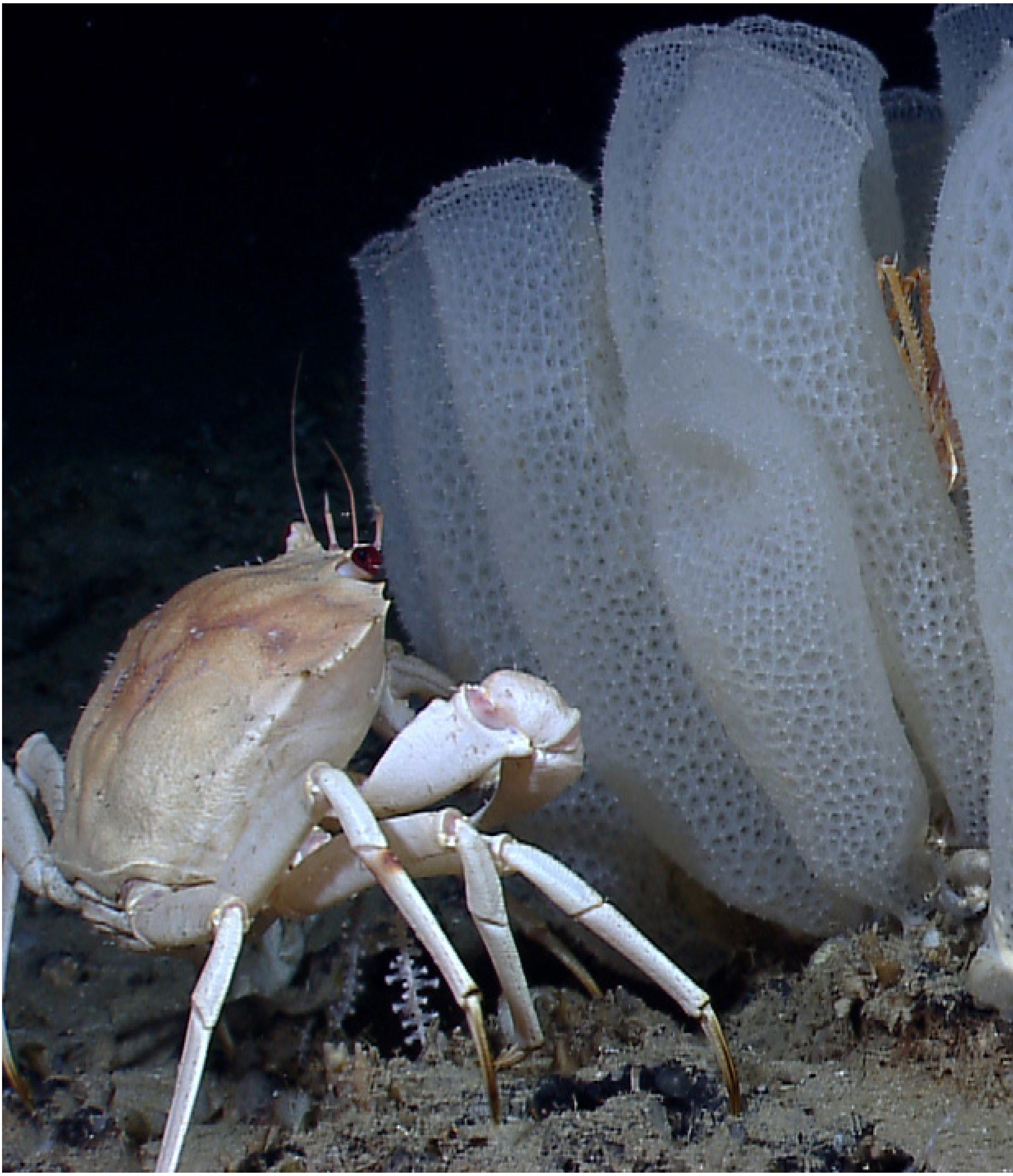
Dr. Aizenberg continues to investigate complex structures at her lab at the School of Engineering and Applied Sciences at Harvard University where she is an Amy Smith Berylson Professor of Materials Science; Professor of Chemistry and Chemical Biology, Radcliffe Professor and the Director of the Kavli Institute for Bionano Science and Technology (http://aizenberglab.seas.harvard.edu/index.php?show=research_project&proj=58).

Just one of the lines of investigation is that of Adaptive Hybrid Architecture (of material) where composite systems are made that can successfully bridge the differences between materials and scales. The goal is to make



Closeup of the top of a venus flower basket sponge

Photo: NOAA Okeanos Explorer Program, INDEX-SATAL, 2010 | Flickr cc



A golden crab (*Chaceon fenneri*) contemplates a group of Venus flower basket glass sponges (*Euplectella aspergillum*).
Photo: NOAA Photo Library, 2012 | Flickr cc

responsive and adaptive mechanisms that are activated by the environmental conditions themselves.

This is an example of "surfing for free". In nature it could be described as the use of favorable thermodynamic pathways by energy transforming organisms to maintain optimum conditions. An example is a bird taking advantage of convective air currents or thermals to stay aloft without expending the energy of flapping its wings. Our previous example of the hemoglobin molecule is a more precise exemplar, since the relative amount of either CO_2 or O_2 in the blood is what triggers the configuration of the molecule that allows it to transport either gas.

In an explanation of design principles for one project the lab has coupled a range of environmental cues like humidity and light intensity to a set of structural elements, including hierarchical systems. This coupling, theoretically, yields an "adaptive, integrated responsive system".

Buehler Lab

At Markus Buehler's Laboratory for Atomistic and Molecular Mechanics (LAMM) lab in the Civil and Environmental Engineering department at MIT, engineers are involved in failure of all kinds; structural failure, that is, of biological materials. In finding out how and why these hierarchical systems fail, they hope to discover new ways to make sophisticated new structures out of cheap materials.

Dr. Buehler is particularly interested in the cross-scale and cross-material properties of these natural systems and has even coined a new phrase for how his lab studies these multi-faceted phenomena: "materiomics". Materiomics is defined by the lab as "the study of the material properties of natural and synthetic materials by examining fundamental links between processes, structures and properties at multiple scales, from nano to macro, by using systematic experimental, theoretical or computational methods".

The lab studies the processes, structures and properties of materials from a fundamental, systematic perspective by incorporating all relevant scales, from nano to macro, in the synthesis and function of materials and structures. Thus they gain an integrated view of these interactions at all scales through some sophisticated computer modeling.

What they look at are proteins, all kinds of proteins, from those in spider silk to tendons, bones, hair and teeth. Unlike biologists, they are examining these living materials using the methods and intentions of civil engineering and architecture applied to the very small. They have divided these proteins into three groups of basic structural building blocks and have looked closely at how these blocks are bonded.

Using their multi-scale modeling and confirmatory testing they have been able to typify the structural and mechanical properties of collagen from the molecular to the tissue scale. They have discovered, for instance, that collagen maintains a maximum strength at 200-400 nm length, and it explains why one sees only this length of collagen tissue. Collagenous materials, like bone, are typically under stress and the collagen protein provides mechanical stability, elasticity and strength to organisms. Tendons, for instance, are made predominantly from collagen.

Naturally occurring shells as biomaterials, and 3D printed bio-inspired composites.

Photo courtesy of Markus J. Buehler and Graham Bratzel (MIT)

L. Dimas, G. Bratzel, I. Eylon, M.J. Buehler, "Tough Composites Inspired by Mineralized Natural Materials: Computation, 3D printing and Testing," *Advanced Functional Materials*, *Vol.* 23(36), pp. 4629-4638, 2013

Orb Weaver of the Dunes (*Argiope floridana*)

Photo: bob in swamp, 2011 | Flickr cc

They have also been able to discover that spider webs owe their superior performance not just to the ultimate strength of the silk thread, but also from its nonlinear response to stress and its alignment within the geometry of the web. The silk nanocrystals are a stacked arrangement with each layer dialed in a different direction. They are held together by weak hydrogen bonds that act together in the stack to resist external force. The weakly bonded array has the ability to reform easily broken bonds and slow the rate of failure. In addition the group found that the size of the nanocrystals was critical to performance; larger crystals which they tested failing catastrophically.

Implications of Current Research

The discoveries being made at the Aizenberg and Buehler labs have broad implications for material and structure development for everything from biomedical devices to buildings. Their *way* of investigating these phenomena also has implications for how we think about design.

Understanding the structure of these biological systems and being able to predict their performance capabilities cannot be done by an examination of the isolated constituent parts. An integrated assessment is needed to test processes, structures and properties across scales. Complex problems sometimes require complex solutions and understanding those problems sometimes requires complex models.

The use of lessons learned from labs like those of Buehler and Aizenberg will represent a significant shift in the concept of structural design for buildings. Here are the elements of that paradigm shift that I think are necessary and, in some cases, have already begun:

- First there will be a change in the notion of working scale, a wider horizon, if you will, of what length scales are effective in solving problems.
- Second, there will be a necessary emphasis on the interfaces of different materials and scales, so that contradictions like strength and toughness can be resolved.
- Third, there will be an overarching goal of optimal integration of structural components and materials. This will be pursued at an entire magnitude greater than currently practiced.

Finally, there must be a concurrent and essential improvement in manufacturing and fabrication techniques that allows these more complex forms to be competitive in installation cost and maintenance. The burgeoning industry of additive manufacturing is an early example.

In the future I do not believe that architects, engineers and industrial designers will be designing static objects and services. Instead they will be analyzing conditions, figuring out how to manipulate those conditions and then designing structures to adapt and respond to (and maybe evolve with) those existing conditions or ones that have been created. It will be more like gardening than house building, but it will be based on a technical knowledge of systems, physics and biological science. ×

Ephemeral Pools (Potholes)

Photo: brewbooks, 2010 | Flickr cc

The Science of Seeing
Small Worlds in a Big Space

Adelheid Fischer

Small Worlds in a Big Space

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

There are places in Arches National Park where you can stand on the edge of a cliff, gaze out over the Big Empty of the Colorado Plateau and swear with both hands on a bible that nothing, nothing lies between you and eternity. These wide-open spaces, framed by flying buttresses of red rock arches, are so knee-buckling beautiful that they attract visitors from around the world. One is even featured on the Utah state license plate.

On today's visit to the park, though, my eyes are glued not to the horizon but to the ground to keep from twisting an ankle as I pick my way up ledges or drop over slickrock balds. I'm hiking off the beaten track on this hot day in late July with ecologist Tim Graham, scrambling to keep pace with his deliberate, but steady, clip. Now and again, though, I interrupt the rhythm of our crunching boots to lag behind and admire the fluted grain of wind-scoured Navajo sandstone as it flows across canyon walls like long, loosening braids of human hair.

Tim, by contrast, navigates this unmarked terrain with the sure-footedness of someone who could traverse it with his eyes closed. He has spent most of his adult life in and around Moab, Utah, including a stint as a biologist for the U.S. National Park Service in southeastern Utah. He has crisscrossed the Colorado Plateau, from Grand Staircase-Escalante National Monument to the San Rafael Swell, probably about as many times as he's run up and down the ball field in town where he plays pick-up soccer several times a week.

About 45 minutes into our trek, Tim slips off his pack and settles down next to a shallow depression the size of a Thanksgiving turkey platter. It's the first stop on a tour that I have been looking forward to for years. "Time for some belly science," he announces with a smile. I look at Tim, then down at the ground. Although the rock is not quite hot enough to fry an egg, it is, nonetheless, mid-day in mid-summer in the middle of the desert with air temperatures pushing triple digits and not a cloud or speck of shade in sight. But I'm not missing this show for the world. Living here in the dimples of slickrock—weathering pits known as desert potholes—are the tiny descendants of species that have called this wind-scoured place home since the Mesozoic era. To appreciate them, you have to adjust your sights. So I drop to my knees and then gingerly lower my stomach onto the toasty rock.

Desert potholes have been on my list of Ten Things to See Before I Die, ever since I had read

Water boatman

Photo: sam dredge, 2012 | Flickr cc

about them in a guide to canyon country five years ago. Southern Utah is ground zero for potholes. They are so common that the map is, well, riddled with them: Pothole Point in nearby Canyonlands National Park, Swiss Cheese Ridge around Moab and Waterpocket Fold at Capitol Reef National Park, for instance.

My guide doesn't get any more expert than Tim, who has studied these diminutive ecosystems since 1987. He even has the discovery of a new species to his credit—a yet-unnamed oribatid mite that lives only in pools on the Colorado Plateau. Just one other species within this new genus has been identified, and it lives clear across the country in the granite domes of Georgia. Another very similar mite, in the genus *Aquanothrus*, is found in ephemeral pools in South Africa.

Potholes, like the shallow depression we're looking at, typically begin to form when precipitation collects in low points along fractures in the sandstone. Studies by Jim Davis of the Utah Geological Survey and his colleagues reveal that the sandstones are composed almost entirely of grains of silica with only small amounts of calcium carbonate and iron binding them together. Over time, the standing rainwater in these self-contained pools can dissolve this weak cement and liberate the sand grains, as can the mechanical action of freezing and thawing. Strong winds carry off the loose sediments, in essence excavating the pits like a slow-motion backhoe. Natural forces acting on vastly different time and spatial scales produce potholes that range from hollows the size of a teacup to ephemeral ponds that are some 50 feet deep.

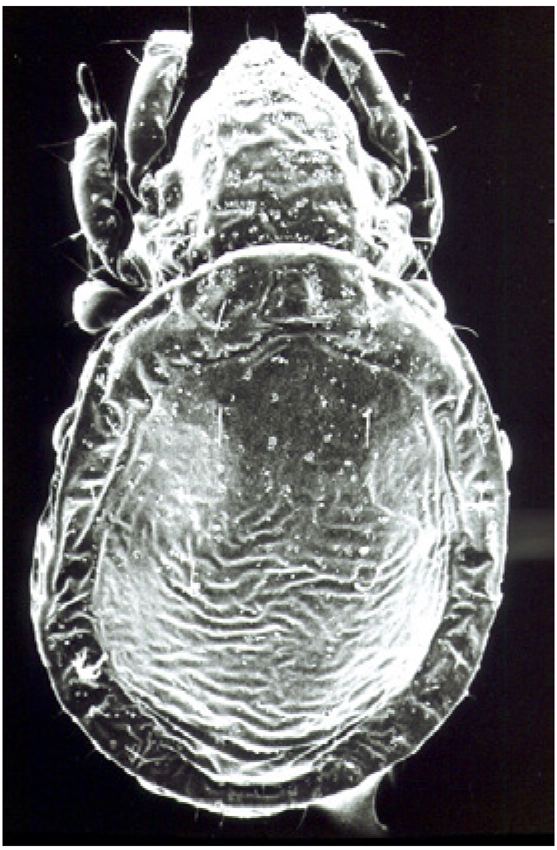
Tim pokes around the thin, powdery layer of sand that has collected at the bottom of the pothole. It looks dry and lifeless. A black bathtub ring of live, but desiccated, microorganisms around its rim however, indicates that it contained rainwater at some point during the year. This community, which includes several species of bacteria, forms an impermeable biofilm that keeps the water from seeping through the sandstone. And where there's a sign of water in a pothole, there's a good chance of finding other kinds of life too. Tim carefully isolates a few dark particles that look, to my untutored eye, like tiny flakes of cracked black pepper. They are oribatid mites.

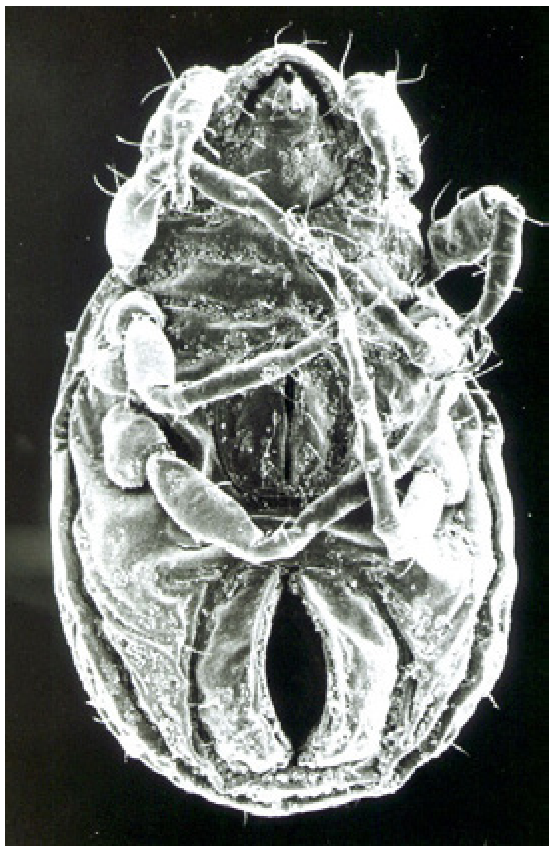
Tim pulls out his water bottle, pours a few tablespoons of liquid over them and then pauses to deliver a brief introduction to mite ecology. Most oribatids are terrestrial and live on plants or in duff on the forest floor where they consume fungi and organic detritus. The three pool-dwelling species of mites, on the other hand, have adapted to life in water. And unlike their vegetarian cousins on land, these mites are omnivores, supplementing a diet of algae and detritus with invertebrates such as nematodes and tiny hunter-orange animals known as rotifers.

Tim pauses in his lesson and trains a magnifying lens on the mites. In this short time, they have been roused from their torpor and have begun kicking around on the edge of the dirt. Their movements are labored and unsteady because mites have pointy, sickle-shaped structures at the end of their feet. In terrestrial environments, they serve as grappling hooks for hanging on to plant material. Even though the appendages are ill-adapted for life in aquatic environments, the pool-dwelling mites have retained these features. The mites are especially ungainly when trying to maneuver through long strands of slick algae, a little like walking in high heels through a bathtub of spaghetti. "They're not very graceful," Tim points out. "They're falling all over each other. They get tangled up."

Tim had observed this behavior early in his pothole studies and confronted a puzzling question. How did the mites survive, he wondered, when one of their staple prey—rotifers—slip in and out of the pores between sand grains with extraordinary ease? These rotifer movements, he says, "are very much like a ballet. How do these clumsy guys feed on these very coordinated, elegant rotifers?"

The answer, it turns out, seems to lie in their differential responses to drought. Every member of a pothole community possesses some extraordinary adaptation for surviving the vagaries of desert rainfall, which is scarce and unpredictable. Even when it does rain, many





SEM photos, dorsal view and ventral view, of yet-to-be-named species of oribatid mite in Colorado Plateau pans.

Photo: John Gardner, BYU

Dry rotifers | Photo: Tim Graham

pools evaporate quickly in the desert's dry air. In this sense, growth and reproduction in desert potholes are a lot like life on the battlefield—long periods of down time during dry intervals punctuated by spurts of frantic energy during wet ones.

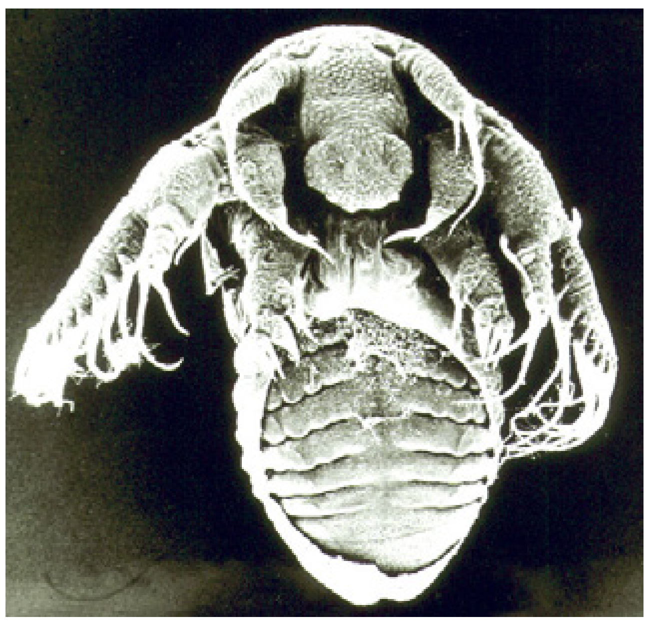
Pothole animals ride out the wild surf of boom-and-bust uncertainty by using one of three survival strategies. The drought escapers include vertebrates such as red-spotted toads and winged insects such as backswimmers and mosquitoes. They possess fast-whirring biological clocks that allow young tadpoles and larvae to quickly mature into adulthood and leave the pool before it dries up.

The drought tolerators stay put and endure punishing conditions that would kill most other animals. Through a process known as cryptobiosis, tiny organisms such as tardigrades and rotifers, as well as the eggs of a trio of freshwater crustaceans—fairy shrimp, tadpole shrimp and clam shrimp, can lose up to 95 percent of their total body water. The eggs can survive 50 years or more on a lab shelf. So tough are they in this cryptobiotic state that astronauts have taken them out of the shelter of space capsules and exposed them to the vacuum of outer space and the full ionizing radiation of the Sun with no deleterious effects. Biomimicry enthusiasts know these organisms as the biological models for creating long-lived vaccines that can be stored without refrigeration.

Other pothole dwellers utilize a third approach, what Tim calls the "Tupperware strategy." Snails retreat into their shells and close their openings using a structure known as the operculum,

Tadpole shrimp nauplius larva (about 7 hours old)

Photo: John Gardner, BYU



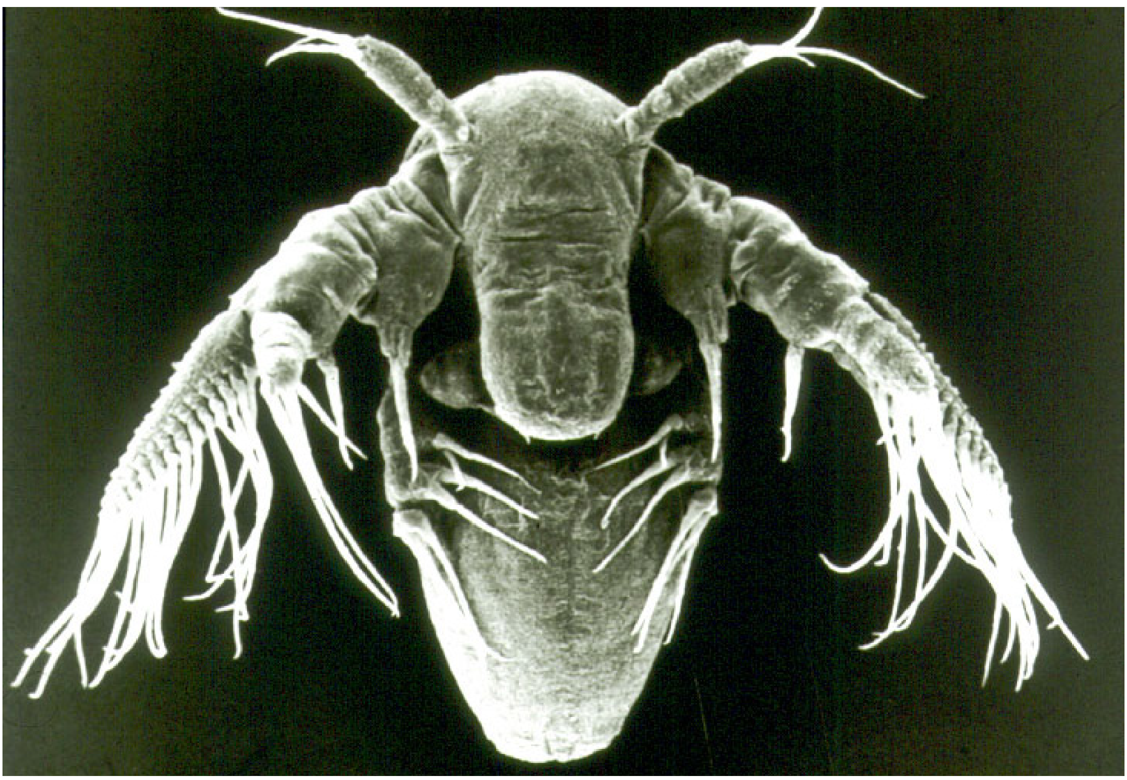
Tadpole shrimp nauplius larva beginning first molt (<10 hours old)

Photo: John Gardner, BYU

which means "little lid." The mighty mites produce sealants such as waxy cuticles and burrow into the mud to minimize water loss.

Each strategy has its trade-offs. Because they are able to retain a large percentage of their body moisture, mites can spring to life as soon as moisture frees them from their dry matrix of soil. Without water, however, the mites can't survive much longer than a year. The desiccated rotifers, on the other hand, can persist for longer periods in their cryptobiotic state. The downside, though, is that it can take anywhere from five to ten minutes to rev up their metabolic motors once rain falls. The mites are able to exploit this lag time, teetering across the sand on their tippy, high-heeled feet as they feast on the comatose rotifers.

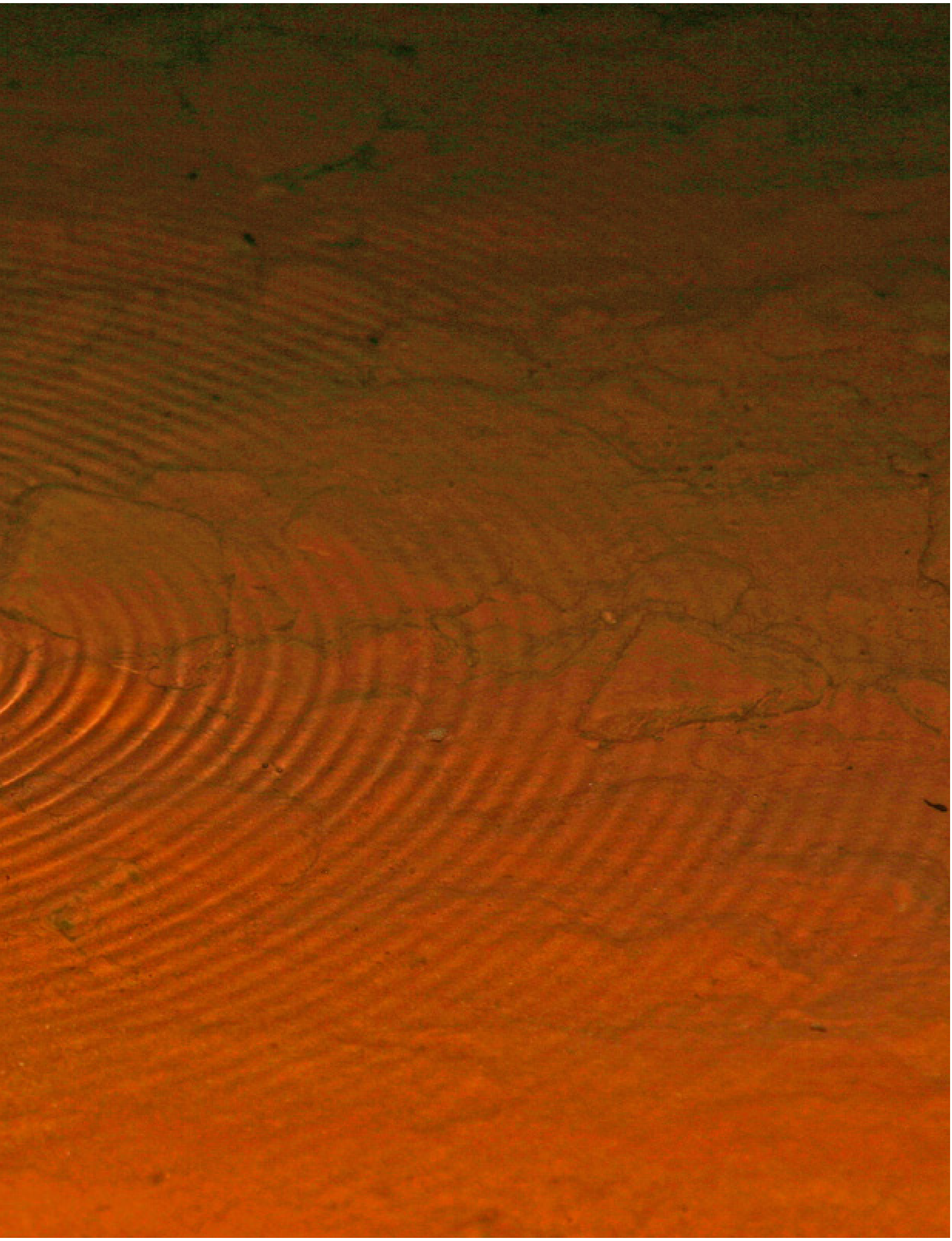
After nearly an hour beside the dried pool, it is time to leave. We have several other potholes to visit before the day is over. By the time Tim has packed up his water bottle and magnifying glass, the sediment already has begun to dry and once again encase the mites in their sarcophagi of silica. I rise slowly to my knees and lean over to peer one last time into the pit. Ecologists call this a Mesozoic lifeboat niche. Hundreds of millions



Tadpole shrimp nauplius larva beginning later molt (about 15 hours old)

Photo: John Gardner, BYU

Red-spotted toad *(Bufo punctatus)* calling | Photo: Tim Graham



of years ago, the species they now shelter were more widespread. But aquatic predators, including fish and diving beetles, largely eliminated them from the more hospitable habitats of permanent water. So, pothole organisms hedged their bets and evolved over time to make the best of a tough situation. And tough it is. Time and again before the year is out, the tiny mites and their neighbors will endure wild swings in temperature, salinity, pH, and oxygen and carbon dioxide concentrations as their little pool refills and then dries out again.

I read recently that the universal posture of awe and reverence across the world is to bow, kneel or prostrate oneself. The fact that I am ending my first visit to a pothole on my knees seems a fitting response to the wonder of the occasion.
×

Triops longicaudatus tadpole shrimp

Photo: Tim Graham

Trees cocooned in spiders webs after flooding in Sindh, Pakistan: An unexpected side-effect of the flooding in parts of Pakistan was that millions of spiders climbed up into the trees to escape the rising flood waters.
Photo: Russell Watkins/Department for International Development, 2010 | Flickr cc

Book

The Systems View of Life: A Unifying Vision

Fritjof Capra and Pier Luigi Luisi

spring 2014

Book:
The Systems View of LIfe

Authors:
Fritjof Capra and Pier Luigi Luisi

Fritjof Capra, Ph.D., physicist and systems theorist, is a founding director of the Center for Ecoliteracy in Berkeley. Capra is the author of several international bestsellers, including *The Tao of Physics* (1975), *The Web of Life* (1996), and *The Science of Leonardo* (2007). He is coauthor, with Pier Luigi Luisi, of the multidisciplinary textbook, *The Systems View of Life: A Unifying Vision* (Cambridge University Press, 2014).

The great challenge of our time is to build and nurture sustainable communities, designed in such a way that their ways of life, businesses, economies, physical structures, and technologies respect, honor, and cooperate with nature's inherent ability to sustain life. The first step in this endeavor, naturally, must be to understand how nature sustains life. It turns out that this involves a whole new conception of life. Indeed, such a new conception has emerged over the last 30 years.

In my new book, *The Systems View of Life*, coauthored by Pier Luigi Luisi and just published by Cambridge University Press, we integrate the ideas, models, and theories underlying this new understanding of life into a single coherent framework. We call it "the systems view of life" because it involves a new kind of thinking — thinking in terms of relationships, patterns, and context — which is known as "systems thinking", or "systemic thinking".

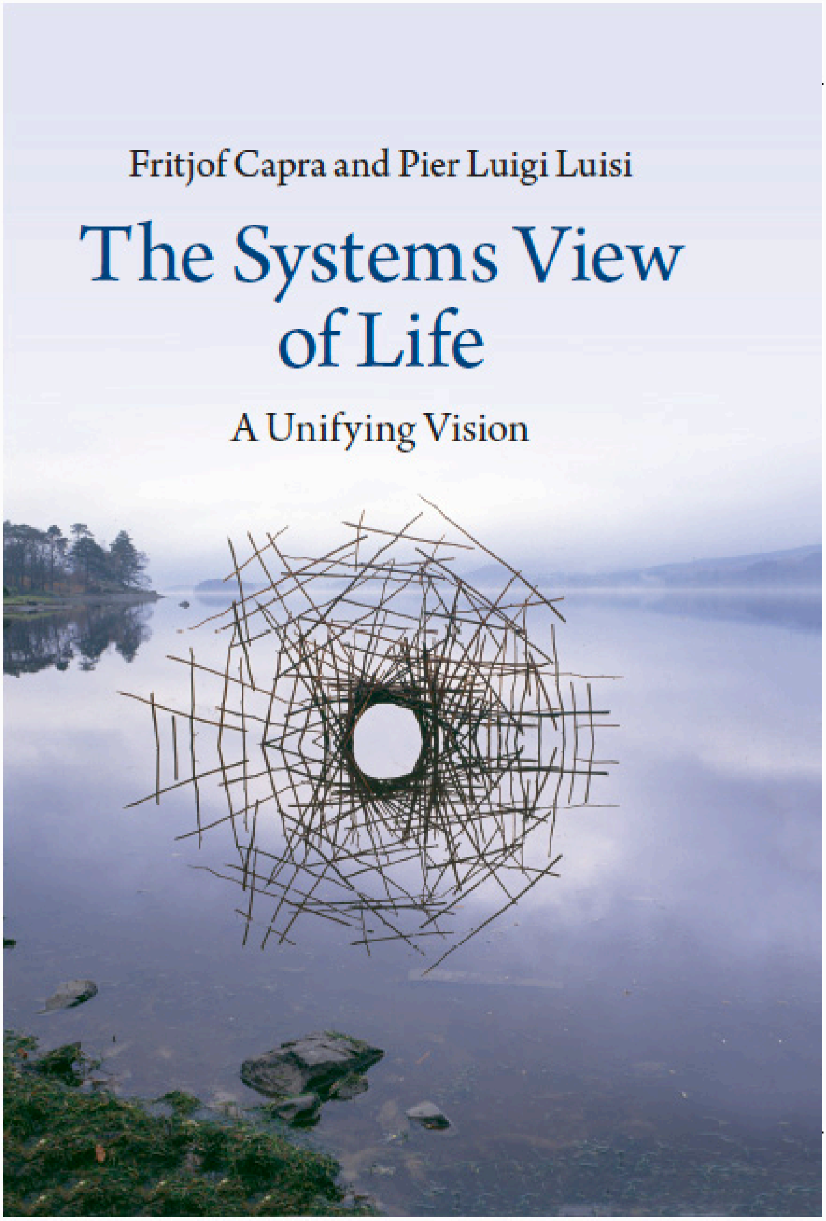
We offer a multidisciplinary textbook that integrates four dimensions of life: the biological, cognitive, social, and ecological dimensions; and we discuss the philosophical, social, and political implications of this unifying vision. We believe that it will be critical for present and future generations of young researchers and graduate students to understand the new systemic conception of life and its implications for a broad range of professions — from economics, management, and politics, to design, medicine, and law.

Taking a broad sweep through history and across scientific disciplines, beginning with the Renaissance and the Scientific Revolution, we chronicle the evolution of Cartesian mechanism from the seventeenth to the twentieth centuries, the rise of systems thinking in the 1930s and 1940s, the revolutionary paradigm shift in twentieth-century physics, and the development of complexity theory (technically known as nonlinear dynamics), which raised systems thinking to an entirely new level.

During the past 30 years, the strong interest in complex, nonlinear phenomena has generated a whole series of new and powerful theories that have dramatically increased our understanding of many key characteristics of life. Our synthesis of these theories, which takes up the central part of our book, is what we refer to as the systems view of life. In this essay, I can present only a few highlights.

One of the most important insights of the systemic understanding of life is the recognition that networks are the basic pattern of organization of all living systems.

Ecosystems are understood in terms of food webs (i.e., networks of organisms); organisms are networks of cells, organs, and organ systems; and cells are networks of molecules. The network is a pattern that is common to all life. Wherever we see life, we see networks. Indeed, at the very heart of the change of paradigms from the mechanistic to the systemic view of life


Fritjof Capra and Pier Luigi Luisi
The Systems View of Life
A Unifying Vision

Trees cocooned in spiders webs after flooding in Sindh, Pakistan: Because of the scale of the flooding and the fact that the water took so long to recede, many trees became cocooned in spiders webs. People in this part of Sindh had never seen this phenonemon before - but they also reported that there were less mosquitos than expected, given the amount of stagnant, standing water that was around.

Photo: Russell Watkins/Department for International Development, 2010 | Flickr cc

we find a fundamental change of metaphors: from seeing the world as a machine to understanding it as a network.

Closer examination of these living networks has shown that their key characteristic is that they are self-generating. Technically, this is known as the theory of autopoiesis, developed in the 1970s and 1980s by Humberto Maturana and Francisco Varela. Autopoiesis means "self-making." Living networks continually create, or recreate themselves by transforming or replacing their components. In this way they undergo continual structural changes while preserving their web-like patterns of organization. This coexistence of stability and change is indeed one of the key characteristics of life.

In our synthesis, we extend the conception of living networks from biological to social networks, which are networks of communications; and we discuss the implications of the paradigm shift from the machine to the network for two specific fields: management and health care.

One of the most rewarding features of the systems view of life is the new understanding of evolution it implies. Rather than seeing evolution as the result of only random mutations and natural selection, we are beginning to recognize the creative unfolding of life in forms of ever-increasing diversity and complexity as an inherent characteristic of all living systems. We are also realizing that the roots of biological life reach deep into the nonliving world, into the physics and chemistry of membrane-bounded bubbles — proto cells that were involved in a process of "prebiotic" evolution until the first living cells emerged from them.

One of the most important philosophical implications of the new systemic understanding of life is a novel conception of mind and consciousness, which finally overcomes the Cartesian division between mind and matter. Following Descartes, scientists and philosophers for more than three hundred years continued to think of the mind as an intangible entity (res cogitans) and were unable to imagine how this "thinking thing" is related to the body. The decisive advance of the systems view of life has been to abandon the Cartesian view of mind as a thing, and to realize that mind and consciousness are not things but processes.

This novel concept of mind is known today as the Santiago theory of cognition, developed by Maturana and Varela at the University of Chile in Santiago. The central insight of the Santiago theory is the identification of cognition, the process of knowing, with the process of life. Cognition is the activity involved in the self-generation and self-perpetuation of living networks. Thus life and cognition are inseparably connected. Cognition is immanent in matter at all levels of life.

The Santiago theory of cognition is the first scientific theory that overcomes the Cartesian division of mind and matter. Mind and matter no longer appear to belong to two separate categories, but can be seen as representing two complementary aspects of the phenomenon of life: process and structure. At all levels of life, mind and matter, process and structure, are inseparably connected.

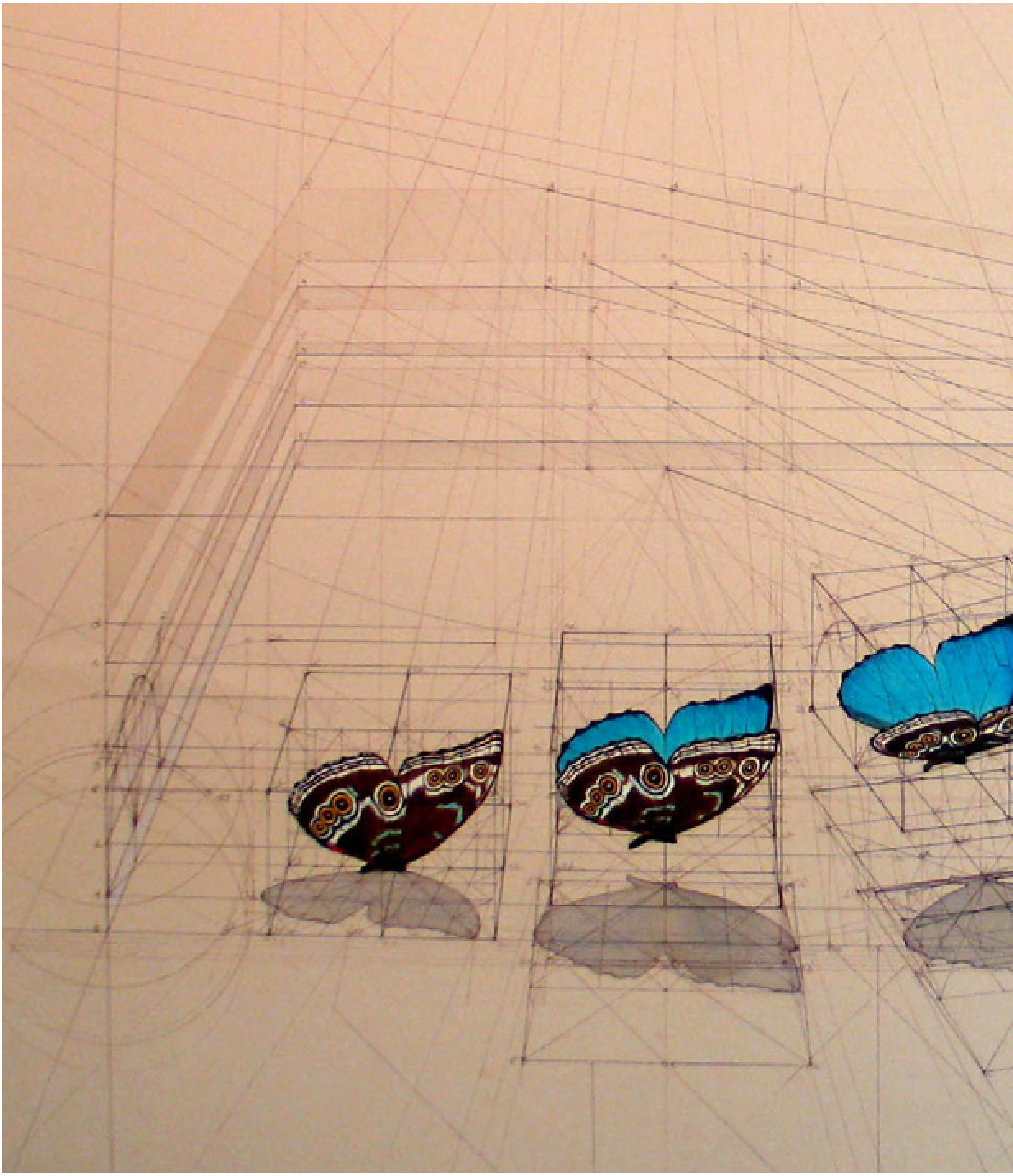
Cognition, as understood in the Santiago theory, is associated with all levels of life and is thus a much broader phenomenon than consciousness. Consciousness — that is, conscious, lived experience — unfolds at certain levels of cognitive complexity that require a brain and a higher nervous system. In other words, consciousness is a special kind of cognitive process that emerges when cognition reaches a certain level of complexity. The central characteristic of this special cognitive process is self-awareness — to be aware not only of one's environment but also of oneself. In our book, we review several recent theories of consciousness in some detail.

Our discussion includes the spiritual dimension of consciousness. We find that the essence of spiritual experience is fully consistent with the systems view of life. When we look at the world around us — within the context of science or of spiritual practice — we find that we are not thrown into chaos and randomness but are part of a great order, a grand symphony of life. We share not only life's molecules, but also its basic principles of organization with the rest of the living world. Indeed, we belong to the universe, and this experience of belonging can make our lives profoundly meaningful.

In the last part of our book, titled "Sustaining the Web of Life," we discuss the critical importance of the systems view of life for dealing with the problems of our multi-faceted global crisis. It is now becoming more and more evident that the major problems of our time — energy, environment, climate change, poverty — cannot be understood in isolation. They are systemic problems, which means that they are all interconnected and interdependent, and require corresponding systemic solutions.

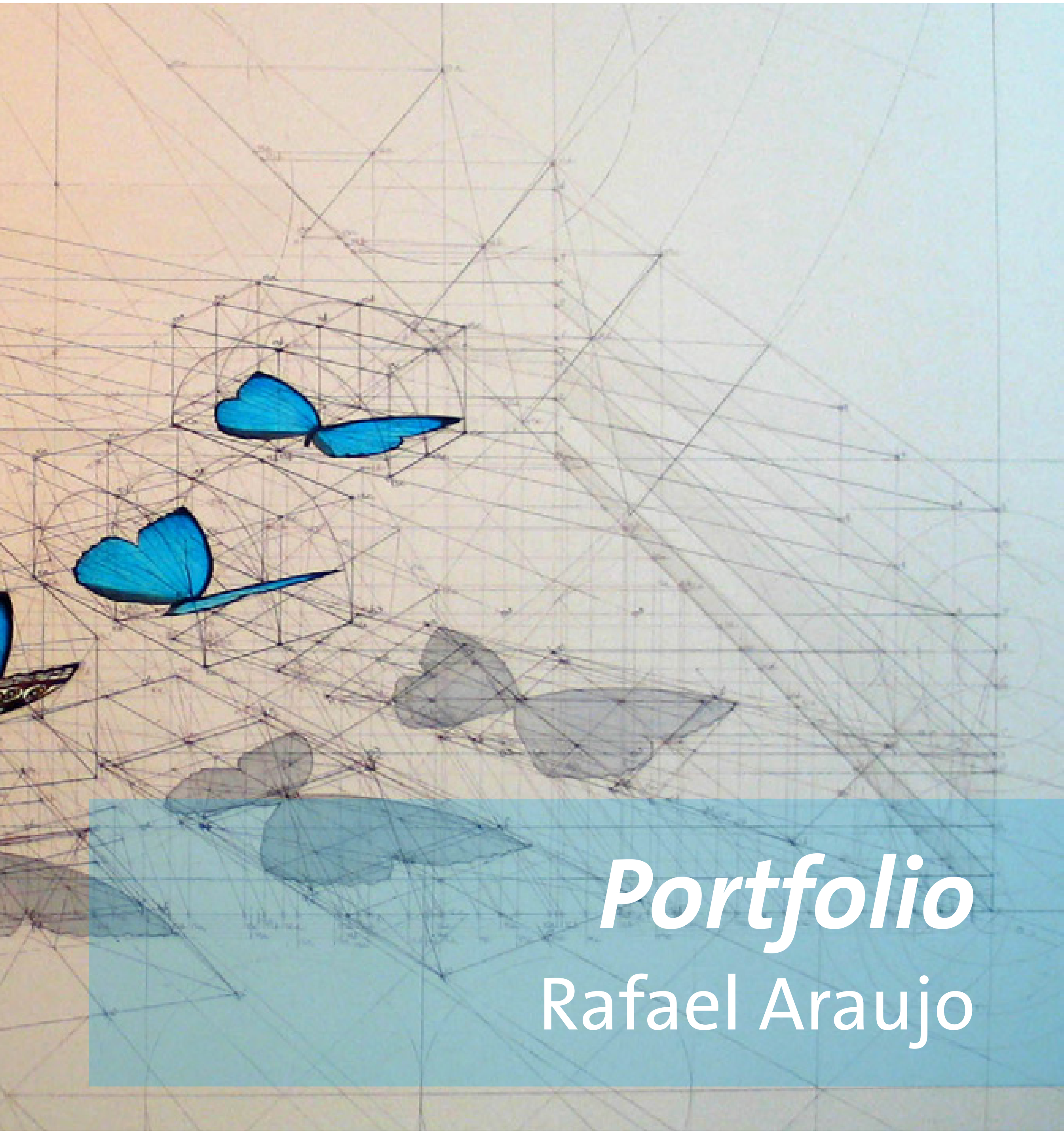
We review a variety of already existing solutions, based on systems thinking and the principles of ecodesign. In particular, we discuss three different but mutually compatible strategies for designing an economy without any fossil fuels, and for achieving this goal by 2050. The three strategies are "Plan B" by Lester Brown, "Reinventing Fire" by Amory Lovins, and "The Third Industrial Revolution" by Jeremy Rifkin. These three roadmaps for going beyond fossil fuels all involve systemic, or ecodesign solutions, which means that they solve not only the urgent problem of climate change, but also many of our other global problems — degradation of the environment, food insecurity, poverty, unemployment, and others.

Together these systemic solutions present compelling evidence that the systemic understanding of life has given us the knowledge and the technologies to build a sustainable future. What we need is political will and leadership. ×



Copia de Morpho

Rafael Araujo



Portfolio
Rafael Araujo

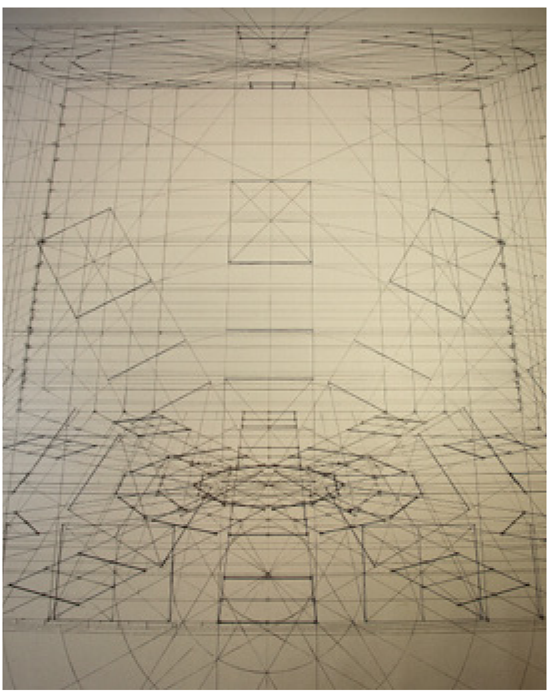
Author:
Rafael Araujo

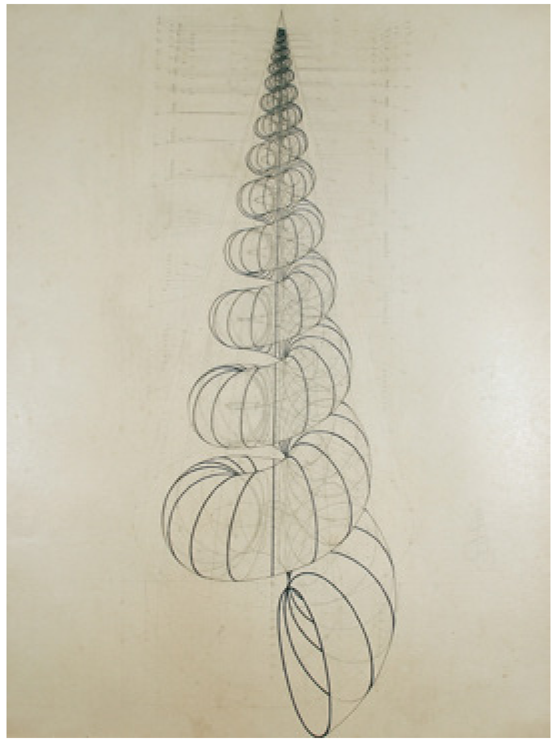
Artist Rafael Araujo's studied Arquitectura at the Universidad Simón Bolivar, in Caracas, Venezuela.

More of his work can be found here: https://www.rafael-araujo.com

Could you tell us about your background and how you got started with the calculation series?

I have been drawing since my childhood, adding perspective into my works intuitively. Someone told me about using a horizon and vanishing points, just to help lines to fit in the proper 3D illusion, which perspective is. Nothing too complicated, just a simple means to improve things.





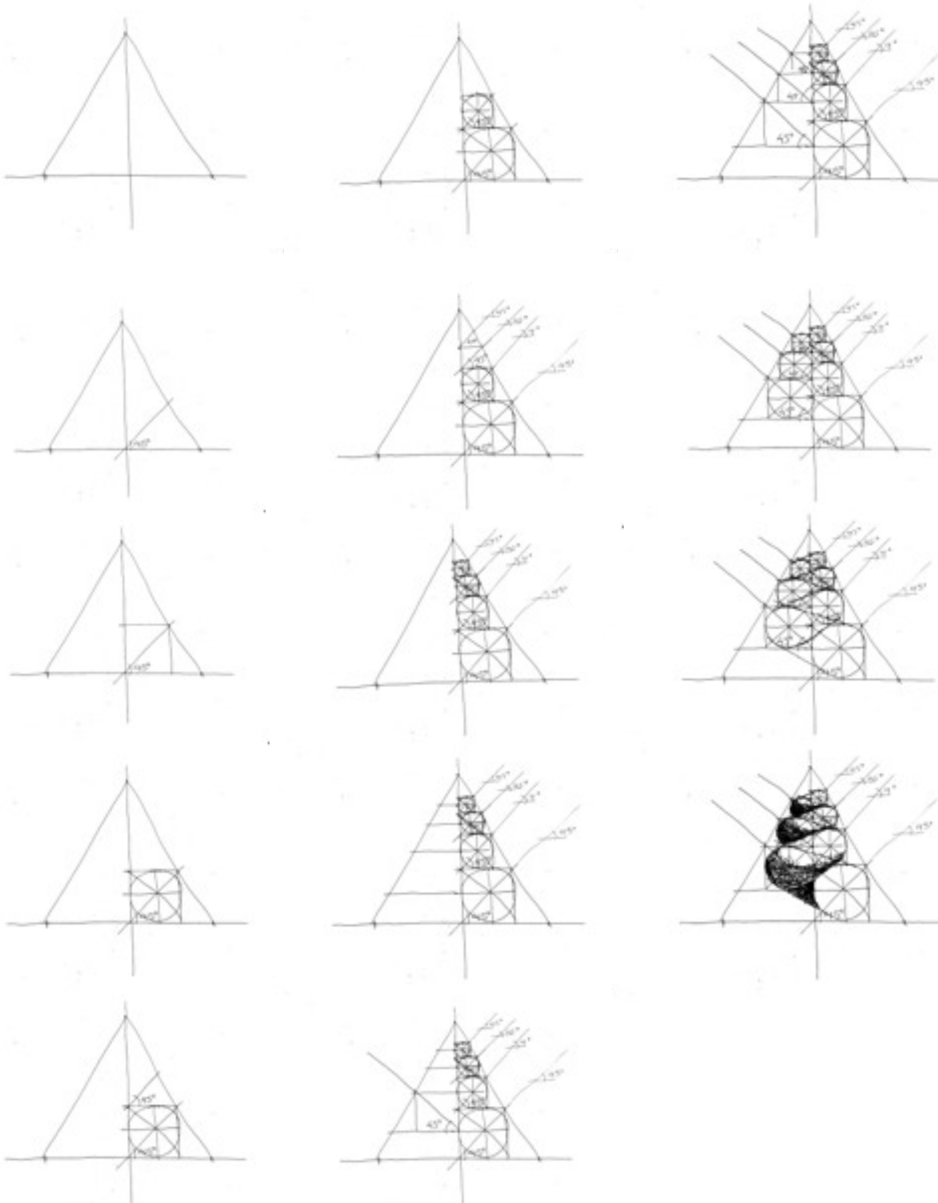
In my teens, the work of MC Escher triggered the need to see beyond, to seek further; it is then that I felt the need for many more tools, geometric tools, to plunge into the calculating world of 3D perspective geometry. After this intensive study of methods of measurements in perspective, which I didn't know before, a whole world of possibilities opened in front of me. I began to construct all sorts of curved tubes, ending with a state of the art approach to develop all kinds of shells, which are tubes coiled up into a cone in a certain particular and regular way.

Calculation phase

Rafael Araujo

Finished shell

Rafael Araujo

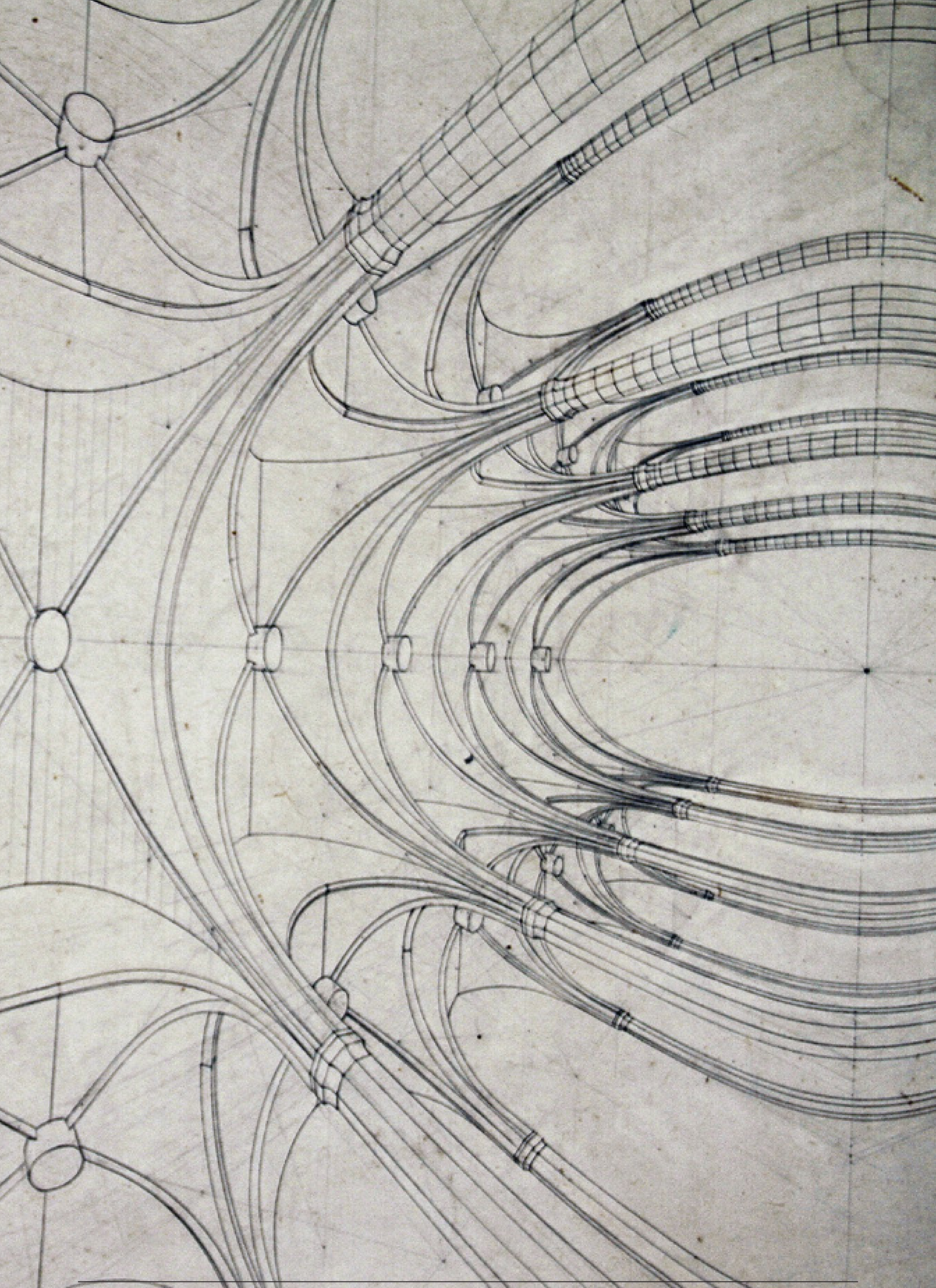


Development of shell

Rafael Araujo

Early calculation

Rafael Araujo



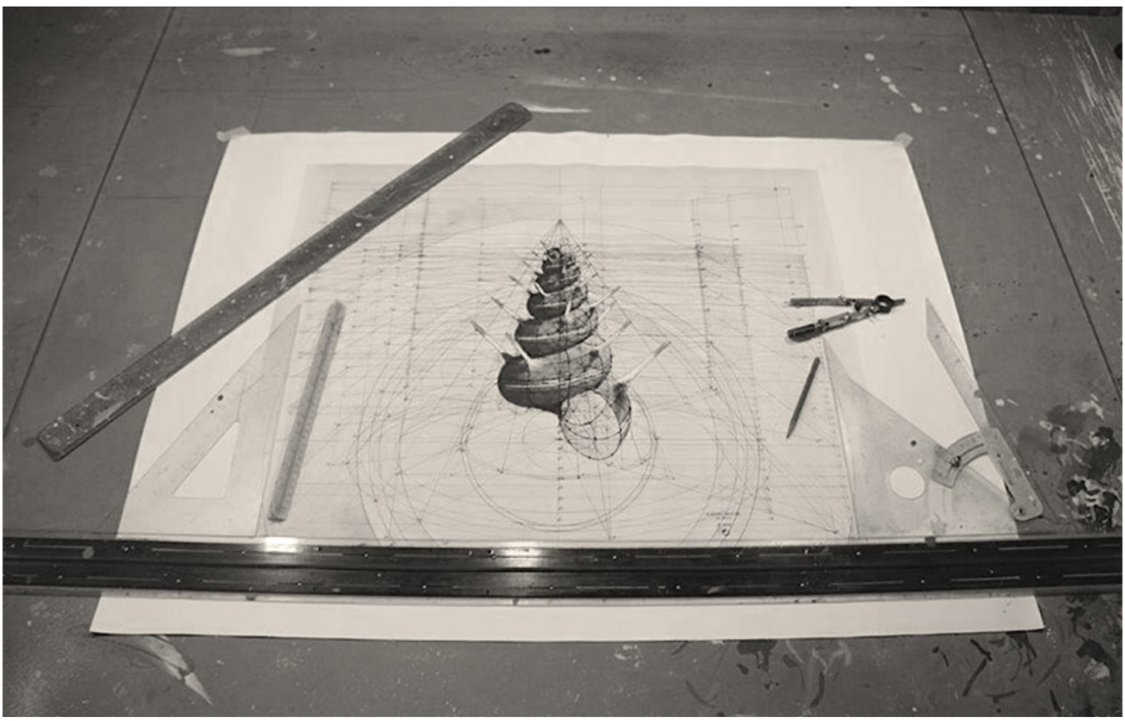
With this newly discovered method it was also possible to develop several 3D constructions as helices of different kinds and shapes.

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

I don't use any Computer Aided Design (CAD) tools at all. I use the old ways of architects, but instead of paper I use canvas.

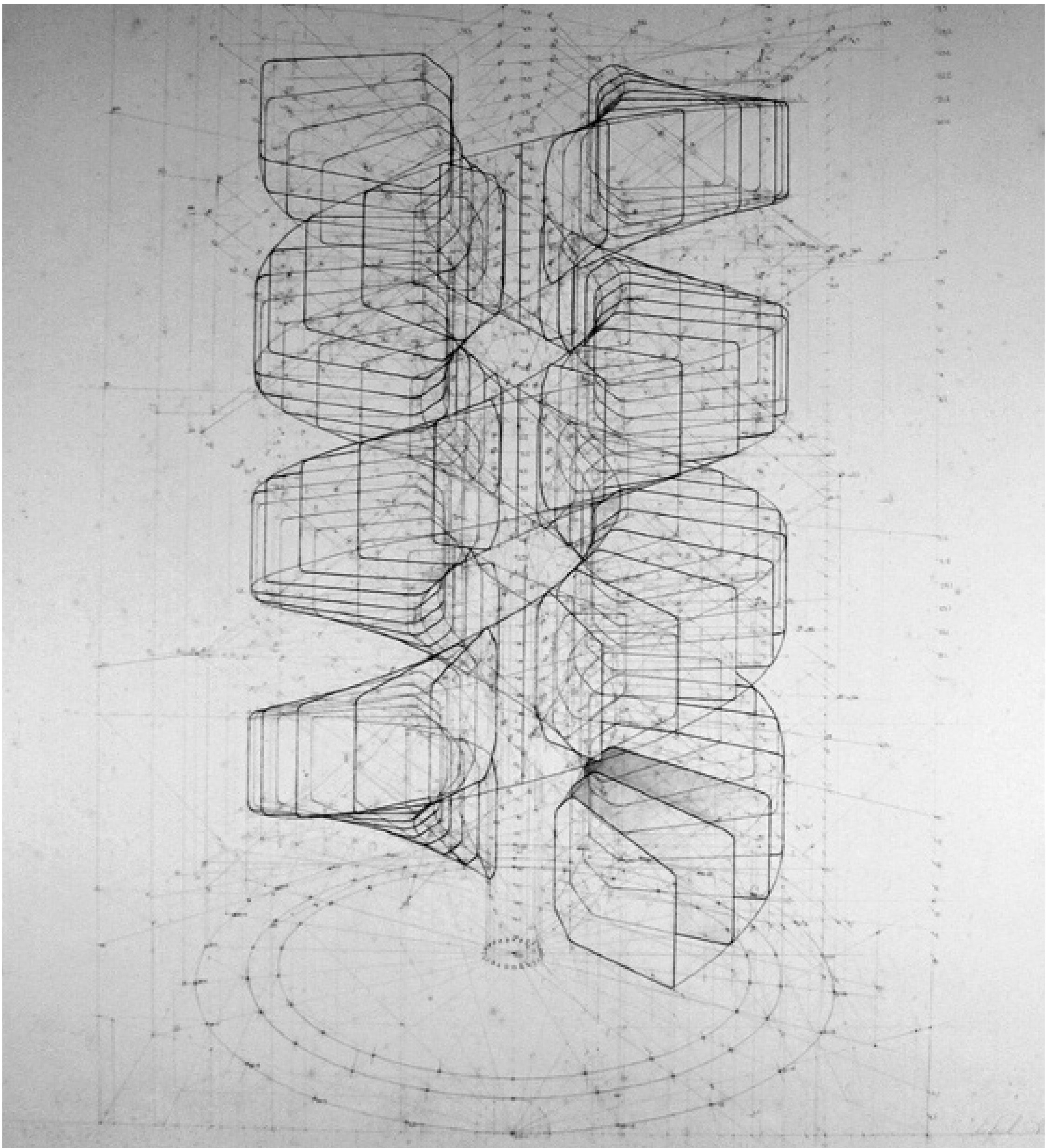
Your work shows a careful geometric construction for an artful result. Can you write specifically about how you much you use geometry and mathematics to make these constructions?

When working with complex problems such as casting the shadows of apparently random flying butterflies, I use a very rigid geometrical frame based on "Polar Geometry" (http://en.wikipedia.org/wiki/Polar_coordinate_system). I do not use much math at all, perhaps some "beautiful" logarithmic formulas when in the search of specific curves (spirals, mostly). But at the end all must be translated into polar geometry and then into a 3D perspective drawing.



The artist's drawing board

Rafael Araujo



Double helix

Rafael Araujo

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

I began with lines, dots, curves and geometry. Lots of excitement but very limited knowledge or skills, and absolutely no color at all. Lack of craftsmanship was happily replaced with enthusiasm and as I became more knowledgeable, good results began to appear. I also thought a lot about the subject of perspective itself.

Afterwards I began to explore color and I really learned to work with it by doing professional architectural rendering in the traditional way, with watercolors. From this point I made the jump to landscape painting where I became very adept and a pro in acrylic painting.

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

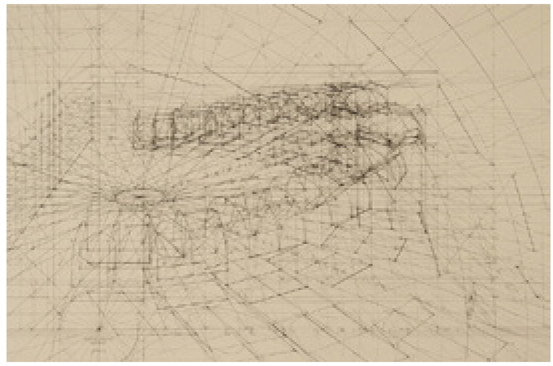
There I can't answer you. I have seen things this way – whichever way that is - always!

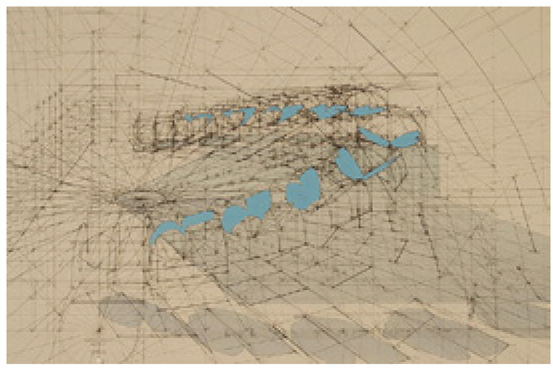
Who/what inspires you creatively? What do you 'feed' on the most?

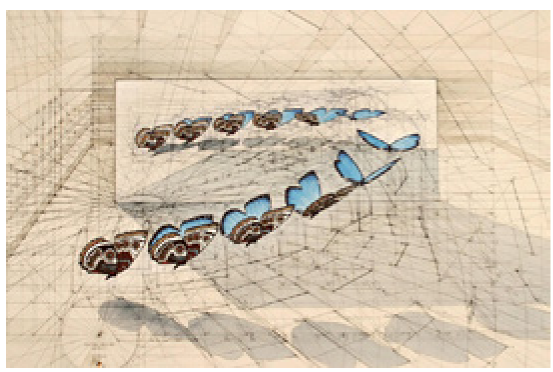
Nature. By far, nature. I also like music, more than any graphic or any other art. As for the music, I'm a baroque flute player myself (not the best), and love Bach over all things possible.

What influence do you think your art has on the viewer? How do you hope to influence him or her?

Well, it's sort of presumptuous to hope you could influence other people with your work, but, if







Calculo Espejo Fia sequence

Rafael Araujo

so, I'd wish it to be in the much needed love and care for a very neglected environment, by showing some of its beauty in detail.

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

I do calculation and landscape at the same time. I'm doing a triple helix at the moment...it's very demanding work. Landscape is easier!

Is there a natural extension of your current work that you would like to pursue, say an animation, or three-dimensional version, or other iteration or subject?

I just want to do what I already have been doing, and do it well ...there is not enough time in a single life to achieve the dream of perfection.

What is the last book you enjoyed?

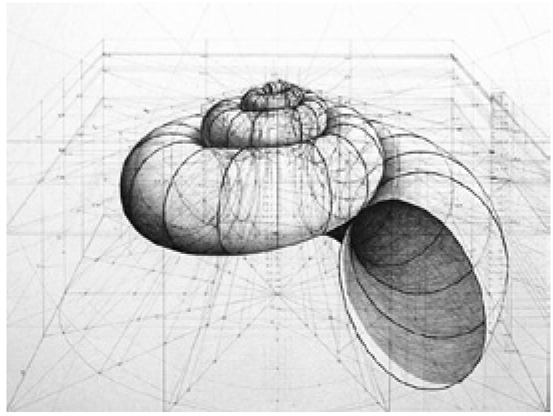
I've been reading Winston Churchill's history *The Second World War* ...most interesting and detailed, and quite well written (won a Nobel Prize in 1953).

What are your favorite 3-5 websites?

Amazon's bookstore, Wired, Colossal and my not very interesting local paper's websites (I live in Venezuela).

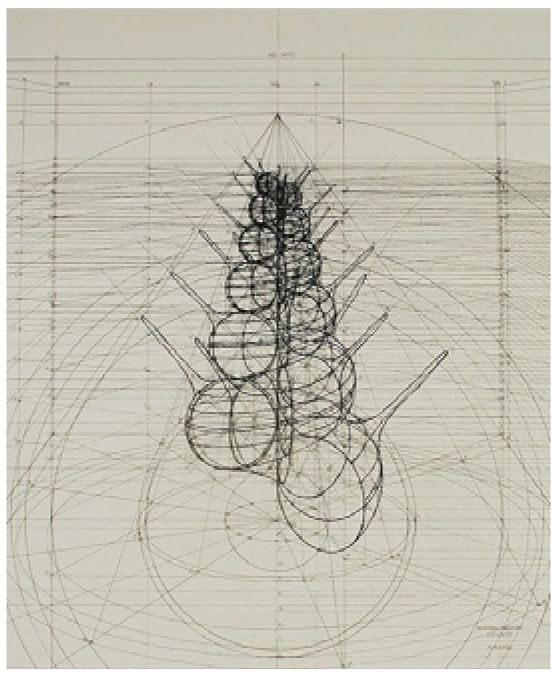
What's your favorite motto or quotation?

Sic transit Gloria mundi. ×



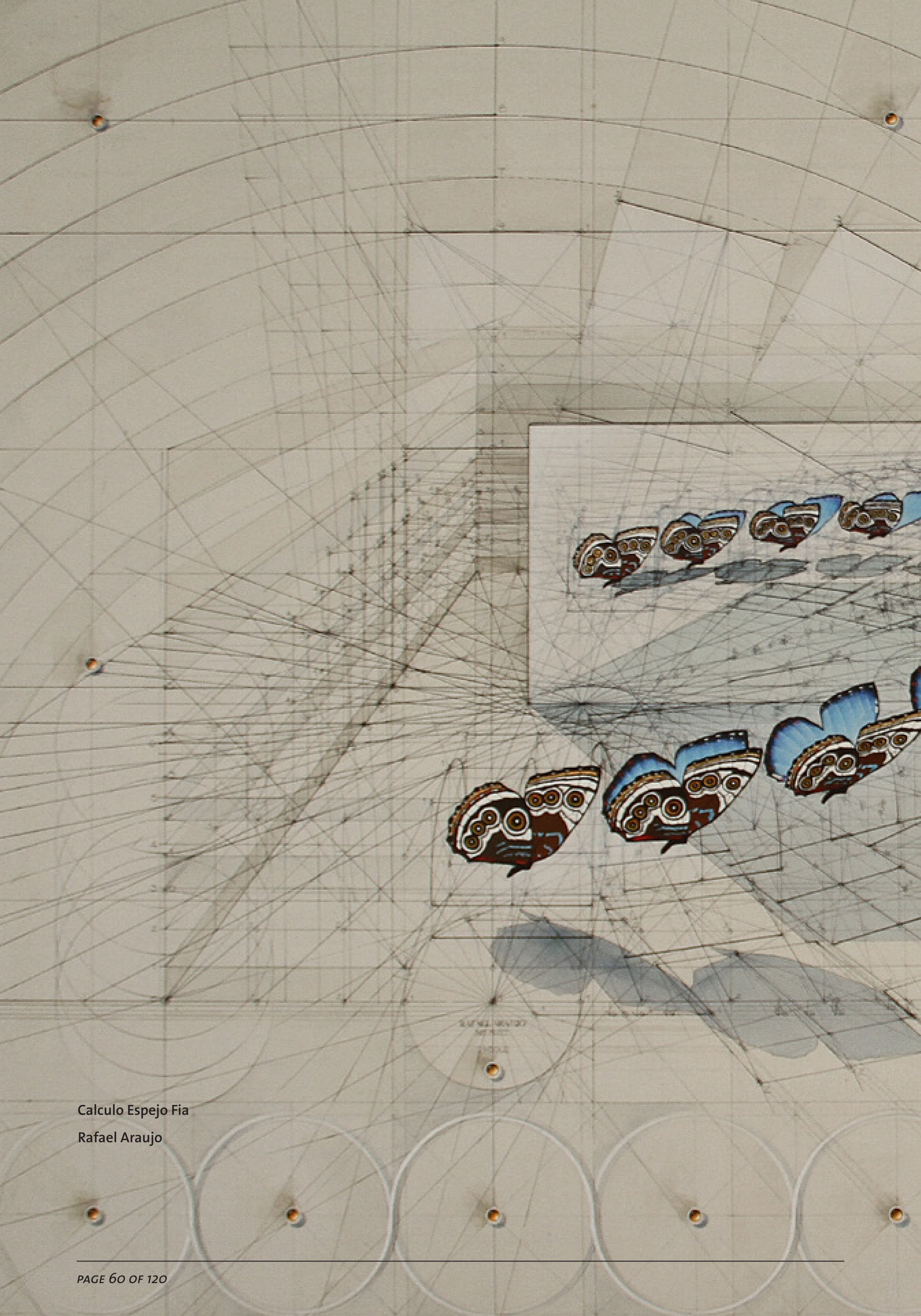
Calculo

Rafael Araujo



Caracol con azules in progress

Rafael Araujo



Calculo Espejo Fia

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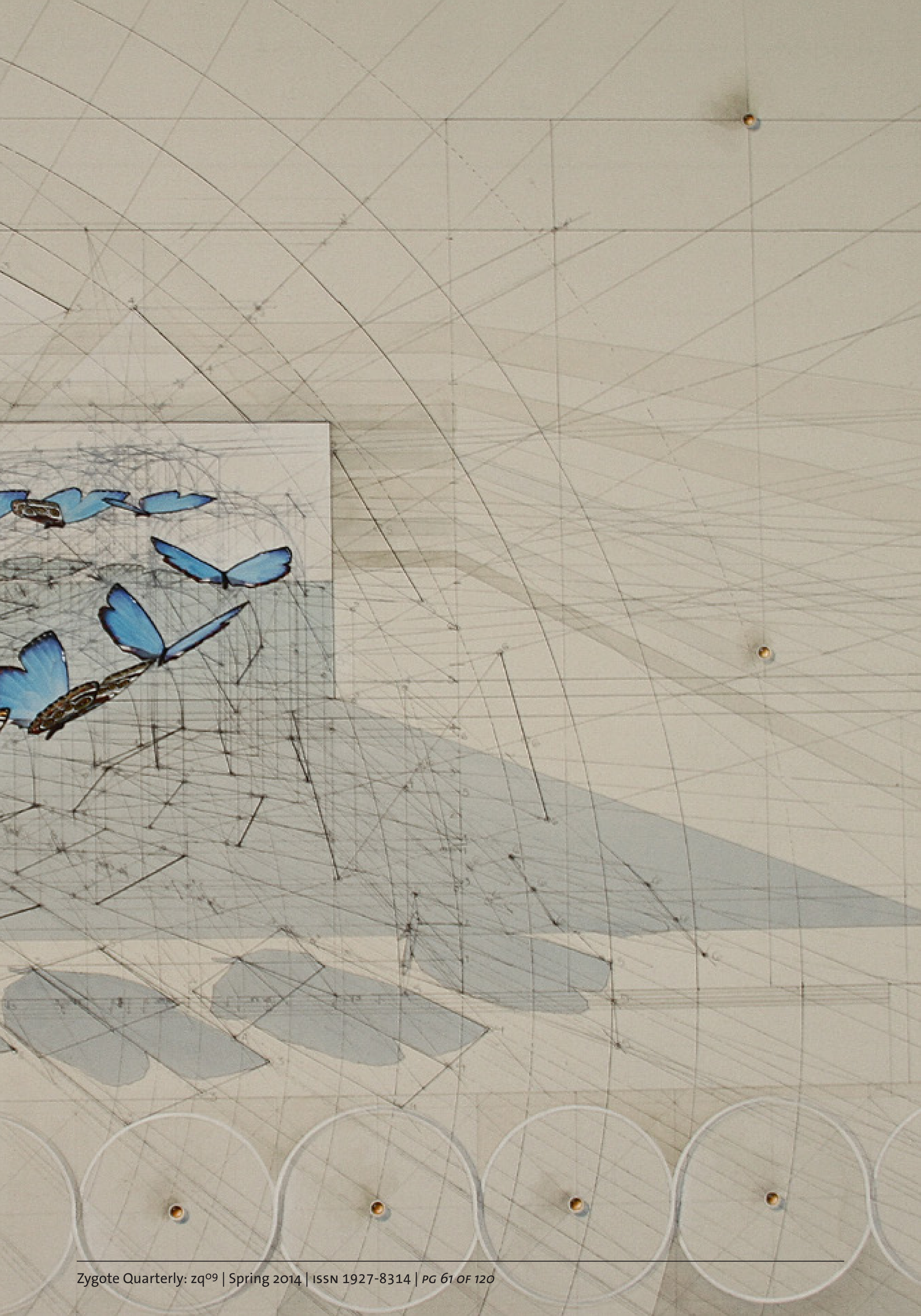
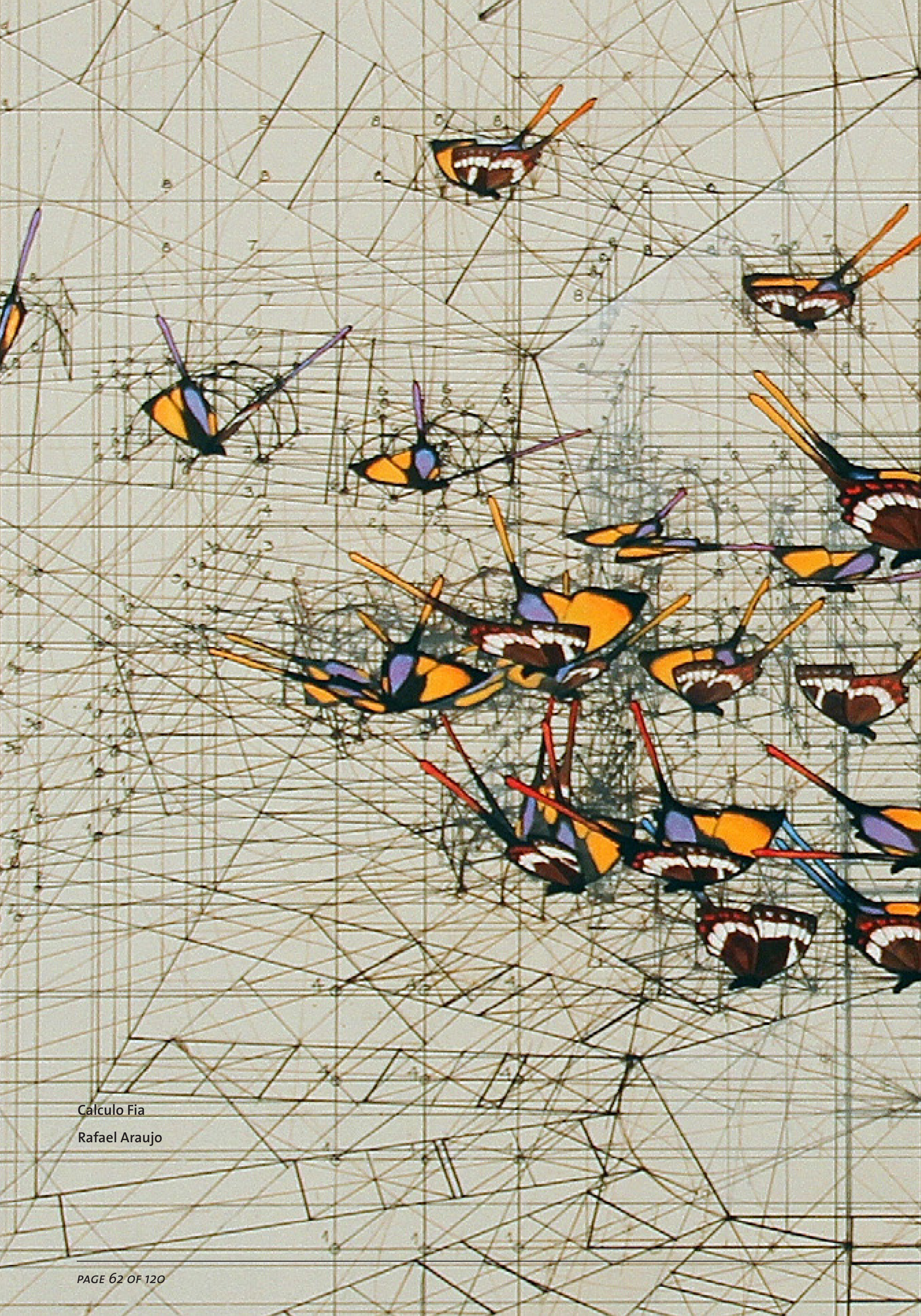
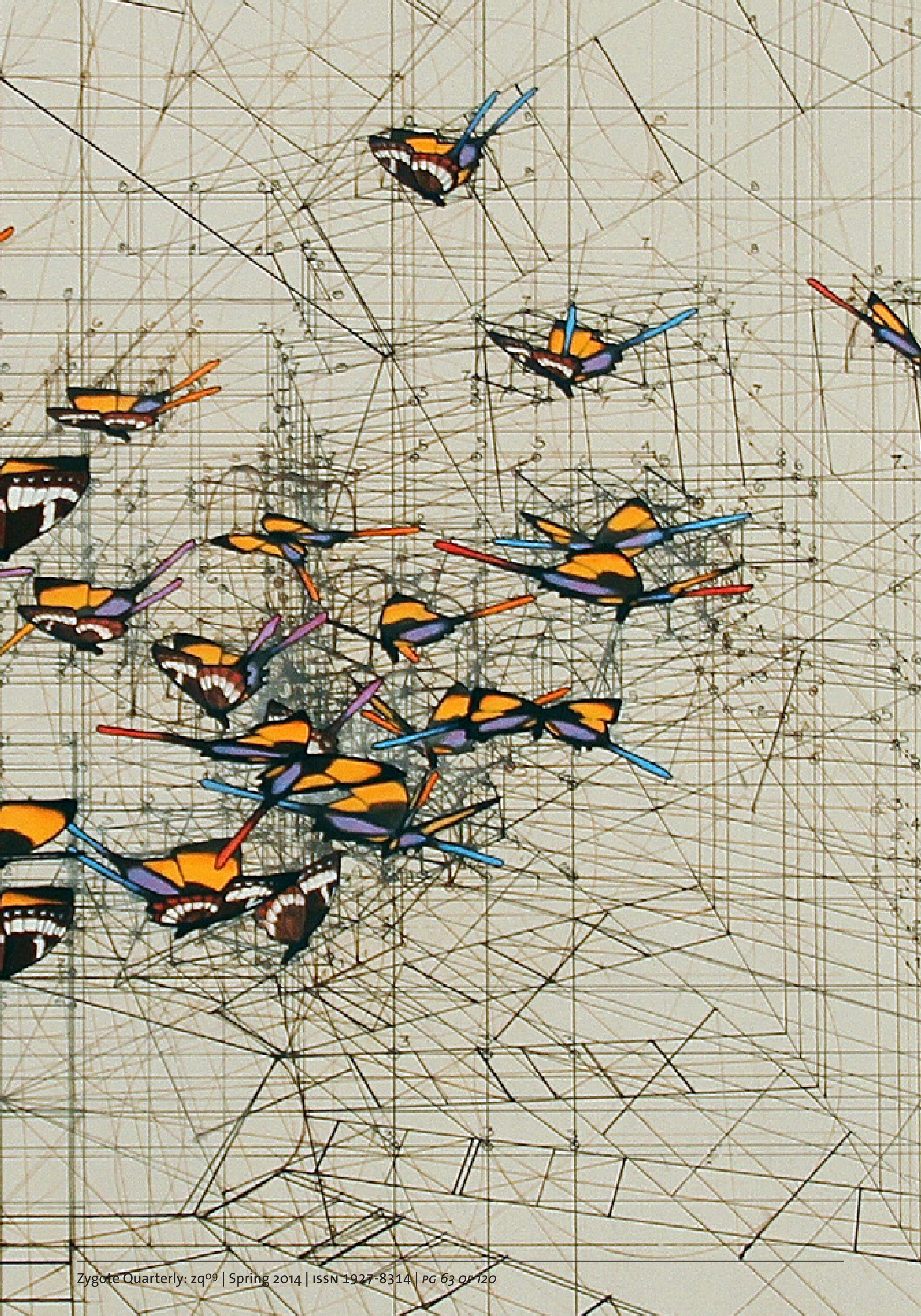
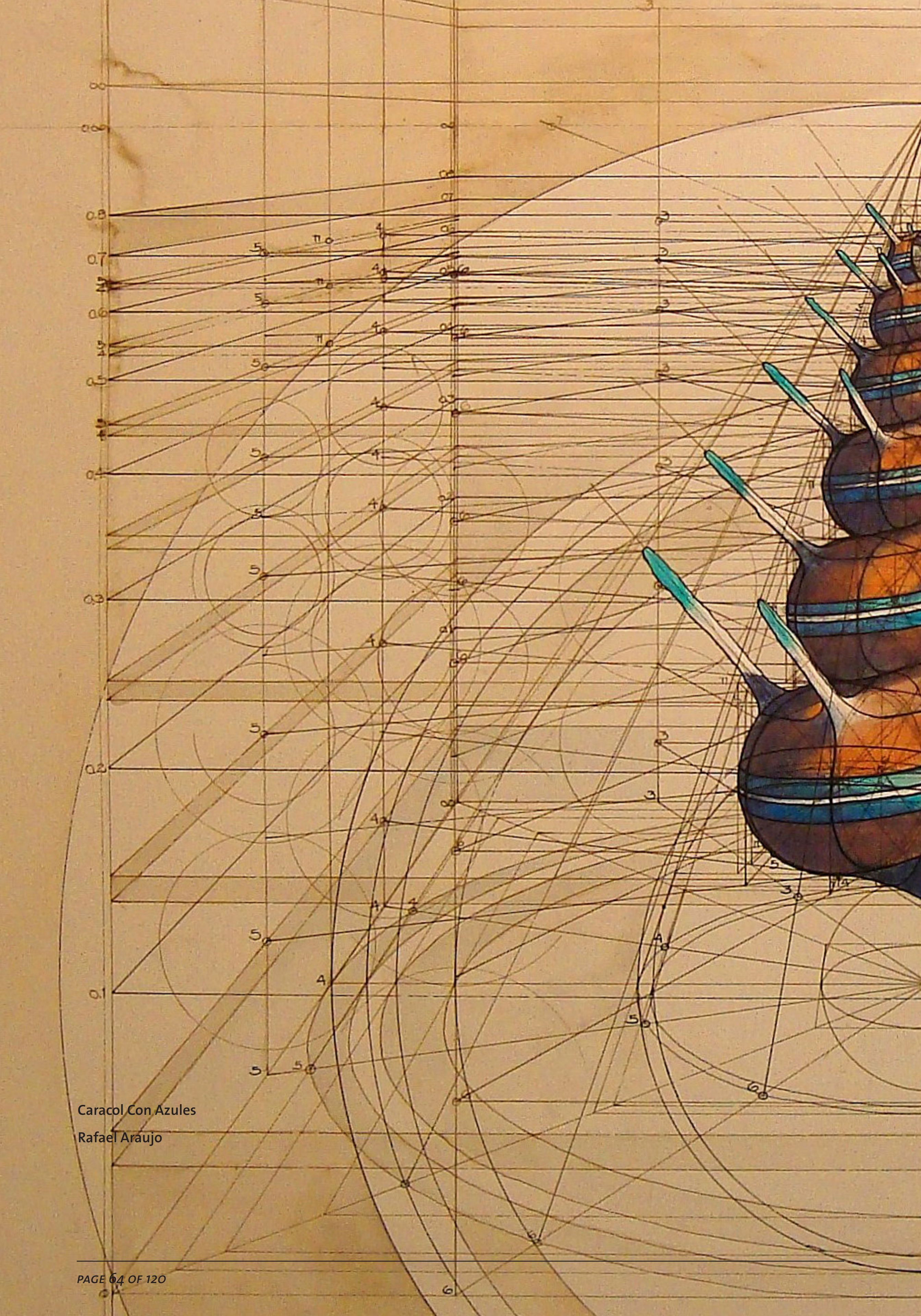




Calculo Fia

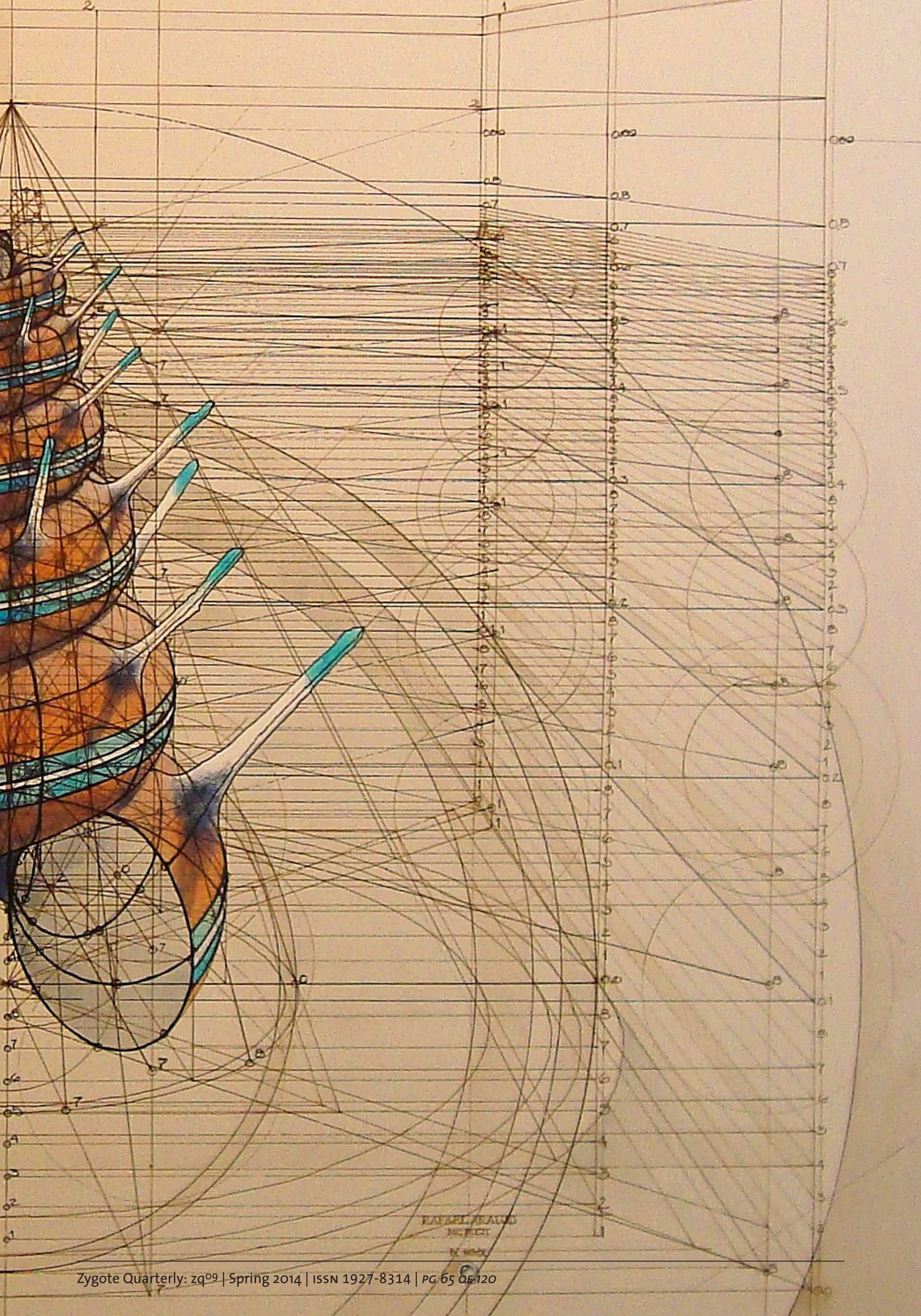
Rafael Araujo

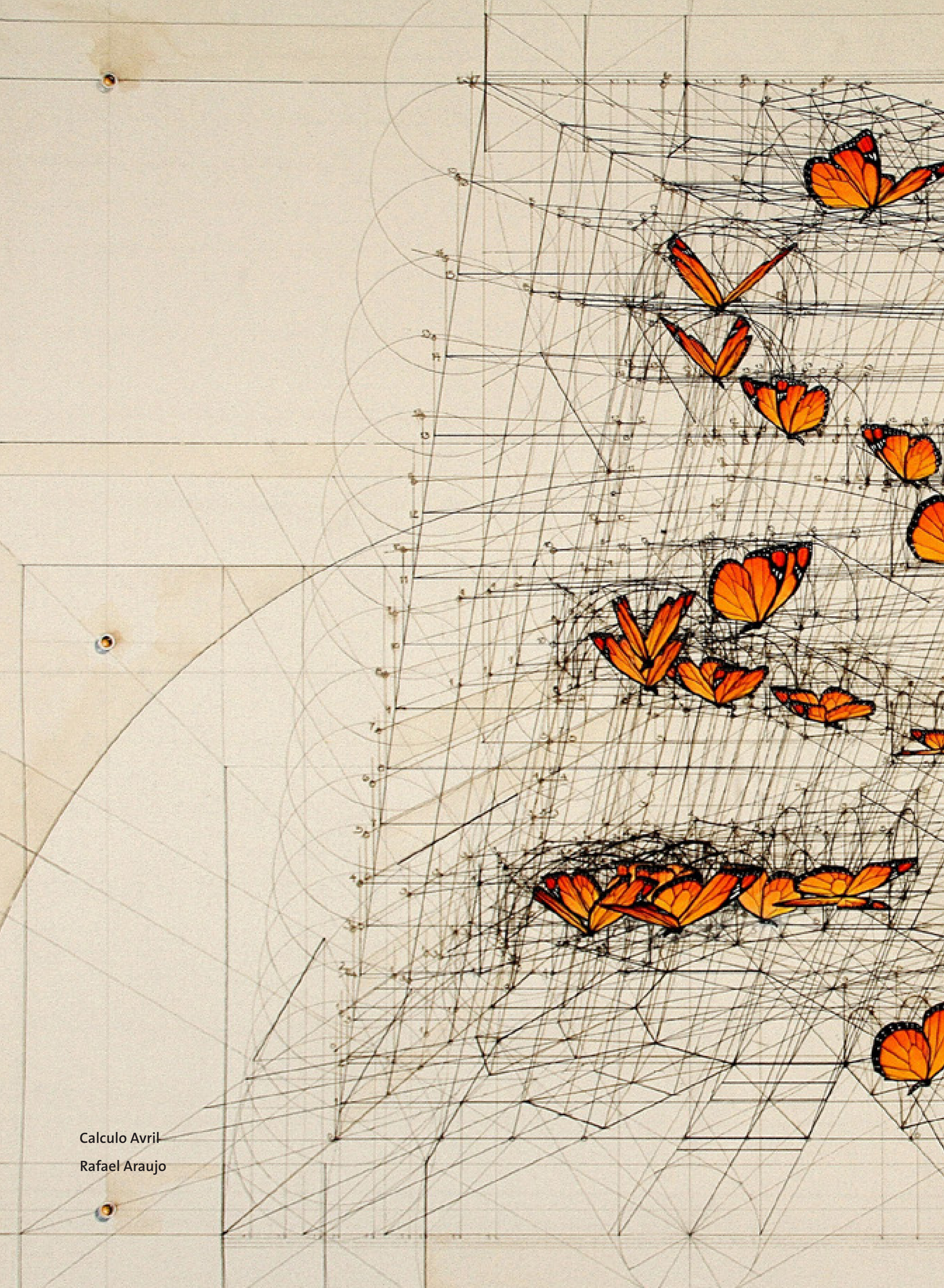




Caracol Con Azules

Rafael Araujo





Calculo Avril
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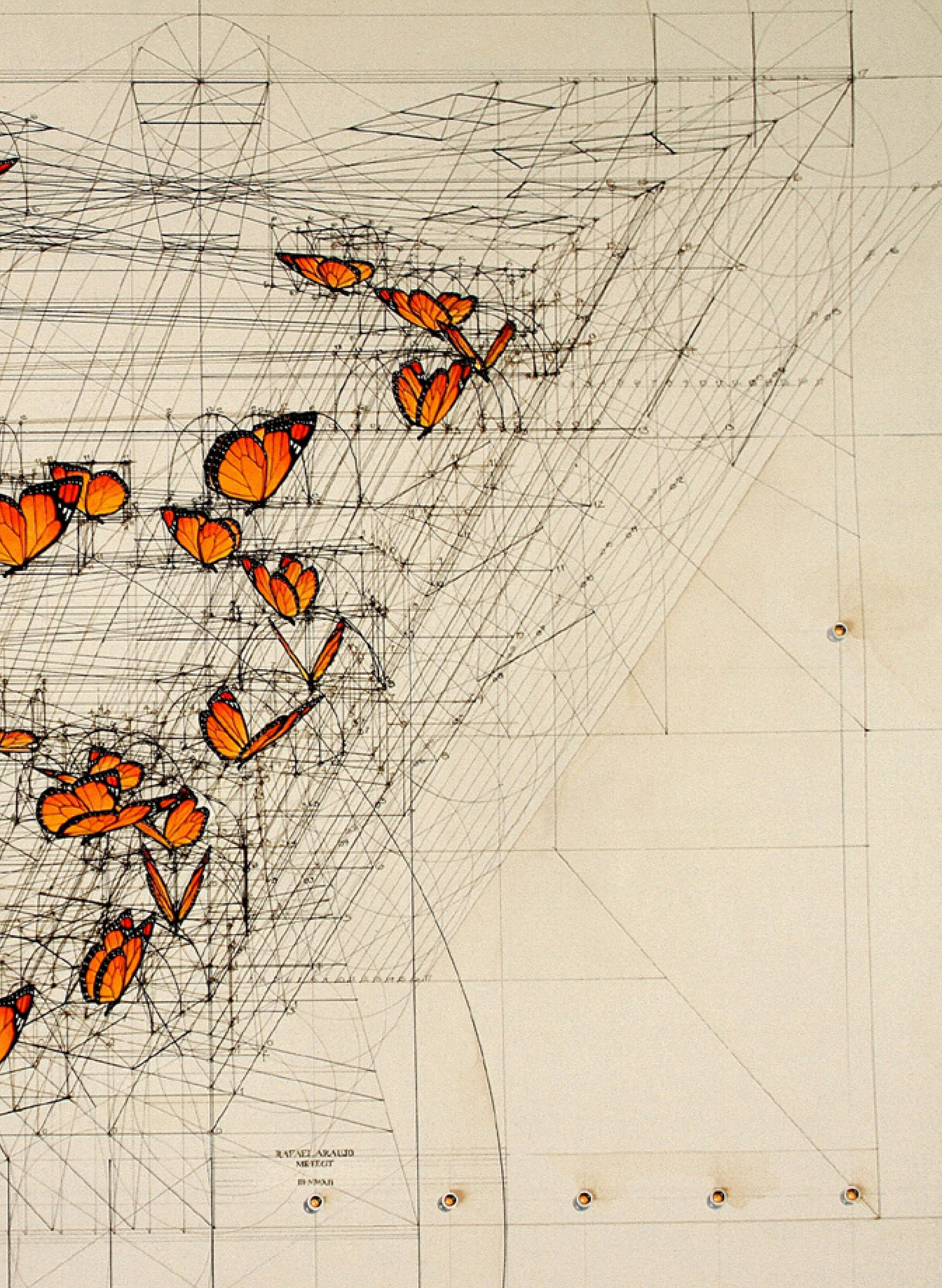
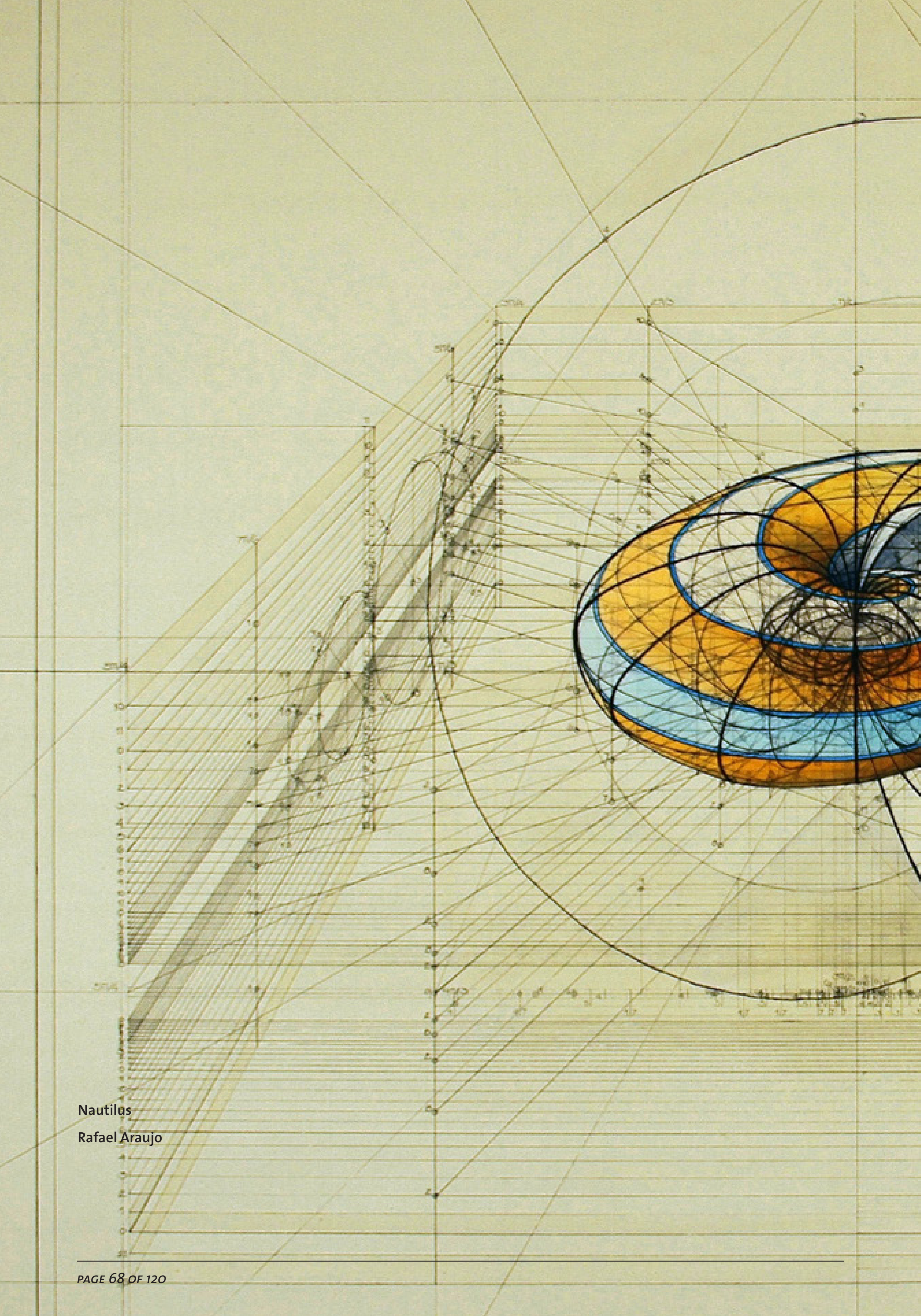
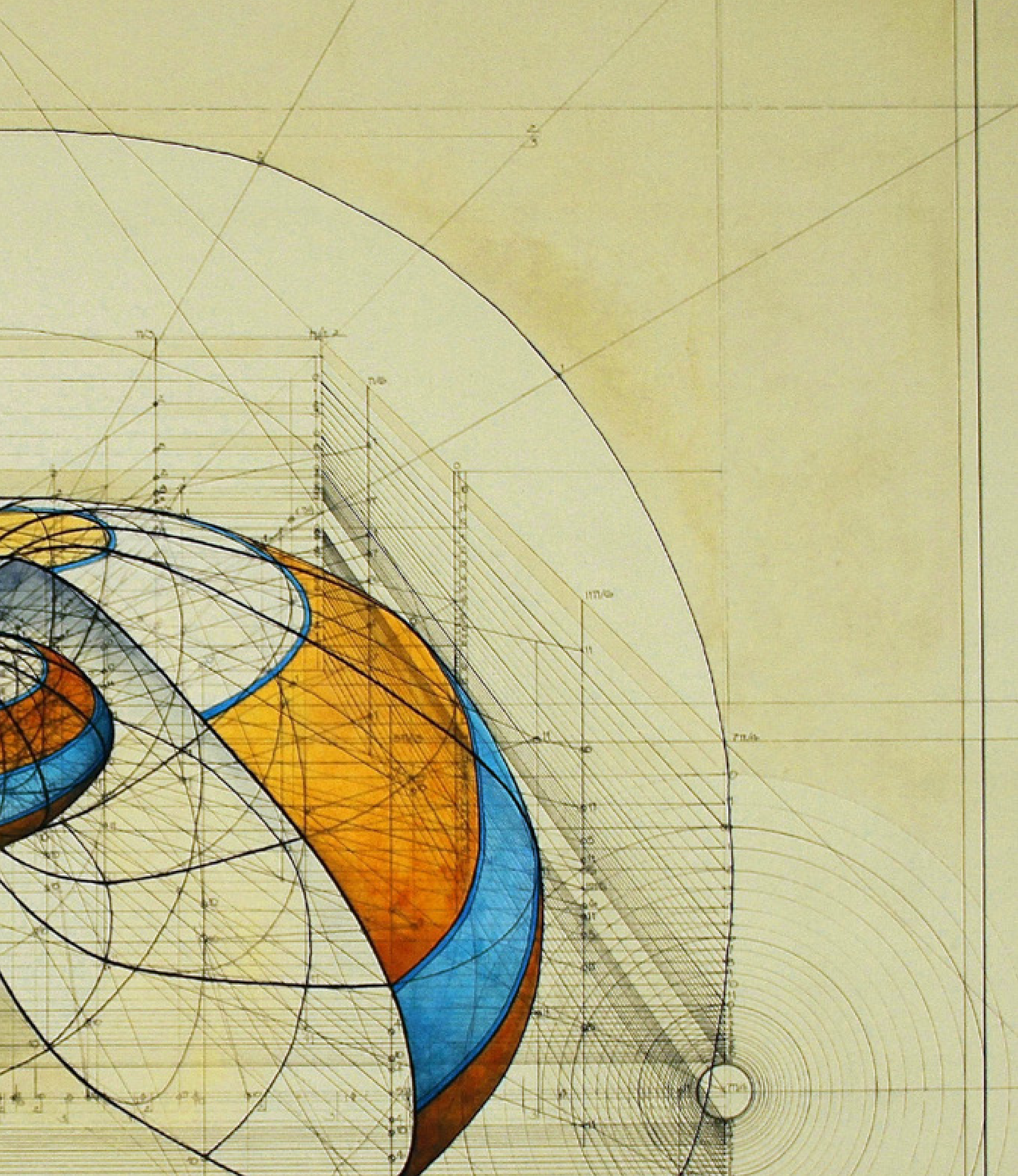
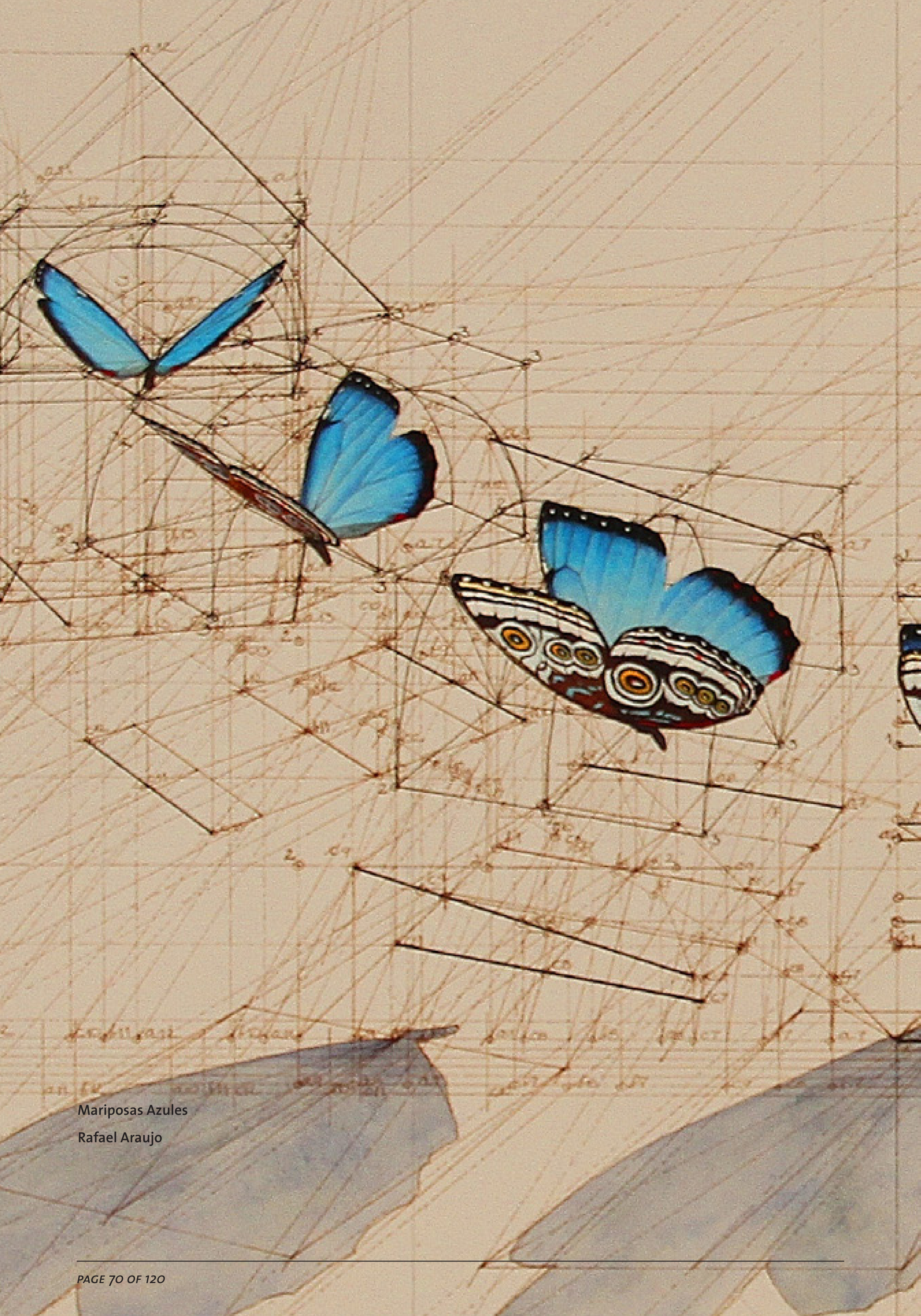




Nautilus

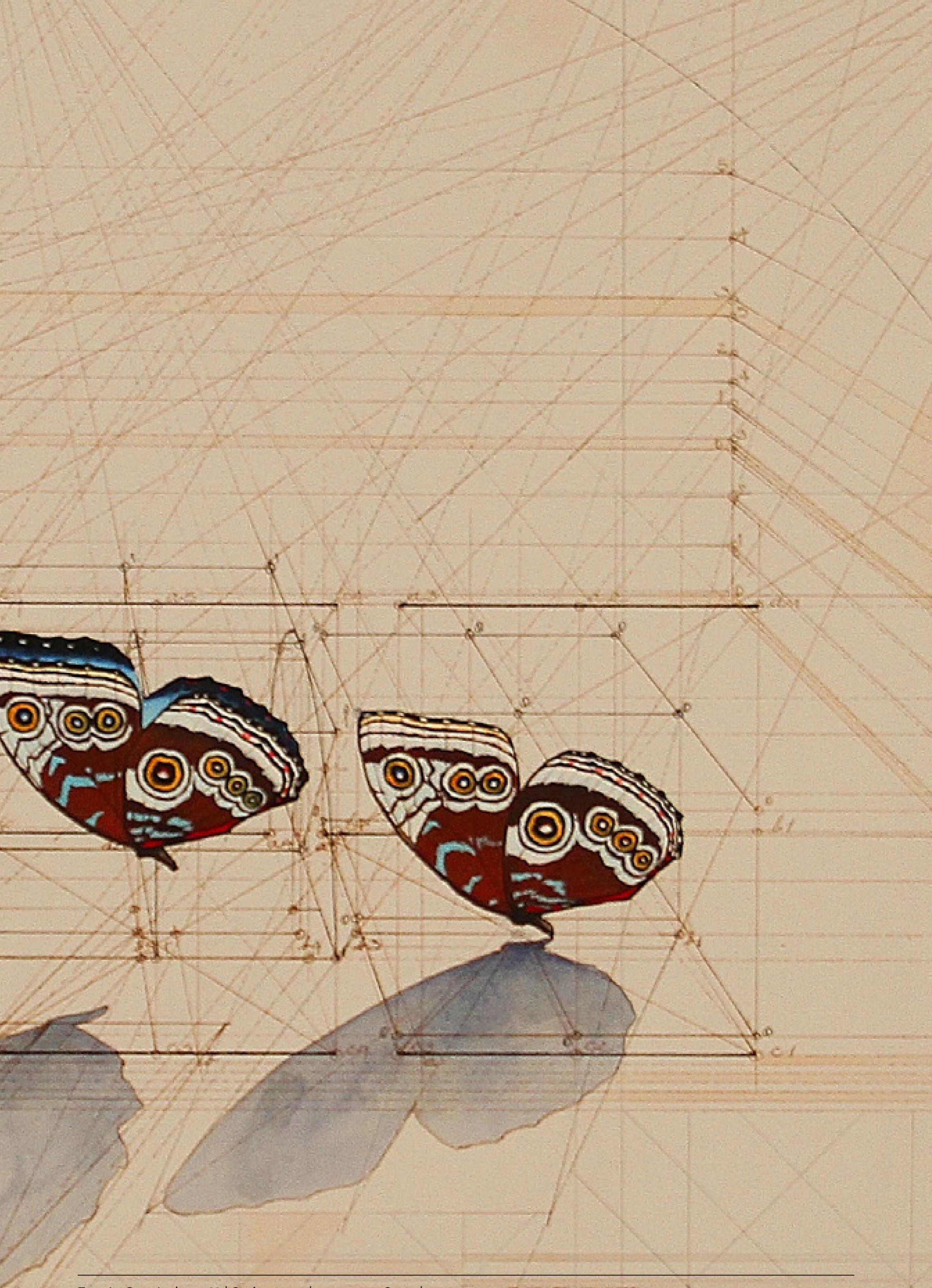
Rafael Araujo





Mariposas Azules

Rafael Araujo


RAFAEL ARAUJO
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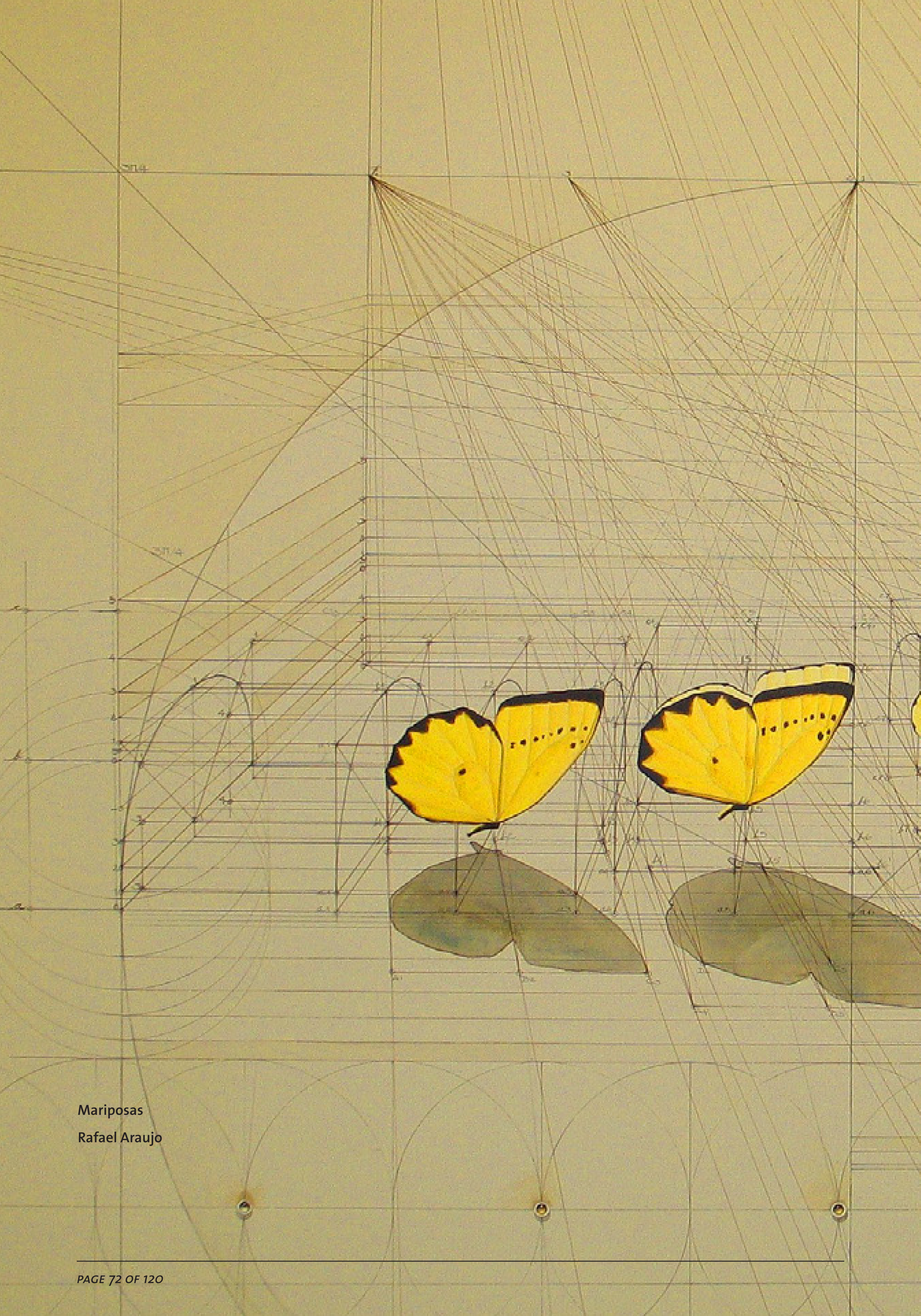
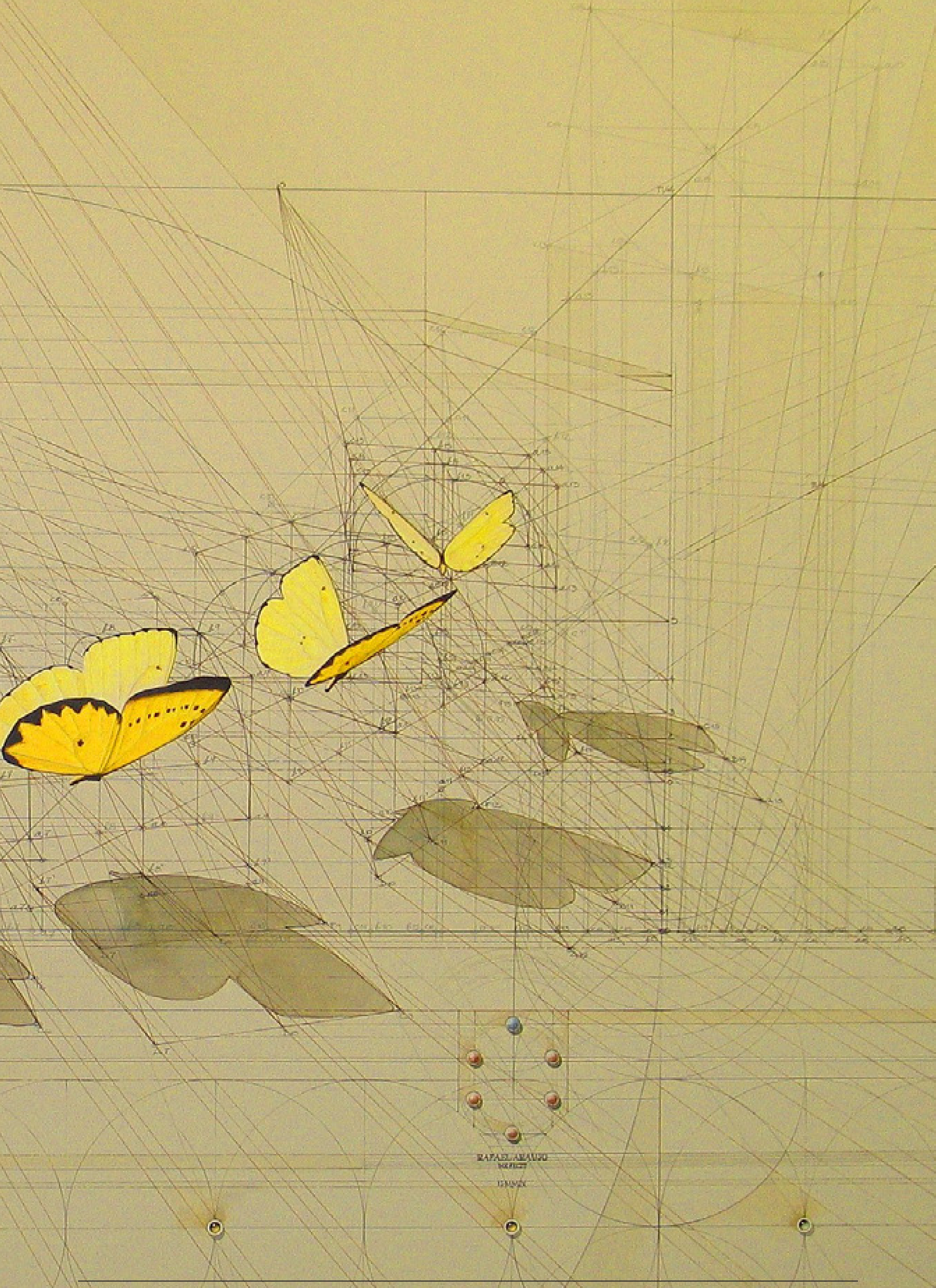


Mariposas

Rafael Araujo



Paper Kite

Photo: Vicki's Nature, 2011 | Wikimedia Commons

People
Interview with
Randy Olson and Brian Palermo

Sleeping Snow Monkeys

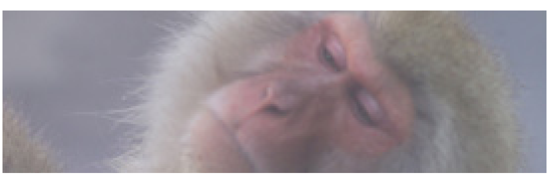
Photo: Stuck in Customs, 2010 | Flickr cc

Interview

Randy Olson and Brian Palermo

Randy Olson is the writer/director of the feature films *Flock of Dodos: The Evolution–Intelligent Design Circus*, (Tribeca '06, Showtime '07), *Sizzle: A Global Warming Comedy* (Outfest '08), the author of *Don't Be Such a Scientist: Talking Substance in an Age of Style* (Island Press '09) and *Connection: Hollywood Storytelling Meets Critical Thinking* with Dorie Barton and Brian Palermo (2013). His work focuses on the challenges involved in communicating science to the general public and the current attacks on mainstream science in fields such as evolution and climate science. He is a former marine biologist (Ph.D. Harvard University) who achieved tenure at the University of New Hampshire before changing careers to filmmaking by obtaining an M.F.A. in Cinema from the University of Southern California. He is an adjunct faculty member with the Wrigley Institute for Environmental Studies at USC. His production company, Prairie Starfish Productions, is based at Raleigh Studios in Los Angeles.

Brian Palermo is an actor with a wide range of performances in television, film, and top comedy venues. Palermo graduated from the University of New Orleans with a Bachelor of Arts degree in Communications. He has been a performer, director, and teacher with The Groundlings, Los Angeles' premiere comedy theatre for over 15 years. On the other side of the camera, Palermo was a staff writer on the animated series *Histeria!* for Warner Bros. and has written scripts for Disney's *The Weekenders* and *Dave the Barbarian*. He's also written and produced promotional commercials for Fox and The Disney Channel, among others.



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

Randy: I would start with the word "inspired" – I think that's at the core of the entire subject. Whether humans can replicate the design of plants and animals or are simply "inspired" by it, the whole concept has great communications potential because it produces so many great stories, and the one thing we know about communication is that great stories are communications gold.

Brian: YES, people think in story. My first thought at hearing "biomimicry" is that it didn't work for Icarus. Granted, that's a pretty glib joke, but why would anyone (including me) remember Icarus? Because it was a story well told. I find the whole bio-inspired design (BID) idea fascinating, in part because of the interdisciplinary nature of it. In this, BID mirrors improv, where we teach you to listen intently to your partner and build from their ideas. In biomimicry, your partners are nature's lifeforms. And although Nature has a long track record, it hasn't had to deal with humans until very recently. In order to increase the likelihood of mutually beneficial outcomes, it may be worthwhile looking for inspiration within the context of the past and current relationship of humans and nature, identifying opportunities that would help this relationship evolve to a more healthy and vibrant state.

What do you see as the biggest challenges?

Brian: The biggest challenge has to be the actual work of design and implementation. I have nothing to add on that point. But another challenge may be funding and there maybe I can

Japanese Macaque

Photo: Fg2, 2006 | Flickr cc

offer something. To win over investors or get grants you have to capture the attention, minds and hearts of your audience - whether they are the public at large or one person who can fund your work.

The challenge here is to keep your story *relatable*. Your average listener will tune out if you get too deep into what I call your “Splendid Esoteric Obscurity” - that one thing that absolutely thrills you to death at just the thought of it, and yet ... leaves most people saying, “Um ... yeah ... whatever excites you, I guess.”

But if you keep it relatable to what the audience can understand as beneficial, you’ll win them over. An example is the Sharklet innovation that helps prevent bacteria from getting a hold on surfaces in hospitals. That’s insanely amazing. And because the incidence of infections in hospitals is so high, many people will relate.

Randy: Similarly, I see the greatest challenge to be the need to find the “narrative thread” of whatever you’re presenting to the world. The geneticist and evolutionary biologist Theodosius Dobzhansky wrote an essay in 1963 titled “Nothing in Biology Makes Sense Except in the Light of Evolution” where he identified evolution as the narrative thread (basically “the story”) of biology in general. Without that thread – with that “light” as he termed it – all you have is “a pile of sundry facts, some of which might be interesting or curious, but ultimately fail to paint a meaningful picture.” He was an amazing scientist and that was an amazing quote.

And it leaves you with the question of what is the narrative thread of biologically inspired design? I’ll let you ponder that question and offer up his sentence as a tool, which is your template with which to find the narrative. See if you can fill in the blank to this sentence, “Nothing in Biologically Inspired Design makes sense, except in the light of ___________”. What goes in that blank? That’s for you to solve. If you can figure out what goes in the blank, that is your narrative for telling the story of biologically inspired design.

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

Brian: Effectively communicating success stories: it is essential to pick examples that people can relate to. Sports works for some. Science fiction, although looked down upon by the scientific community, can also be a useful bridge.

Randy: I’d say work on the stories in general. The heart of a good story is the source of tension or conflict. In human drama, it’s usually matters of love, life or death. But for science, the tension can come simply from well crafted questions. That’s where you want to focus your energy – on what the questions are that fire people’s minds up so powerfully that they won’t let you walk away until you answer the question. Biologically inspired design is filled with these questions. The best ones begin with something like, “How in the world do you think this animal manages to ...?” Just like so many “who dunnit?” murder mysteries, great questions are at the core of great stories, and that is what leads to great communication.

Brian: Another dimension of effective communication is the endless challenge of making your material “relatable” to your

Human expression

Photo: Claudio Gennari, 2009 | Flickr cc

Hold Me Tight | Photo: San Diego Shooter, 2009 | Flickr cc

audience. If you want to explain ocean acidification to a teenager in Kansas who has never seen the ocean, you need to find a way to make a meaningful connection, which may involve fish sticks. You must always be asking yourself about this: “Am I sure that my audience can even relate to what I’m talking about?”

How have you developed your interest in transferring knowledge between biology and other disciplines?

Randy: As a scientist I was trained to have an endlessly skeptical thought process. I tend to bring this same thinking to communication. This leaves me skeptical at times of the idea of incorporating Arts in the new STEAM (Science, Technology, Engineering, Arts and Mathematics) curriculum. People like to talk about this as though it’s as simple as pulling together a group representing these various disciplines, feeding them some cookies and tea, then watching them “cross pollinate”. It ain’t.

For years I’ve watched well–intended events in Hollywood where they try to pull together the best scientists with the best filmmakers, hoping for the same sort of mixing of great ideas. But most of the time you show up at the event and there’s the scientists on one side of the room talking amongst themselves, and there’s the filmmakers on the other side. This stuff is very, very difficult. It’s different cultures and tribes you’re talking about. I knew it would be tough when I headed into this challenge, but I’ve found it to be even tougher than I expected. Which is part of what makes it fun and rewarding when you’re able to overcome these divides.

How did you get started collaborating with Brian and Dorie?

Randy: That’s a great question and cuts to the heart of my overall approach to communication. After the publication in 2009 of my first book *Don’t Be Such a Scientist*, I was invited by many science institutions to run workshops on storytelling since that was my main recommendation in that book – “get better at narrative dynamics”. I knew I wanted to bring in more breadth of knowledge by recruiting a couple of co–instructors, and initially thought about inviting a couple of professors to join me – for example a professor of communication and a professor of theater. But I split communication into cerebral versus visceral elements. I already had a pretty good grasp on the cerebral side, which meant what I really needed help with was the visceral. That means finding people whose job is to actually make stories work in the real world – people whose entirely livelihood depends on their ability to be successful with stories. That is not the job of professors. But it is the job of actors.

As a result, I recruited Brian and Dorie. And furthermore, the two of them end up splitting storytelling itself into cerebral versus visceral. Dorie’s expertise, in addition to being a very accomplished actor, is with the more cerebral side of stories which is narrative dynamics. She works as a script consultant to screenwriters. Brian is at the other end of the spectrum. His area is improv acting which is a set of techniques to help actors “come down out of their heads” – down into their hearts for emotion, their gut for humor and intuition, and even down to the sex organs for sex appeal. Together they have provided the more practical side of storytelling that I needed help with, producing a great team overall.

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

Randy: There was a speech given recently called "The Gettysburg Address" (hey – recent in geologic terms, right?). My buddy Park Howell, who teaches storytelling in the Business School at Arizona State, pointed out two months ago that it's an ABT!

What's an ABT you ask? Ah, ha! Time for you to watch my Dot Earth interview and read my letter in Science last December. We are increasingly of the opinion that we have discovered "the universal narrative template" which is the sentence structure of "and, but, therefore". Every story can be compressed down into that template. If it can't, it isn't a story.

Just as an example, I could tell you the story of a little girl in Kansas who lives on a farm AND she's bored with her life BUT then one day a tornado sweeps her away to the Land of Oz, THEREFORE she must embark on a journey to find her way back home. Every story fits into it, including all of the stories of biologically inspired design, such as the one Norbert just told me about how companies typically use centralized building

Brian Palermo, Dorie Barton, and Randy Olson

Photo courtesy of Randy Olson

management systems AND these systems can control peak power production that can be 20-50% of the monthly electricity bill. BUT these systems are expensive, hard to install, require ongoing maintenance and are sometimes not effective. THEREFORE REGEN Energy researched swarm theory to develop a low-cost distributed power controller that is easy to install, continually configures itself and significantly lowers peak electricity demand.

It's a very powerful communications tool. Every graduate student should be forced to figure out the ABT of their research project. "There isn't one" is not an acceptable answer.

What are you working on right now?

Randy: I was one of the speakers (along with Bill Nye) at the University of Missouri "Decoding Science" symposium (http://lssp.missouri.edu/decodingscience) to help "reconnect and rekindle the conversation between scientists and the public".

Brian, Dorie and I regularly present our CONNECTION Storymaker Workshop (http://thebenshi.com/?p=4469) that helps participants construct stories that take the audience on a journey and help reach a broader audience by connecting with listeners in a way that is meaningful to them. We have developed an Android and iOS app to help participants practice what they have learned immediately and regularly.

What is the last book you enjoyed?

Randy: "Moneyball" – I saw the movie and then had to read the book. It is the same story as what we're doing with storytelling – trying to introduce a tiny bit more scientific approach to something that has traditionally been purely intuitive (and thus nebulous when it comes to teaching). I don't like the idea of a world consumed by "metrics", but when there's a total absence of the power of scientific thinking it's really kind of a waste. That's what we're doing with storytelling. Hollywood figured out long ago that there is a certain amount of science to the structure of stories. People outside of Hollywood are only just starting to realize this.

Who do you admire? Why...

Randy: I find Spike Lee to be both knucklehead and truly great leader. He spoke at the University of New Hampshire in 1990 when I was just starting to get interested in filmmaking. The stories he told about confronting the Hollywood establishment in his struggles to tell stories in the real voice of an African American were truly inspiring. Almost as inspiring as biologically inspired design!

What's your favorite motto or quotation?

Randy: "Nothing in biology makes sense except in the light of evolution" as I've already explained in detail above.

Brian: "Action, not thoughts, and the universe will reward you with feedback." I don't know who to attribute this to. I picked it up in a workshop 25 years ago!

Untitled

Photo: Roxnstix, 2010 | Flickr cc

Snow Monkeys | Photo: sitsgirls, 2008 | Flickr cc

What is your idea of perfect happiness?

Randy: Asking Brian Palermo to add to his presentation a good story about the Groundlings actors he's worked with, then hearing him give his talk and tell the story of the first time he saw Groundlings actor Melissa McCarthy (who was nominated for an Oscar for "Bridesmaids") perform in a play. He said she had a bit part as a diner waitress – almost an extra – not likely to be noticed. But on opening night when it came time for her to enter her scene, she walked out wearing a pirate eye patch with a peg leg and parrot on her shoulder, none of which was in the script, causing the director to melt down but making the audience explode with laughter. Hearing Brian pull that story out of nowhere in response to my simple request was an experience in pure happiness.

Brian: For the record, it was only a patch and a limp. No parrot. And you have a very simple idea of perfect happiness. Mine would be universal enlightenment. Or beach camping with my family.

If you could choose another profession or role, who/what would you be?

Randy: Professional surfer who studies starfish larvae and makes comic films when there's no waves.

Brian: I'm happy being me. ×

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Macaca fuscata, Social grooming

Photo: Noneotuho , 2009 | Wikimedia Commons

Day 39: Seed Pod

Photo: Craig Strachan, 2010 | Flickr cc

Tools

The Systems View and Your Bio Toolbox

Curt McNamara

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Author:
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Enhancing Bio-inspired Design via System Techniques

Designs, organizations, and biology are all composed of systems. Systems in turn are composed of interacting parts that, together, create a unique behavior or function.

Systems methodology allows a designer to explore the network, structure, or item of interest, understand its components and relations, and comprehend how that system connects to the world.

The bio-inspired designer has a variety of tools: a database of biological functions [1]; mapping a need to function [3]; design process flows (http://biomimicry.net); the bio-design cube [20]; an analogy database [11]; and examining systems with a structure-behavior-function perspective [15]. This article adds the system explorer, a way to examine interconnections in design and biology to enhance perception of systems.

Knowledge and awareness of system interconnections allows for optimization of design outcomes [32] while considering Earth's operating systems [3]. A systems view can be used to tie a design into nature's cycles [13], and improve its effectiveness by creating a better fit of a solution to its environment [16].

The alternative to a systems view is reductionism: seeing the parts and not the higher-level systems, designing with "known good components" (elements used in past work) and limiting consideration of interactions or context. This is design for the part, in contrast to design for the whole. Design for the part can have unintended consequences if the larger systems are not considered [20, 21].

How can a designer identify and use a systems view? The first step is awareness of perception, reflection, and how they relate to systems.

Perception and patterns

Humans perceive their environment by sensing, identifying, organizing and interpreting their sensory data [33]. This process uses a set of known configurations or patterns when encountering a new situation [10]. This allows them to construct a cohesive and consistent worldview. The set of configurations or patterns is built up over time as new situations are mapped to previous experience.

What is a pattern? There are numerous examples to consider:

- A pattern is a repeating arrangement of material, energy, or information [17, 31].
- A pattern is a resolution of forces [19, 29, 14].
- A pattern is a common feature, system behavior, structure, or function [24].

Birch Polypore

Photo: Phil McIver, 2010 | Flickr cc

Birch Polypore | Photo: zanzo, 2011 | Flickr cc

In other words, a pattern is a regularity that is visible across multiple contexts. It is the result of interacting forces or elements in the environment. A pattern can be perceived where systems (or their components) interact.

A system is a set of interconnected components that is distinct from the universe [9, 25]. The interconnection gives rise to one or more behaviors or functions – a system is more than the sum of its parts [9]. This behavior or function is visible when the system is placed in the context of its super-system.

Every system has a boundary or boundaries, and consists of sub-systems (or modules) that have relations to one another and are organized as a structure. These sub-systems or modules have commonalities across system types and levels [26]. These aspects of system can be recognized as patterns.

A given pattern, therefore, might represent an aspect of a system, a set of components that make up a system, or the behavior/function of a system. A system component can be seen as a pattern, and a pattern as a system compon-

Pinecone

Photo: Geekybiker, 2008 | Flickr cc

ent. As a result, perceiving a pattern can be used to gain knowledge of the system in which it is contained.

For example, a door is a pattern found in buildings. It resolves the forces between inside and outside and typically consists of two sub-systems - a closure, and a means to control that closure. The door might be wood and have hinges. Or it might be a curtain and have a catch to hold it aside. Or it might be the extended opening to an igloo.

In all cases the door is composed of sub-systems like those above, and in turn is embedded in higher-level systems (a building and wall). The door is at a pattern level similar to windows or wires that also bridge the boundary. Perceiving the door can lead to an exploration of the surrounding systems and system components.

A cell membrane protein performs a function analogous to the door. It allows certain molecules or signals in, and passes certain molecules and signals out to the external system. The external system might be a mass of cells or a fluid (in the case of a blood cell). There are structures in the cell boundary or cell wall at the same level as the protein, and the protein is a sub-system of the cell wall and of the cell itself.

Since an individual's set of patterns is fixed at any instant of time, perception of a design situation or system is based on past knowledge of elements and configurations. As a designer studies existing solutions as well as examples from nature and system fundamentals, their set of known patterns can increase. A larger set of patterns (or "building blocks") allows a designer to perceive more variety, and in turn create more varied combinations of material, energy, and information. This increased knowledge of patterns and interconnection allows perception of more solutions, and awareness of how a solution fits into both smaller and larger systems. Incorporating multiple viewpoints or representations will also increase the number of patterns that can be perceived [23].

The images on pages 95-101 illustrate patterns in nature, and the higher-level systems in which they are contained. Each is an aspect of a system that was created and exists in a context of systems, responding to external forces and resources. For example, consider how each pattern and system is utilizing forces (or flow) in the environment to achieve a function or behavior [30]. Each entity in the illustration is an element in larger systems. For instance, the pinecone is an element in the larger system of a tree and its reproductive strategy. Each is also composed of lower level sub-systems. In the case of the female pinecone the lower subsystems would include woody bracts and seeds.

As illustrated, the patterns we perceive may be parts of a system, or the system itself. The overall system surrounding the perceived pattern can be explored using the following techniques.

- Explore the system that the pattern is contained in - look for larger and slower entities [19].
- Identify levels inside the pattern - look for smaller and faster parts.

Pine-flower | Photo: tortipede, 2010 | Flickr cc

- Observe other patterns or system components -look “across” or for patterns at the same level.

In other words, we may use these techniques to expand our view to see higher-level systems, lower-level sub-systems, and systems at the same level of scale. Note that we can identify a system based on its boundary(ies) and connections to universe, by its behavior or function, and by its elements.

The systems context

Since a pattern or system feature is a resolution of forces existing at an interconnection of other system elements, how can this be represented in a diagram?

Every system (or pattern) is a set of strong connections between elements, with weaker connections to the environment [7, 25]. This allows us to identify the boundary between system (and pattern) and both larger and smaller levels of scale.

The diagram can be a simple representation that includes the item we are focusing on (design situation, system element, or pattern). It should include larger or higher levels, smaller or lower levels, and items at the same level of scale.

Figure 1 is a first step in representing the known and potential interconnections and resources. It is similar to a systems map [27], however it is a more structured approach that examines system levels and adjacencies. A diagram can also be made in 3D [24]. The items in the diagram can be represented by words, graphical elements, or images.

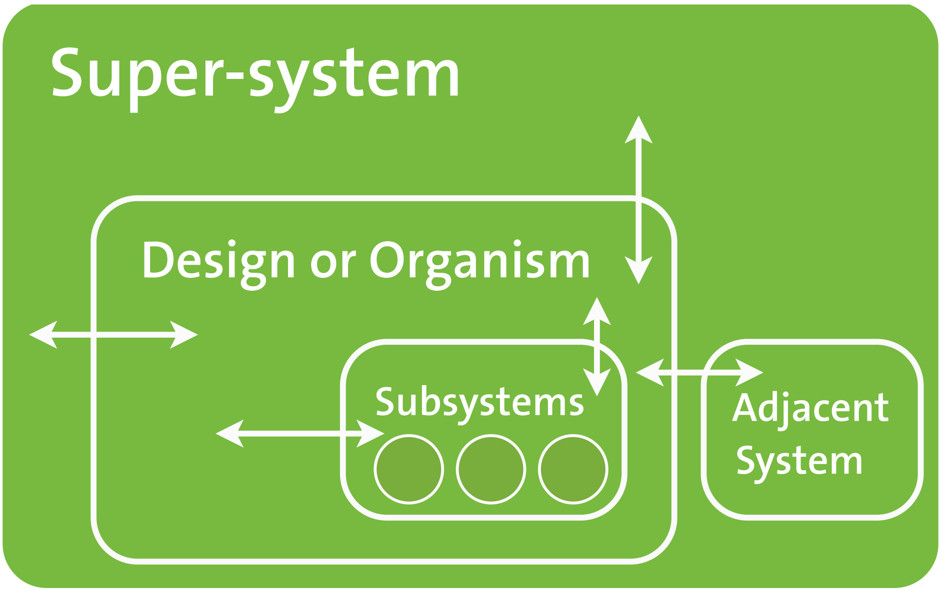
Creating the diagram incorporates perception, reflection, and analysis of actual and potential system connections. The outcome is an increase in understanding of the overall system and design situation [28]. A diagram will enable perception of more design alternatives, and can illustrate alternate ways that a design can be connected to its environment.

The connections in the diagram are at the interfaces or boundaries of the items. A boundary is the connection point where energy, material, and information can move between the items [13]. The connections that define a system boundary and structure are strong links, while the connections between systems are weak links [7, 13, 25].

Designs and organisms “fit” into their environment by taking advantage of the forces and flows of material, information and energy in that environment. These forces and flows are sensed and utilized at system boundaries.

These boundary connections between systems or elements exist:

- Inwards to smaller levels of system (lower level sub-systems - below, within, or faster)
- Outwards to larger levels of system (higher-level super-systems - above, outside, or slower)
- Across (at the same level of scale)



Farnsworth identifies system coupling in the areas of intra-system (sub-systems within an individual entity), between adjacent systems, across unrelated systems (the elements of which may be combined), and upwards to whole systems or ecosystems.

Each of these potential interconnections can be a resource for the designer. A solution might be created by using resources from higher, adjacent, or lower level systems [19]. For example, a perceived transportation need could be satisfied by messaging or sharing resources, instead of moving an organism.

One way to use this diagram is to explore the area of interest:

- Where is the situation located? (i.e., what are the surrounding systems above, below, and adjacent).
- What is the goal for design or understanding? Which aspect needs to be better, and which tends to get worse? (i.e., what is the contradiction) [19].
- What is available? Resources can be found in structure, process, or system [3], and these correspond to matter, energy and information [29].

In addition to evaluating other levels and systems as resources, the diagram can be used to explore competitors, constraints, or opportunities.

Figure 1: Placing the system in context

Boundary opportunities

The boundary is the interface between system levels, and also between the system of interest and its environment. Many design situations occur at boundaries. These examples all involve boundaries:

- Transportation comprises moving a design element in a fluid (air or water).
- Friction between moving parts results in a loss of efficiency.
- Adhesion (and non-adhesion) between systems, or systems and surfaces.
- Reflection of light can create color by structure.
- Organizational design includes the interface between people and other entities. The nature of the boundary and the signaling at the boundary are critical.

Color by Structure: Red eyed tree frog (*Agalychnis callidryas*)

Photo: iwishmynamewasmarsha, 2009 | Flickr cc

Many biomimicry success stories are based on boundary relations or interfaces:

Example	*Approach*
The leading edge of the bullet train was formed into a shape that eased transition between different regions of air [1].	Consider the design interface to environment at a variety of operating conditions [6].
The shape of the boxfish car is based on the flow characteristics between the vehicle and its surroundings [1].	Look to nature for analogous examples and metaphors [11].
Gecko tape is based on surfaces that bring molecular forces into play [1].	Investigate the boundary attributes at the smallest level of scale [30].
REGEN Energy power management systems are based on horizontal (or adjacent) coupling and signaling between controllers (system elements) [1].	Explore adjacent systems, alternate architectures, and networks [8].
The Eastgate Building in Harare, Zimbabwe, Africa, used the energy differential between the ambient air and the ground as a resource for cooling the building air. This required design of a sub-system with boundaries on each side: one to the earth and the other to the building HVAC system [1].	Use higher-level systems as a resource [19]. Investigate both sides of boundary [13].

In the above list, the bullet train, boxfish car, and Eastgate building all involve aspects of the system in relation to the larger super-system. They are boundary issues going "up a level". Gecko tape is "going down a level" on the diagram to explore lower level interfaces. The REGEN energy management system is moving across the diagram to explore combinations of elements at the same level.

Systems Explorer

To summarize:

- Perception begins with recognition of known patterns.
- These patterns are either elements of systems, or a system
- A diagram can aid exploration of other system components, adjacent systems, system boundaries / interactions, and higher level systems
- Many biomimicry applications occur at the boundary between systems

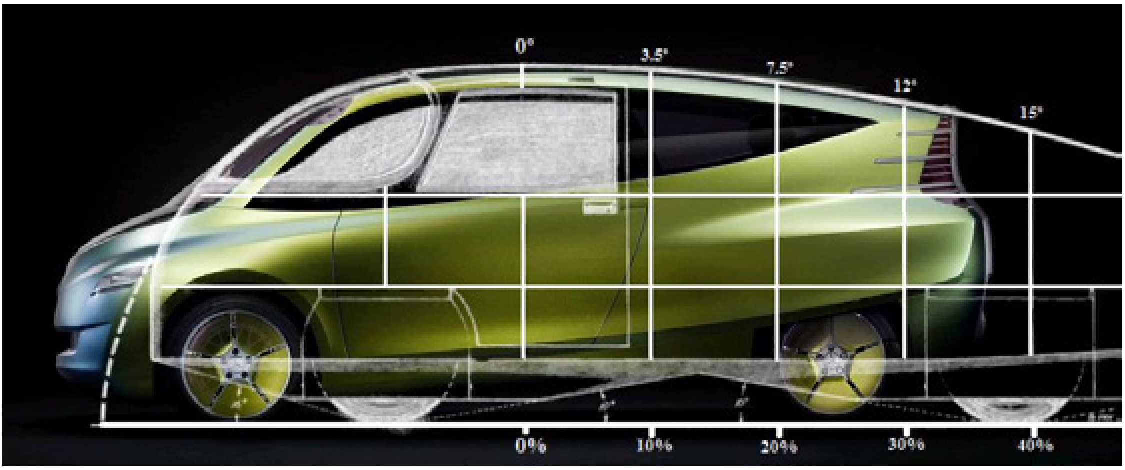
The ideas in Figure 1 were expanded to emphasize system adjacency and higher-level systems. The form of the new diagram is based on the systems operator tool [19, 29]. This process created the Systems Explorer tool (see Figure 2). The design situation, pattern, or system element of interest is placed in the center of the matrix with higher level systems above, lower level systems below, and adjacent systems to the left and the right.

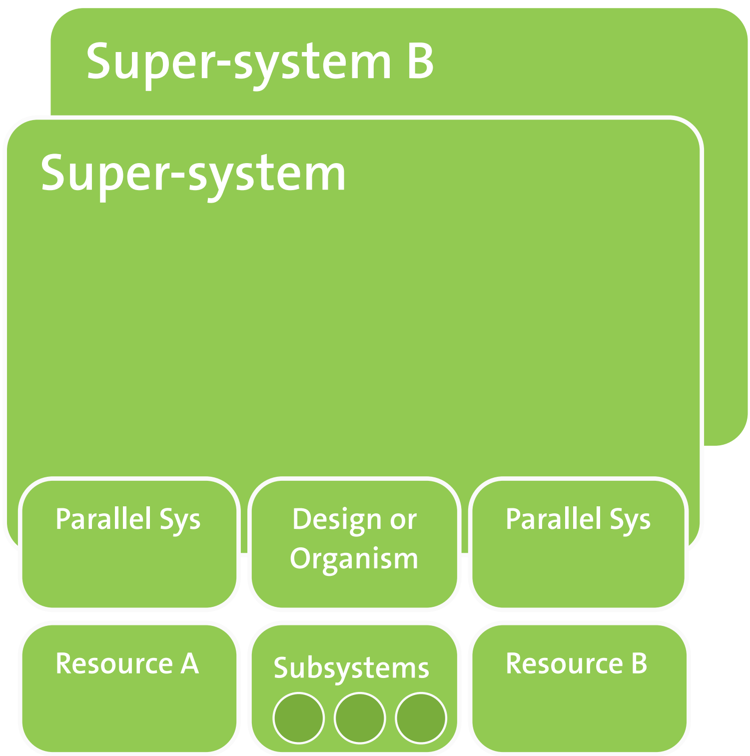
The System Explorer:

- Highlights the boundaries between the situation, super-system, adjacent systems, and sub-systems.
- Focuses on system structure and interconnections (up, down, and adjacent).
- Can capture system interconnections, coupling, and lifecycle graphically. For example, consider the flow of material and energy needed to create a product, and the outflows from the process into larger systems.
- Enhances interdisciplinary communication and partnerships when used with a team [24].

Using the Explorer:

- The pattern, system element, or design situation is placed in the center of the diagram. The elements on the left and right represent systems, system elements, or patterns at that same level of scale [8]. Exploring the adjacent items can locate other elements in the system of interest, as well as available resources. In addition, this level of scale and context will contain "parallel" systems that have solved similar challenges [8].
- Super-systems are at the top level of the diagram, and are shown as physically larger than the system of interest. The diagram can be used to explore the biological context by considering air, earth, energy and water as super-systems. For a design or organization, super-systems aspects of culture, economy and context can be considered.





Comparison of Mercedes-Benz-Bionic (boxfish) Concept
Car body shape to an ideal streamlined half-body
Photo: Ryan Somma, 2013 | Wikimedia Commons

Figure 2: Systems Explorer

• The lower level is composed of smaller elements. This sub-system view reminds the viewer that all systems are composed of sub-systems, and each level shows emergent properties that are not apparent in the level below.

The Systems Explorer can be used to investigate a situation for connectivity, membership and resources. As noted previously, a resource at a higher/larger/slower level of system might solve the challenge [12] In other cases, sub-system elements can be used to support a new solution or create a new structure (i.e., animal fur is composed of multiple layers).

Recall that lower level sub-systems are smaller and generally operate faster, while higher-level systems are larger and usually operate on slower time scales [19]. To investigate both higher and lower level systems, deliberately change scale in space and time.

Using the Systems Explorer shown above, enter the design situation or biological phenomena as the center element. In this first effort, use a simple definition of the situation, pattern or need.

In subsequent steps, change the center element in one or more ways:

• refine the description

• use a different focus (level of scale) or perspective (point of view)

• use a system pattern such as boundary, modularity, hierarchy, sensing, decision, motion, feedback, and storage [13, 14, 26]

In each pass, examine the connections to lower, higher, and adjacent system levels.

• Move "up" a level. What systems encompass the design situation? These systems might be larger, slower, have a higher-level function, or include multiple systems like the design problem. What are the boundary issues, challenges, and opportunities?

• Move down a level, and explore the elements (modules or patterns) within the design situation. The elements may be smaller, faster, or consist of sub-functions or lower level functions.

• Look at the inside of the boundary (where lower level systems exist). What forces and resources are present? How could a new connection allow a different solution?

• Look at the outside of the boundary (where the system connects to external systems). What forces and resources are present? How could a new connection allow a different solution?

• Consider adjacent systems for resources, connectivity, and insights (where the same function is performed in different ways).

This process enhances perception of the design and system environment, along with potential resources (above and below), and the forces that surround and support the pattern (in design or biology).

The super-system and sub-systems of the design contain the forces that created the pattern. These may not be obvious at first glance, and may require viewing the situation over time, or with a higher-level view. For example, a beach pattern (boundary) is created based on the interacting forces of water, land, and wind.

When we focus on a detail (a structure, behavior or function) in a design or organism, our perceptions separate this aspect from the systems to which it is connected. This technique is normal and natural for a designer or scientist. It allows us to break a problem into parts (decomposition) and then work on the individual elements or aspects [18]. It also allows us to create modules, work breakdown structures and to coordinate complex projects [2].

However, this focus on a particular pattern means that the part is separated out from the larger and smaller systems that it is connected to. This activity is known as reductionism, and can be countered by explicitly considering how the perceived pattern or element fits into higher, lower and adjacent level systems. This process is enabled by the fact that every system is composed of sub-systems, and every system is an element in a larger system [26].

Both of these processes are very powerful, and can be described as working both upwards and downwards from the building blocks to higher and lower level systems, including the environment [18].

Using the Systems Explorer

The Systems Explorer gives the designer, engineer and biologist a new lens through which to view both design challenges and organism functions. Use of this tool allows both to be explored, and allows generation of multiple design alternatives.

The following examinations are some of the possibilities:

- Slower and larger systems (wind, air, water, sun, organization, society)
- Smaller and faster elements (bacteria, root structures, neural processing)
- Parallel elements and systems (mesh networks, tree roots)
- New connections between elements to form a structure or network (geodesics)
- Cycles and feedback to higher level, lower level, and parallel systems (systems thinking, leverage points)
- Resources from the ecosystem (gradients, flows, cycles, energy, materials, and structure)

Design and system leverage points

In the first stages of a project, a designer maps the challenge to define the existing relations and what is needed. This understanding allows the designer to perceive the situation and need from both the users' perspective and the forces affecting various elements within the system. The designer and client then create a new set of relations that can fit into the "ecosystem" of the design user.

The design solution may:

- add a new component/module or feedback to the situation [25]
- create a structure that captures, stores, or transforms material, energy or information [26]

Beach patterns

Photo: inyucho, 2008 | Flickr cc

- optimize the interface between two systems via shape or surface to increase efficiency [1]
- optimize the interface between modules or sub-systems for signaling or protocol [2]

Each of these approaches can be seen as a set of elements, relations, boundaries and coupling on the diagram.

Organisms, Functions and Systems

The discussion so far has focused primarily on the environment of the design, and finding connections between the perceived pattern and higher and lower levels of system. The same technique can be used from the biological perspective to enable a deeper understanding of a function and how it fits into its environment [34].

Biomimicry, biomimetics and bio-inspired design can be done at the form, process, or systems level [3]. If a match is made between biology and design at the level of form (structure), it can be a static or fixed pattern (shape or surface), and might not consider the larger context in either biology or design. Finding a match based on process (behavior over time) or system (interconnection of components) is more likely to consider the systems context in both biology and design [21]. In all cases, it is advantageous for a designer or scientist to use a tool for exploring downwards, upwards and sideways to determine system interconnections.

This is the essence of systems work: to perceive both the whole and the parts of the subject and the relationships that create the end product or process. Design and analysis are incomplete if they are performed at just one level or perspective.

Using the Systems Explorer in Education

The original Systems Operator has been used for several years in the systems classes at the Minneapolis College of Art and Design Master in Sustainable Design program. It has proven to be the most useful tool for investigating systems among several used.

Nadine Kummel used the system operator tool extensively in her work (see Figure 3) and commented:

> *"When I first got to know the system explorer tool I really liked the visual aspect about it. The basic tool is really easy to understand and helps to put things you observe, while thinking about a design problem, in a sensible order which enables you to work with them. As designers we are not working in a vacuum and a problem never comes alone. We always have a status quo, which consists of different elements. Observing and realizing connections as well as commonalities between these elements and in a second step ordering them into the categories of systems, super systems and subsystems helps enormously to understand the whole picture and to keep every part in mind, while working on a solution.*
>
> *In another project, while analyzing common and sustainable production processes, it became important to have a closer look at the elements crossing the system boundary. I was able to extend the tool for this special purpose very easy and again found it really helpful to*

order my creative and some¬times chaotic designers thoughts and to develop unexpected solutions due to this new perspective."

Super System	Market (sphere of influence +) Users (consciousness +) Users (prosperity +++) Supply and Demand Competitors (number +) Government
Crossing the Boundary	Materials (+++) Energy (+++) Water (+++) Information (+) Knowledge (+) Money Chemicals (+++)
System	Obsolete Production Process
Subsystems	Workers Machines Organization (+) Buildings

Figure 3: Nadine Kummel System Operator Example

Stef Koeller comments on the systems approach and ideas of super and sub-systems in her master's thesis and Biomimicry Student Design Challenge entry:

> *"Prior to learning about systems thinking, I assumed that a product designer's role in sustainability was mostly about increasing efficiency, using earth-friendly materials, and consuming less. By engaging in MCAD's sustainable design program, I have gained an understanding that designing the object itself is just one of many dynamic parts of a whole system that will only be relevant (and successful) if supported by a well-designed service and organization.*
>
> *As practitioners of sustainability-focused design, we seek to ask different questions, targeted at uncovering systemic needs. Tools such as the System's Explorer make it easier to comprehend the various, sometimes daunting, dynamic parts of the whole system when seeking to understand a design challenge on different scales, with different perspectives, and for attending to both environmental and social sustainability.*
>
> *When learning, practicing, and embedding ways of thinking that align more with Nature, methodologies of Biomimicry and systems thinking (such as the System's Explorer) go hand-in-hand. In breaking down each part and attending to the conditions and functions of that part within the context of the greater system, patterns begin to emerge, and can in-turn be applied toward more synergistic solutions. By shaping my thinking skills in a whole-system context, I found it easier to learn from the vast world of Nature (biomimicry thinking) as well as learning from other humans while integrating insights from nature's models, patterns, and sustainability principles.*
>
> *My design practices are now deeply rooted in the marriage of design thinking, whole-systems thinking, and biomimicry thinking because it's not about the things we're designing, it's about creating conditions for whole systems to emerge, flourish, and evolve in our turbulent times."* (35)

Summary

In this article we have outlined how system features and properties are often perceived as patterns. This can lead to perceiving a whole without the parts, or the parts without the larger context.

Looking above, below, and sideways improves the perception of systems and the forces that act upon them and therefore the interconnection of a bio-inspired solution to larger systems.

We have covered the following topics in this discussion:

- Fundamental properties of systems and how they are useful to designers.
- Perception of patterns and their relationship to systems
- The Systems Explorer as a tool to place and investigate a design or biological problem in a larger context
- Use of the Systems Explorer to enlarge the space of problem-solving to include potential

system interconnections by examining system levels above, below, and in parallel with the situation

Our intent for this article is to enlarge the BioToolbox of approaches to design situations and we hope that using the Systems Explorer will provide that wider range of problem solving. ×

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Pinecone

Photo: cluczkow, 2011 | Flickr cc

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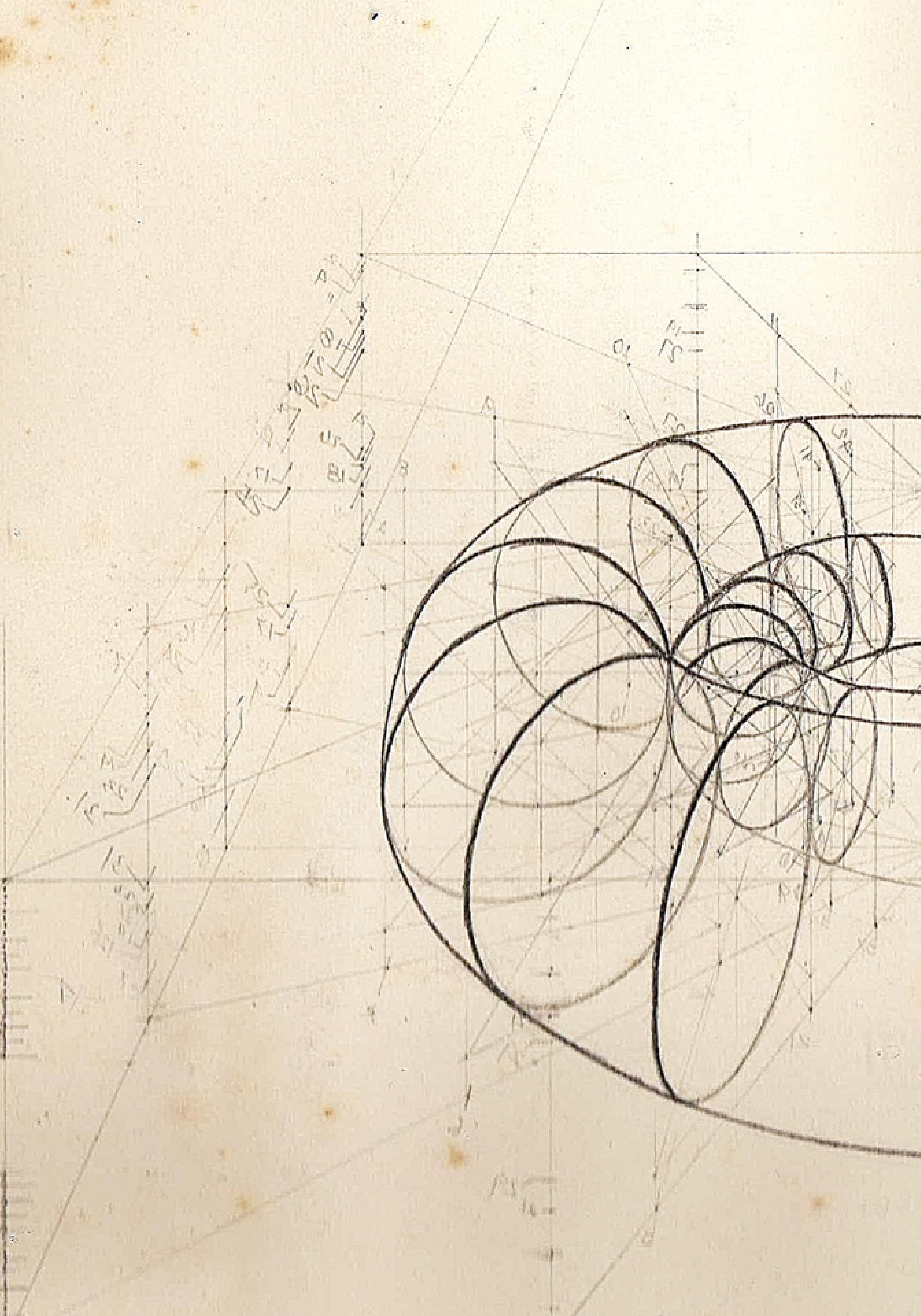
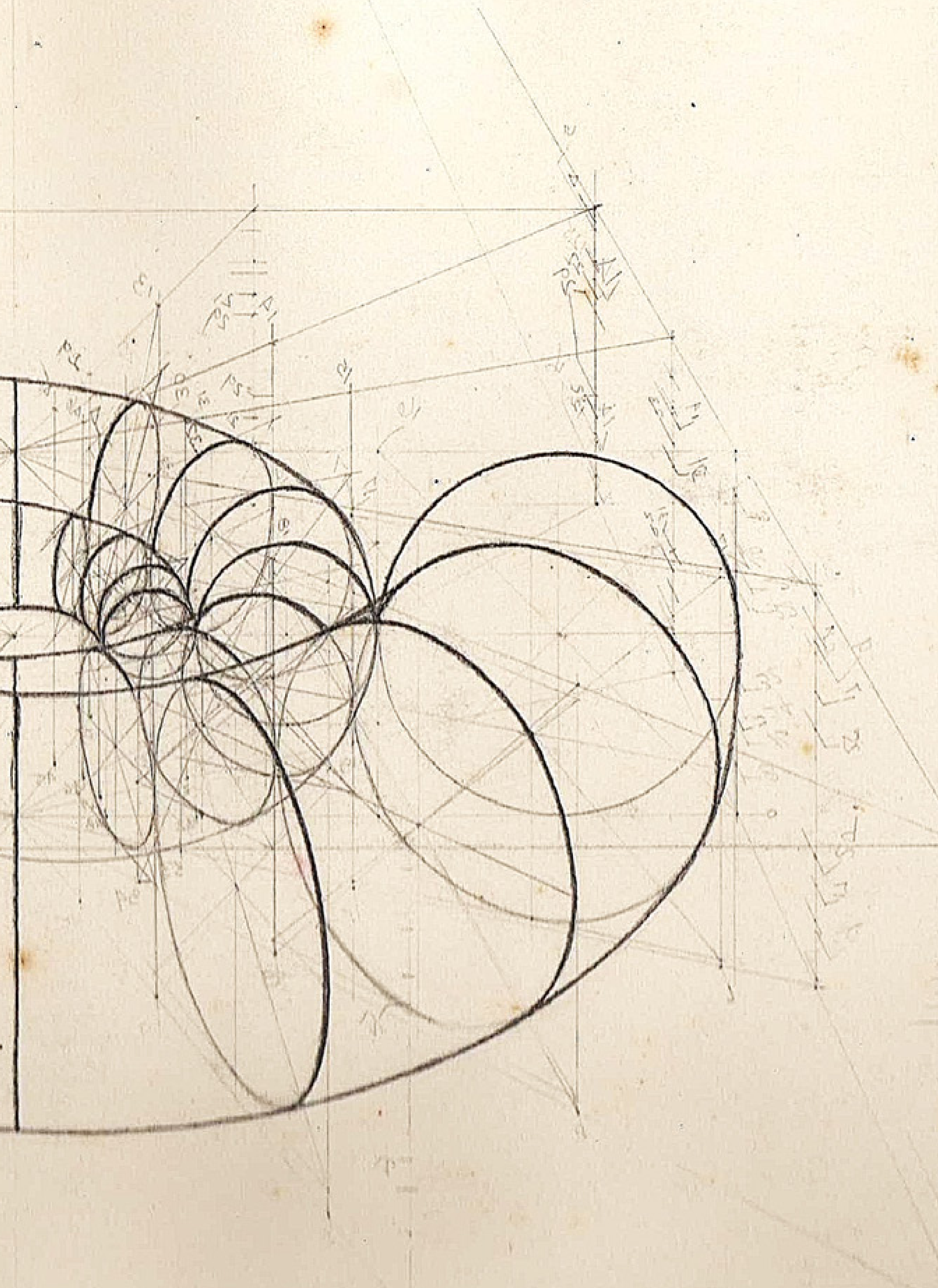
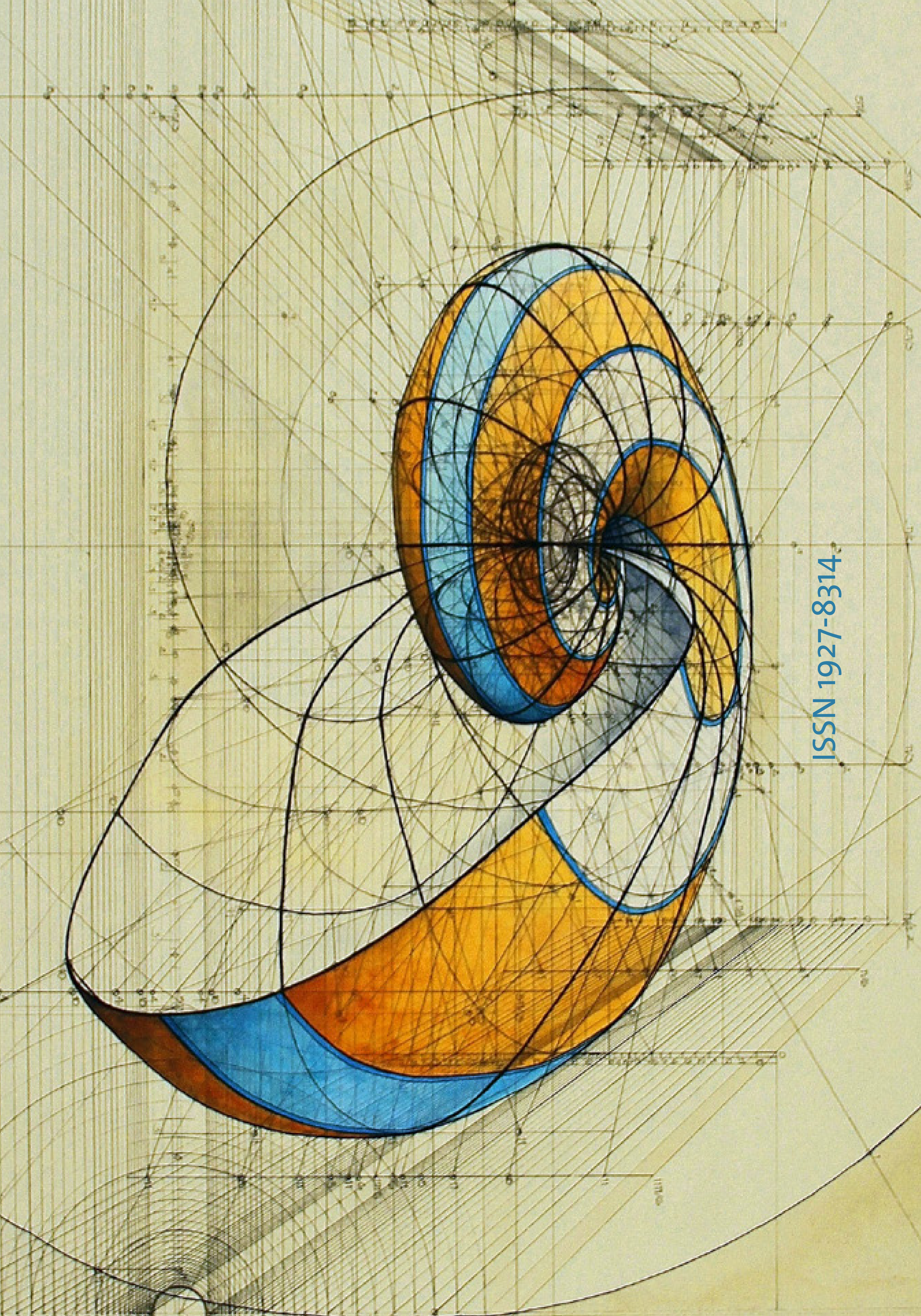
Pine-flower 2

Photo: tortipede, 2010 | Flickr cc







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