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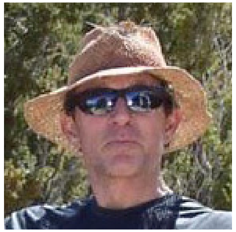

Dennis Dollens

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Architettura, eTrees, & Natura
Architecture, eTrees, & Nature

Innestare prestazioni biologiche in architettura significa creare, crescere, sintetizzare attributi biologici e pensare l'architettura come una natura/cultura metabolicamente evoluta. Questo processo richiede una strategia di integrazione fra design, biologia, arte, orticultura, simulazione mediante *e-plant*, vita sintetica, bio-mineralizzazione e metodi di fabbricazione avanzati. L'integrazione fra la ricerca in campo botanico e in quello industriale ha l'obiettivo di introdurre specifiche risposte di tipo ambientale in campo architettonico. Questo contributo illustra un approccio alla progettazione architettonica che utilizza la simulazione digitale derivata dalla biologia - in particolare gli algoritmi di generazione di *planto-architetture*, quali ad esempio quelli che si fondano sulla fillotassi e sull'allometria - in fase ideativa.

One vision for grafting biological performance into buildings includes inventing, growing, and synthesizing biological attributes for architectural life—thinking of architecture as metabolically evolved nature/culture. This requires a parallel strategy fostering collaborations between design, biology, art, horticulture, e-plant simulation, synthetic life, bio-mineralization, and advanced fabrication. It encourages designers to integrate industrial and agricultural information as design research with the goal of embedding specific environmental-life responses in architecture. This text discusses and illustrates induced evolution in one emerging method for design realized through software simulation—in this case, plant-to-architecture generation based in naturally occurring algorithms, found for example, in botanic phyllotaxy and allometry.

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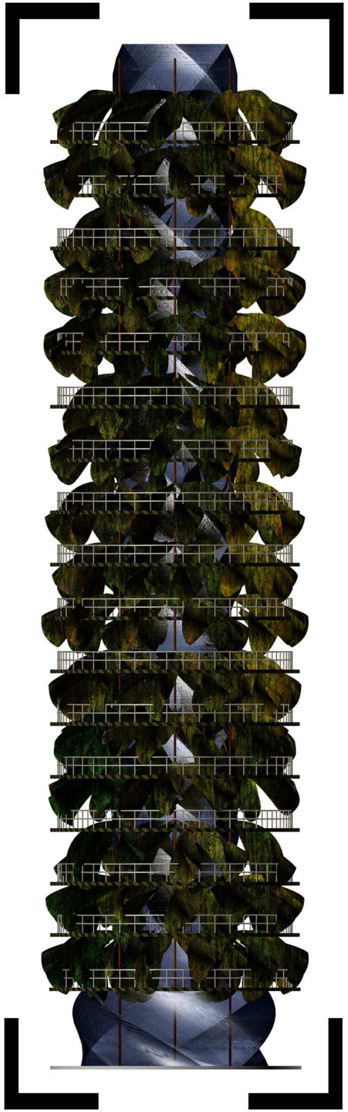
Fig. 1, 1a. Pagoda. 2010. Following the BioTower (*Fig 7*), this project considers ideas for sensor-activated, moving, bio-robotic façade elements, designed as architectural leaves—with lichen-like growth and coloration hybridized into the leaf materials.



INTRODUCTION

Underpinning everything that follows is the conviction that architecture practiced through an evolutionary perspective holds lessons for positive environmental change. As today's toxic buildings fail and die, replaced with fitter species, architecture will re-acclimate itself in nature. Stressing that design conducted through a filter of morphology and metabolism supports biological extrapolation, the essay proposes architecture evolved through natural systems, bio-synthetics, and generative design. This emphasis encourages design compatible with emerging technologies and materials reliant on, for example, programmable matter or synthetic life. Already, embryonic building designs are being nurtured from theory and experimentation. Ultimately, semi-autonomous bio-architectures will emerge—and, eventually, they will self-regulate.

The following projects illustrate my process for generating structures with plant- and tree-like characteristics (*Fig. 1, 1a*).

This method has come into my practice over the past fifteen years through software simulation, experimental gardening, physical modeling, and microscopy. The idea is not to make buildings look like plants.

The plan is to interlace naturally occurring botanic algorithms with architecture, enabling the design of biomechanical buildings stepping toward living architecture. In this process, investigating nature is design research, while categorizing architecture, as culturally evolved nature is expedient.

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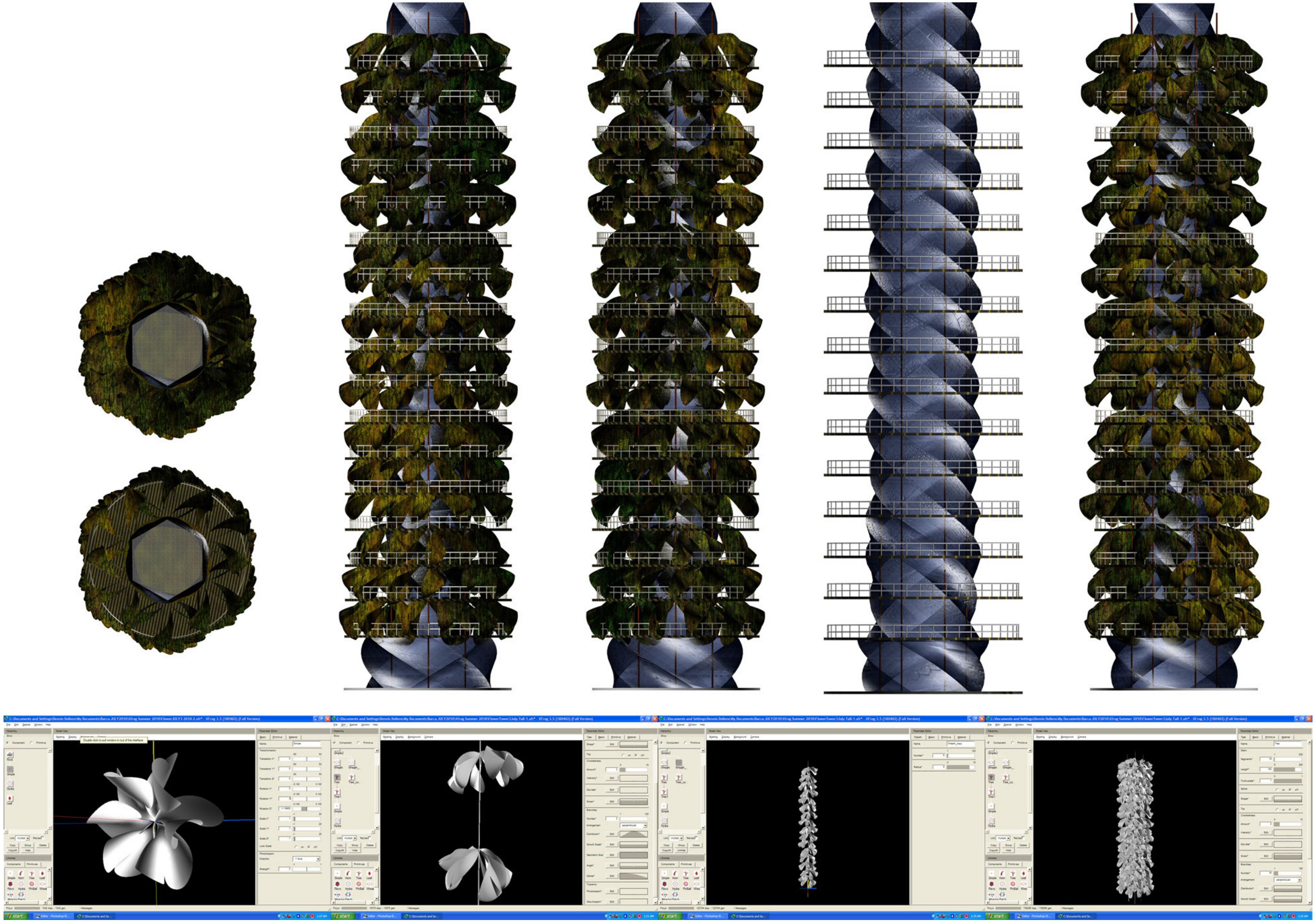
Fig. 1a.



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Subsequently, it is important to note that these projects are partly a reaction to my pessimistic assessment of current political and economic options for environmental remediation. I think more radical design experimentation and teaching programs must be cultivated. Future design necessarily requires radically reconceptualizing our place in nature and reorienting architecture and cities as metabolically stable, linked into urban agriculture, wetlands, oceans, and forests. With this conception in mind, the ideas, projects, and models presented begin to etch DIY (Do-It-Yourself) methods for building components and thinking structures. The work's overall aim is to foster environmentally responsible architectural species incorporating natural attributes in materials, mechanics, communications, and form.

Designing prototype structures to remotely sense and execute tasks with passive shape-shifting facades for aerodynamic configuration, thermal control, pollen filtration, heat transfer, and water collection justifies the expectation that experimental bio-architecture will necessarily collaborate with science and technology. I am not suggesting designers become scientists; my thought is for designers to look at nature as collaborative forces for experimentation and to synthesize advancements achieved in science and technology. In this realm, I think contributions from bacterial, synthetic life, for example, as it is currently being designed and prototyped by Craig Venter will prompt ideas for converting toxic building performance into metabolic stability [Simpson, 2010; Dollens, 2009, 2010].

Building components derived from logarithmic plant simulations are good options for reintegrating structural morphology with nature. My digital simulations, derived from tree characteristics and expressed as self-reinforcing columns, beams, and trusses, illustrate unusual bio-skeletal organization. Paired with bio-surfaces, panels, and floors the constructions must evolve to demonstrate autonomous and continual, biological performance by, for example, producing oxygen.

Design tools and experiments surveyed in this text include generative, computational software, botanic algorithms, and ideas for emerging materials, but they also survey history. Slavoj Žižek has written: "the only way to grasp the true novelty of the new is to analyze the old. If [something] is really an eternal idea

...it is eternal not in the sense of a series of abstract-universal features that may be applied everywhere, but in the sense that it has to be re-invented in each new historical situation." In the spirit of Žižek's quote, I appropriate information extrapolated from experimental and historic science, for example, mapped seedling circumnutation1 from Charles Darwin's *Power of Movement in Plants*; morphological transformation from D'Arcy Thompson's *On Growth and From*; and electromagnetic plant impulses from Jagadis Bose's *Response in the Living and Non-Living*. I also search pathways through which science and technology entered architecture during the origins of modern buildings—especially through Louis Sullivan's organic theories and botanic designs, realized in his texts, drawings, and buildings [Bose, 1910; Darwin, 1895; Dollens, 2005; Sullivan, 1924; Thompson, 1917; Žižek, 2009].

Importantly, the simulation of design elements becomes part of the thinking/making process, not an arbitrary production step. The basic use of branching trees, as parents for columns and beams, results in original structures no longer looking like trees, but carrying their parent's biological ratios and curvatures. Acknowledging the role of computational simulation is therefore fundamental as part of the thinking process necessary for originating design forms infused with tree strategies. This search, extrapolating ideas from nature, involves finding methods to construct branching structures by translating simulations from digital trees to structural trusses. Metaphorically, I associate the generation of simulated plant structures to bonsai techniques developed for deforming, twisting, and bending while seeking balance, form, and expression.

Biology, botany, and nature are, of course, not new sources for architecture. Design inspired by nature, articulated by idea-eye-hand production has been used for tens of thousands of years. Architecture's ancient craft origins viewed through ur-building technologies, such as cooking, weaving, knotting, and pottery, may be understood as appropriations from nature [Herrmann, 1984]. But contemporary design looks more to industry for inspiration than it does to nature—a bias that has set architecture apart from the environment. Accordingly, design could learn from, and collaborate with agriculture, forestry, gardening, biotechnology, biochemistry, and material sciences.

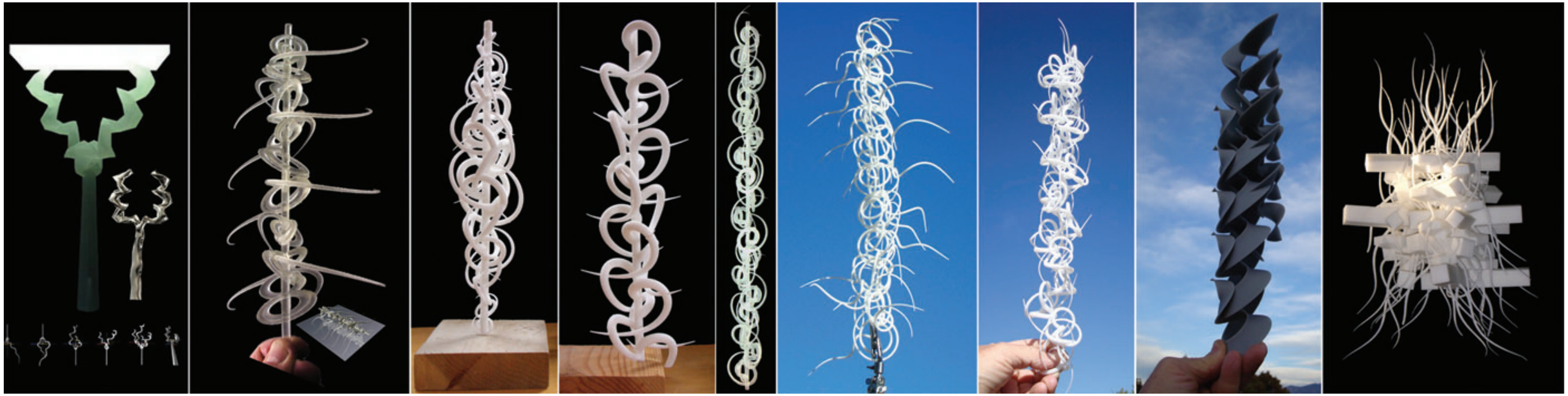

Fig. 2. eTree Evolution. 2000-2009. Generative development of nine, software-generated, STL eTrees modeled as truss structures whose branches grow, curving back into their trunks. In the final four images to the right, the tree trunks have been evolved out of the structure, leaving only interlocking branch structures. In the last eTree, flower nodes have been expressed as pods and boxes (*Fig. 10*).

ETREES & EPLANTS

I call the plant simulations eTrees to distinguish between living trees and the models. The programs I use most are Xfrog and Rhino. Xfrog is frequently used to computationally "grow"—simulate—lifelike digital trees and flowers for films. It can produce forms based on botanic growth, imparting to its 3D files selected attributes of living organisms—for example logarithmic proportion, branching, gravitropism, sequencing, and spiraling. But its design-growth parameters can also be tasked to generate original structures based on the organically derived algorithms it uses to mimic, say, an oak or an elm. Or, Xfrog can substitute solids—spheres, cubes, cones—for leaves, stems, or branches. Figuratively, such manipulation results in generic species of digitally grown branch structures. For example, tree branching may be transformed—computationally hybridized—to produce experimental forms with botanic heritage. From this process I build self-reinforcing, recursive structures with some attributes of a tree and some of an industrial truss, buttress, or brace.

Looking back to the prototype STL models I made between 1999 and 2009 illustrates a path of biodigital evolution for structural and aesthetic expression. From the first primitive tree (*left, Fig. 2*), begun with two gnarly limbs, the eTree's branching was changed until the models preformed complex, inter-nodular subdivision, while exhibiting double curvature, fused intersections, and faceted surfaces. In the final image of the sequence (*right, Fig. 2*), an STL model of the Arizona Tower (*Fig. 10*) sprouts roots and branches at forking nodes, from which, over scaled pods and cubes were reprogrammed into roomlike volumes.

In a project simulated as a grove of four eTrees, prototyped from Xfrog and Rhino files, and built as an STL model, you see a schematic building frame (*Fig. 3*). For this 1996 design, looping sim-branches were programmed to reinforce their neighbor, fusing, after piercing each other, and thus, structurally locking. This process, used in all subsequent eTrees, technically allows the elimination of traditional trusses' collar beams, straight braces, tie beams, and queen posts. The truss elements are replaced with algorithmically, self-similar, looping, eTree branches. Alternating with the looped branches, a second set of limbs, programmed straight, delineates floor positions. This iterative approach was intended to re-visualize steel trusses and cage-frames from early-modern bridges and skyscrapers. It was also part of an ongoing experiment to evolve recursive, interlocking

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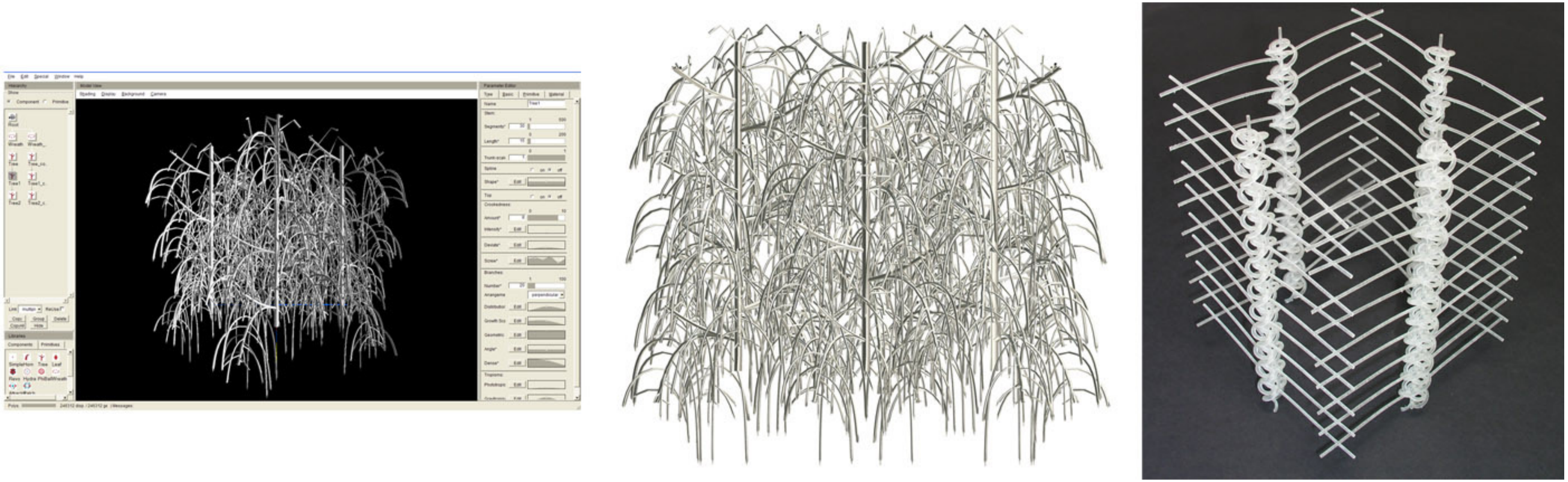

Fig. 3. Frame System. 1996. Left to right: Xfrog screen illustrating early, software-grown eTrees developed into trusses and a cage system for an STL model.

components that could function in various structural configurations, even as they followed differing plant-branching algorithms.

The e-Trees simulate trunks and branches following natural geometries formulated by Xfrog's proprietary growth rules and its modified L-systems [Prusinkiewicz and Lindenmayer, 1990; Lintermann, 1998; Dollens, DBA, 2005]. The tree-to-truss design process relies on natural proportions and simulated attributes in a process that does not copy nature. It numerically models facets of nature's growth patterns, calculated from the biological analysis of living plants and trees. In a sense, the resulting models hold coded/scripted relationships for evolving structures, thus opening conduits for this architecture to mimic and learn from nature [Jean, 1995; Niklas, 1994].

The digitally grown and STL-modeled e-Trees have implications for machine fabrication. Their looping, tapering forms may be materialized with springlike qualities allowing them to flex, bend, and fold (*Figs. 4, 6, 12*); or they may be stiffened for inflexibility and strength. Their spiraling, branch design equally braces the construction in X and Y directions, making the overall component a self-reinforcing, three-dimensional structure—flexible or rigid—with some attributes of natural trees.

Furthermore, when an eTree is skinned (*Figs. 5, 9*), it takes on enhanced unibody strength. Compounded and mutually reinforcing, the components—skin and branches—become lightweight monocoques (the type of construction used in airplane wings and fuselages). The importance is: skin becomes more than a protective surface, it engages as an integral part with endo- and exoskeletal duties. Industrial vibrations and seismic buffering are obvious tasks eTree trusses could perform (*Fig. 6*). Equally valuable, if further away, are shape-shifting facades reconfiguring for self-shading, temperature control, or collecting rain. These design examples, derived from leaves, branches, and trees bringing to mind Claus Mattheck's suggestion to consider, "trees as instructors for designers" [Mattheck, 1998].

Digital-Botanic Heritage

To begin a project I attempt to identify structural movements specialized in plants. A leaf unfolding, for example, involves life-dependent performance for the plants' survival; actions illuminating for designers seeking to develop bio-capable buildings [DeFocatiis, 2001; King, 1996]. Secondly, I transfer the plant information to digital models via software

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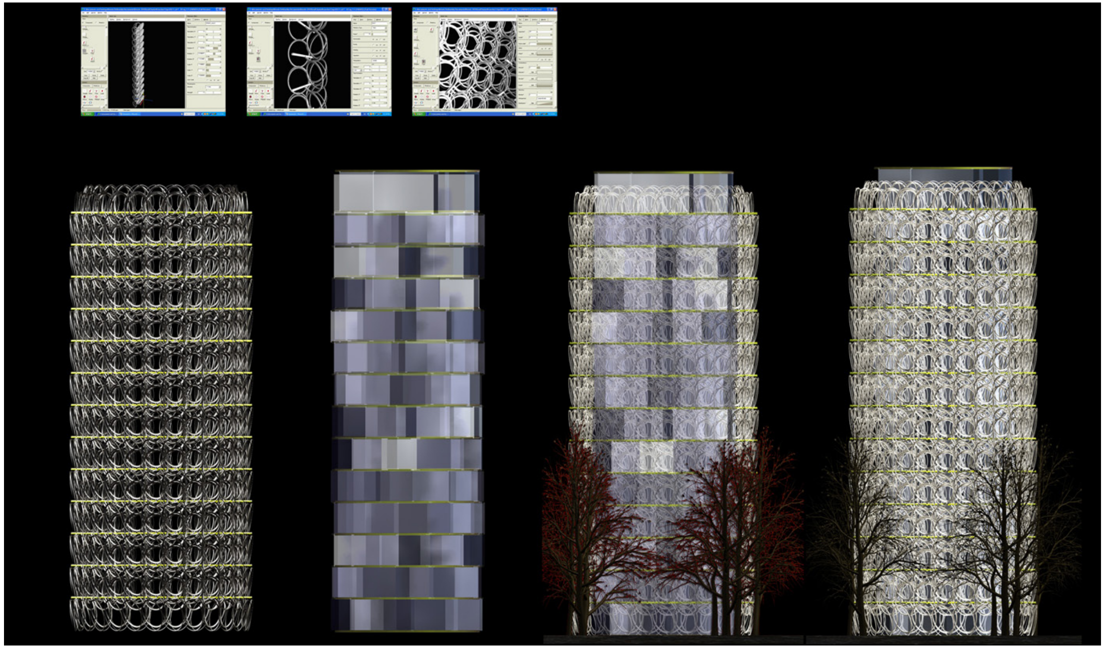

Fig. 4. Loop Tower. 2010. Interlocking branches and eTrees digitally grown as a facade system with secondary growth transformed into cubic offices. Top insert: Three Xfrog screen shots of the developing eTrees and looping branches.

Fig. 5. Los Angeles Tower. 2008-2009. Generative Tower Sequence. Software-grown eTree (left) programmed to grow branches into a self-supporting structure with outstretched branch tips defining a point-cloud for later glass skin generation (middle) and, finally, (right) ParaCloud generated components derived from almond shells as 3D surface components. (Also see *Fig. 11*).

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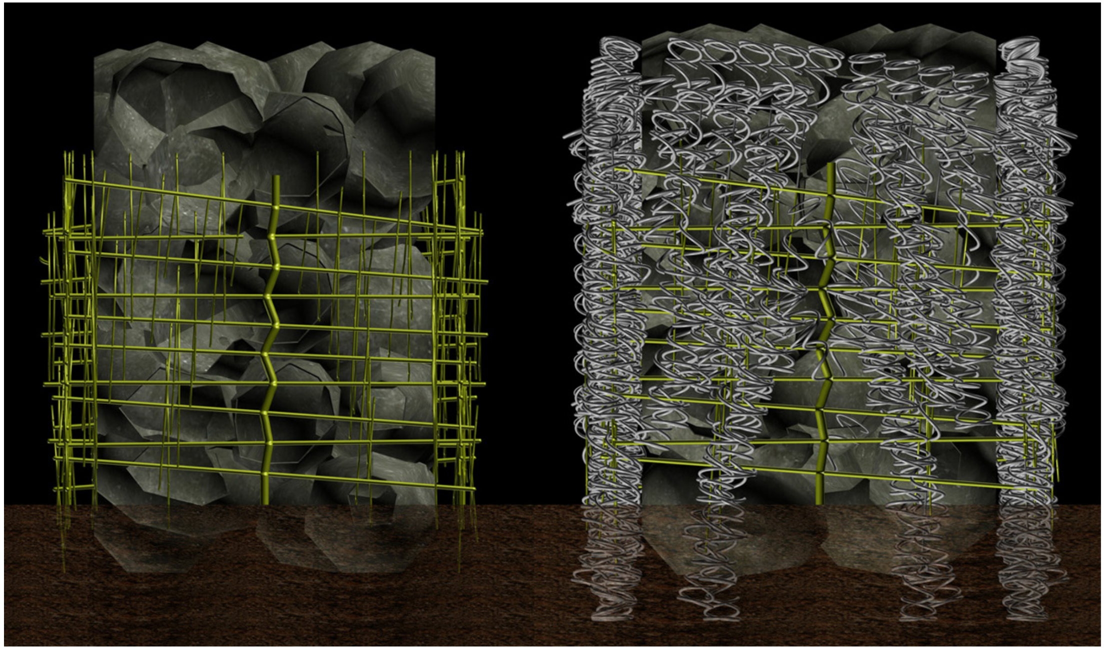

Fig. 6. eTree Frame, eTendrils, & Pods. 2010. Test for attaching long curving and looping tendril-forms to eTree frames and then generating pods from the tendril tips.

simulation until, gradually, they take on architectural interest. Thirdly, I build physical models from junk found in the streets (and gardens) or, going to the opposite extreme, I build STL models—both types of models (DIY or tech) illustrate different aspects of crossing biological information with design.

Design experiments with plants used to simulate botanically encoded, digital projects, instills a natural, generative heritage, into sibling digital files. The projects do not exactly mimic a plant's aesthetic, morphology, or anatomy but are, nevertheless, relations infused with plantlike characteristics such as clustering, folding, or warping. I emphasize that the work doesn't produce prototypes that look like plants. For example, in the summers of 2008-2010, I planted and observed tendrils and vines from peas, morning glories, grapes, and squash.

Long ago these plants evolved tendrils (or tendril-like functions) to environmentally anchor and stabilize themselves. And, fortunately for my work (or anyone interested in looking), tendrils are so widespread in the plant world, that they are almost effortless to find, just search open lots, parks, and gardens.

Tendrils show us nature getting a grip (sometimes a strangle-hold) on the physical world (sometimes their neighbors). I like them because they move fast, frequently, and with determination (and when captured in time-lapse videos, wildly swaying and lurching, they look sentient). They are sense-flaying their way in the world, trying to hold steady. The resulting biological movements can easily be charted and indexed in a design lexicon or shape grammar—documenting form and growth strategies, along with repercussions interesting in terms of design (tying, coiling, curling, springing, spiraling, cabling, and knotting). With examples from tendrils, I attempted to simulate derivative eTendrils, mimicking the original's exuberance—expansion, contraction, reverberation—as torsion devices.

The project that resulted (*Fig. 6*) is structurally related to earlier eTrees (*Figs. 2, 3*), but here eTendrils are grafted into, and stabilizing, an eTree. Responding

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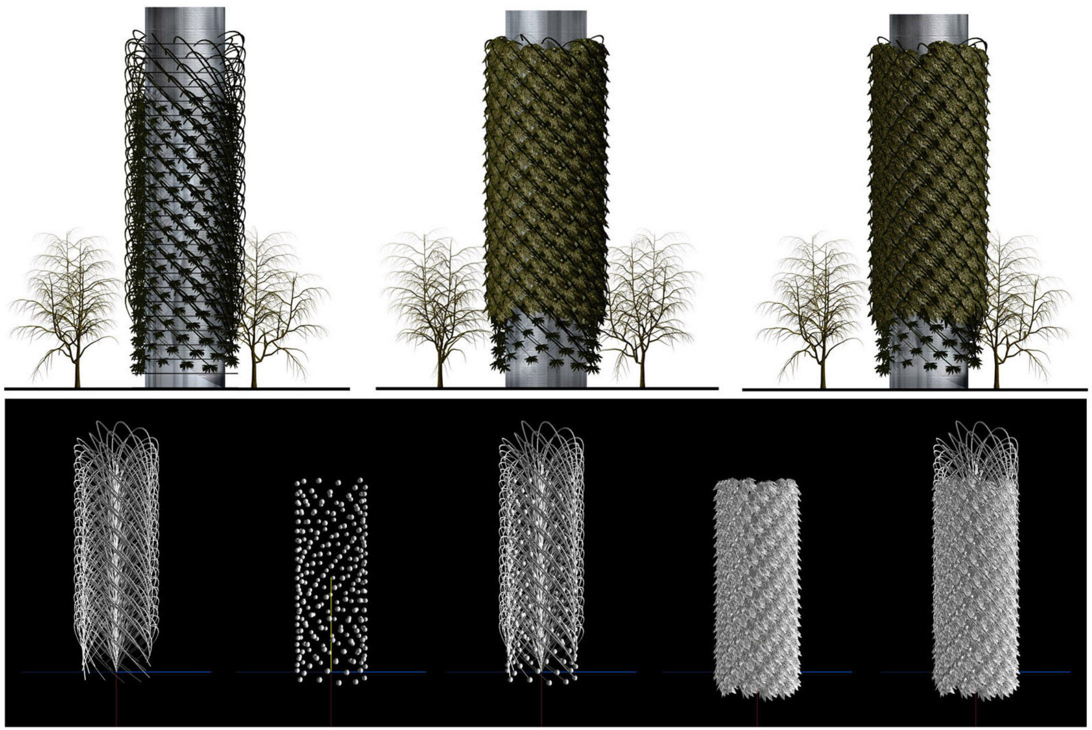
Fig. 7. BioTower. 2009-ongoing. Branch matrix supporting leaf-cluster systems for air filtration, ventilation, sound baffling, and heat/light control. Bottom insert: Xfrog screen shots of digital growth sequences; (right to left), eTree branches, sensor nodes (pods), branches & nodes.

to environmental conditions asks buildings to sense changes and address them. Leaves and flowers exemplify perceptual sensitivity beautifully. Being responsive to chemicals, light, heat, motion, magnetism, and temperature, flowers and leaves are sensitive beyond (or at least differently than), many of our own abilities. Integrated components such as remote sensors, robotic actuators, and digital intelligence are currently mimicking options for architecture—and good ones-—but, ultimately, biological living materials, bio-prosthetics, and hybrid, semi-living/semi-mechanical components will be necessary. The job of biomimetically achieving some of the performance of a tree, leaf, flower, or tendril in architecture is a target for experimental designers. When breakthroughs come, then design, botany, technology, experimental gardening, software, and DIY ingenuity will result in living architectural species.

ARCHITECTURE FROM ETREES AND PLANTS

Beyond digitally simulated structural design, botanic abilities enlightening façades, panels, surfaces, and monocoques are subjects of this research. By simulating plant forms and elementary behaviors, the resulting digital files have both developed and undeveloped capabilities. The dormant, nodes may be capable of later expression—additional branching, reduced curling, or different clustering. I think of these transformative actions as embedded, procedural sets of digital code waiting to trigger other simulated or synthetic traits. The latency underpins a building's flexibility for accepting OS, AI, bacterial, or simulation updates. Design speculation and experimentation of this type exemplifies biological and cultural information transmitted in tightly linked packets:

Fig. 8. Yucca flower stalk; *yucca glauca*. 2010. One of the biomimetic sources for studying Fibonacci spirals in plants, as well as iterative scaling and form distribution attempting light, air, and access for pollinating insects.

designer-nature-design-structure-environment, and nature—effectually, evolution stimulating design evolution.

For the BioTower and Pagoda (*Figs. 1, 7*) I concentrated on hovering and clustered digital leaves sensing and moving as hybrid, bio-robotic, filtration screens over the building's exteriors. These sensor-activated façades were inspired by the blooming stalks of (*Yucca glauca*), narrow leaf yuccas (*Fig. 8*). Yucca flowers spiral around a central stem and the blooming sequence begins with flowers opening from bottom to top, bud to flower, flower to seedpod. The flowering sequences chart a route up the stalk identifiable in Fibonacci proportions. In their blooming, I saw the wild flowers around my house in Santa Fe, New Mexico as architectural analogs for building units, while their rhythmic distribution and pedal movements advocated facade responsiveness.

A yucca flower is cream yellow and ovoid in shape. During its May blooming season, the plant grows a towering stalk supporting buds, flower, and ovary/seeds. After pollination, the flower withers, the seedpod ripens. During their brief lives, flowers are spirally-oriented up and around the stalk, as the plant attempts to give each exposure to light, shade, heat, air flow, and easy access for pollinating insects. Among other things, the yucca may teach us how to orient vertically stacked units for distributed light, air, and access—something not usually accomplished in building masses, but a design option if one is infusing plant morphology into a structure's generative files and codes.

The yucca origin of my information is genetically determined in their seed and environmentally variated in the garden. Still, the plants do more than live in their own reproductive universe. Among other things, they inspire viewer's thinking and the design process. With a world population expected to top seven billion in 2011, people and nature are more tightly bound together than ever—and, in my guess, with less awareness of the bond than at any other point in history. The binaries of form/function, humans/nature, and building/nature are collaboratively locked as evolutionary tactics; gradually revealed through science, technology, and design. A small hope in this unequal partnership (nature will survive, architecture may not), is learning to design with biosystems for the expression and generation of human (nature's) ideas. Natural, evolutionary ideas expressed as bioremediation not the underpinnings of Capitalism. I think of sourcing ideas from plants as harvesting idea-seeds—part of nature fertilizing technologies, by fertilizing thought—imparting an ironic twist to Marvell's 17th century: "to a green thought in a green shade" [Marvell, 1681]. In a sense, the generation of this category of ideas, is nature unraveling clues for environmental remediation and its biological implications...

DIGITAL-BOTANIC ARCHITEURE

Cultivar in origin, I see works, such as the Pagoda, BioTower, and AgaveCube (*Figs. 3, 7, 9*), with distinct botanical lineage. The plant geometries/circumnutations, inherited through cultural evolution, biological algorithms, as well as through observation, history, and simulation are partners for determining future directions that could, I think, jump-start the design/fabrication of living characteristics in bioarchitecture's evolution.

From a different design outlook, the Arizona Tower (*Fig. 10*) represented an attempt to hypothetically root a building—to bring into an architectural dialogue, not only the aesthetics of what is seen, but also the potential of what is hidden. My intent is to plot underground anchoring, low-pressure pumping/circulation, bio-

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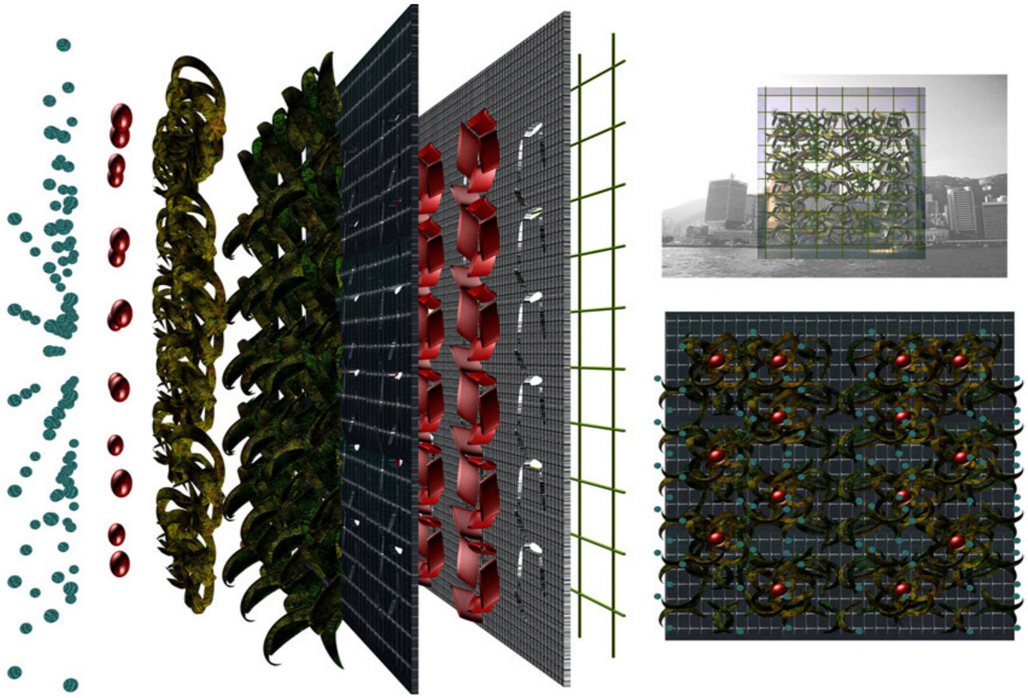

Fig. 9. AgaveCube. 2010. A double-pained, panel system pierced with an inner core from the exterior leaves which support sensor nodes (spheres); closely allied to work derived from almond shells (*Fig. 11*), plant leaves, and earlier monocoques.

digesters, and water storage. Underground forms and configurations may be inspired, not only by roots, but also by rhizomes, tubers, and bulbs (as well as their bacterial symbiants)—all examples of territorial occupancy, colonization, life, and life support. Reasons for investigating root networks are multiple: in nature they secure, service, and balance their aboveground counterparts. Equally important, root cultures point out potential models and mechanisms for architectural participation in below ground ecologies—where bacterial processors/sensors, chemical, seismic, and pollution monitoring (as well as heating and cooling) could collaborate with its above ground counterparts.

The potential of on-site, bio-filtration shifts architecture into a realm of natural processes not usually contemplated at urban scales. The time has come to begin setting building and their waste-processing into large remedial, bio-wetlands connected to other constructed wetlands, instead of existing (often antique) sewage systems. While we often consider primitive shelters—stone or grass huts, tents, and caves as natural architecture—we do not include modern cities and architecture in the same light. Buildings could potentially achieve (above and below ground) biological abilities altering our understanding of cities. Thinking that everything we do or make will be calculated from a perspective of biology, collectively we may come to think of buildings as a metabolizing species, designed from botanic life and our ideas, creating remedial zones, interfacing with, and then synthesizing existing urban conditions and living buildings.

By understanding selected plant functions and trying to channel their qualities into shape, form, and programmatic potential—the plant's mediated (by us) influence on project generation and architectural evolution, continues to the fabricated component. The small scale of my experimentation becomes an indication of how much more there is to do, as well as demonstrating that individuals can do research. Related design processes going on in a few

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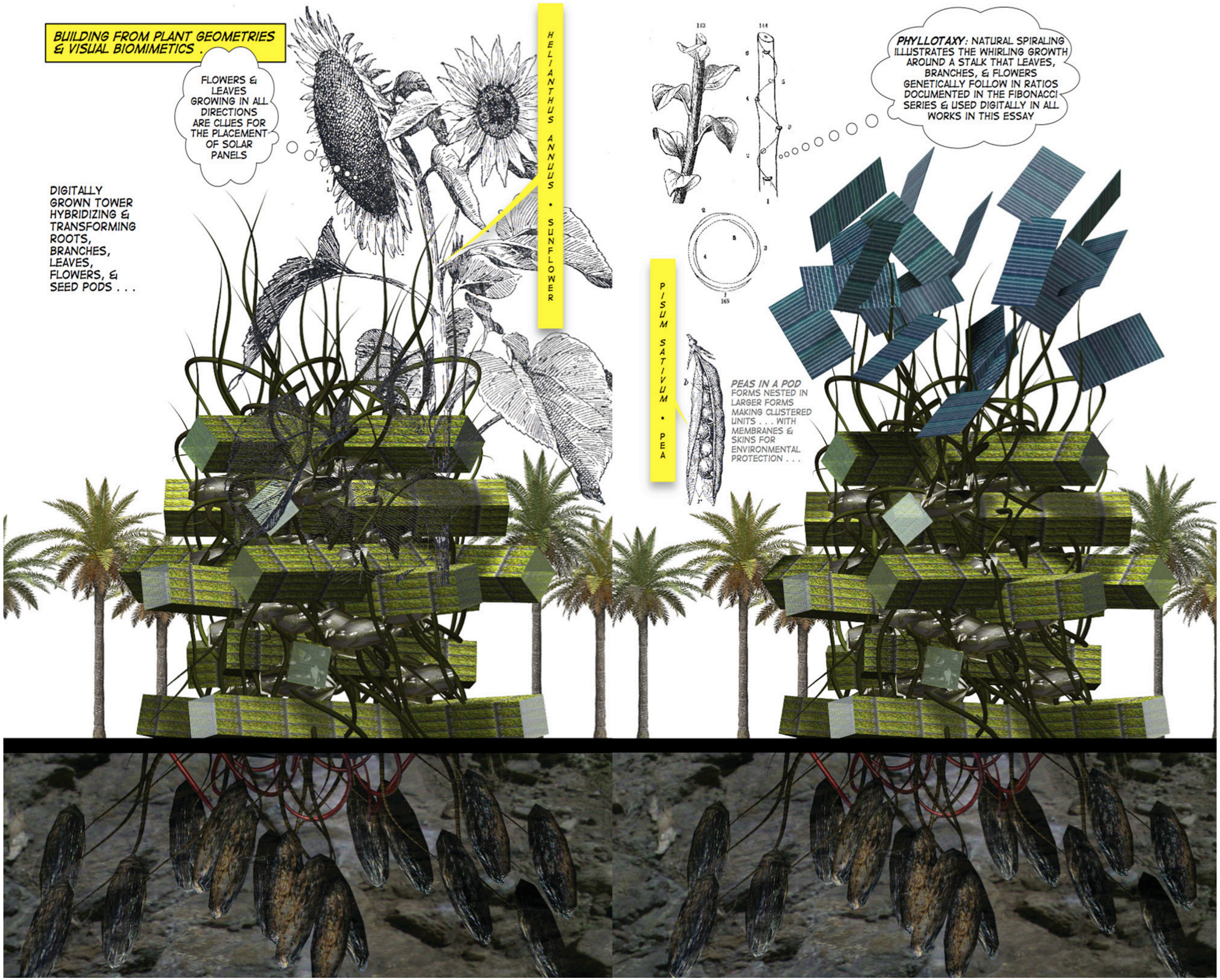

Fig. 10. Arizona Tower. (2006). Two pages from the comic book I wrote as a guide to design-biomimetics for master students. *A Pangolin's Guide to Biomimetics & Digital Architecture* illustrates methods for extrapolating botanic information from plants and translating it into generative and experimental architectural forms.

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universities is beginning to translate extrapolated morphological and/or cellular, generative attributes to theoretical and experimental projects. Still, individual designers could adapt studio tactics from the DIY and MAKE movements and open new bioresearch channels for architecture.

PANELS & MONOCOQUES FROM LEAVES & SEEDS

Leafy trees have populations of relatively small, discrete organisms working to make sugars while breathing in $C0_2$ and exhaling 0_2. Serving many functions, and taking on various forms, leaf collectives support the overall life of the plant and planet; they are electro-chemical synthesizers, low-pressure circulation pumps, food and fodder. If we could sample one of these photosynthesizing, breathing organisms for architectural life, we would have a revolutionary design accomplishment. I think it is safe to say not many people have attempted to mimic a leaf's performance at an architecture scale. Yet, if some portion of a lamina's (leaf blade) performance is achieved in a deployable architectural surface, climate change could probably be reoriented.

As shifting, aggregate formations, leaf clusters illustrate fractal-like, massed, and iterated systems lofted from a structural armature (the trunk and branches) that designers can extrapolate from. For example, some leaves track light, pivoting to face or avoid direct sunlight; some react to storm winds by reconfiguring their shape and reducing aerodynamic drag. Similarly, leaves change their profiles in extreme heat by wilting, curling, buckling, and drooping to minimize surface exposure, thereby conserving moisture and reducing sunburn damage. Further, a leaf's constant fluttering—shape-shifting—casts animated shadows over its neighbors, producing micro-shade for micro seconds. These movements are environmentally determined as well as sense-based reactions, a form of bio-intelligence and a hallmark of nature, but almost lacking in architectural/urban networks.

Knowing leaves breath through pours—inhaling and exhaling—sent me wondering how their biomechanics worked, and how they might (simplified) inspire a building component. I found that lamina pours are called stomata and that relatively few are located on a leaf's light-facing, upper surface, but there are millions on the

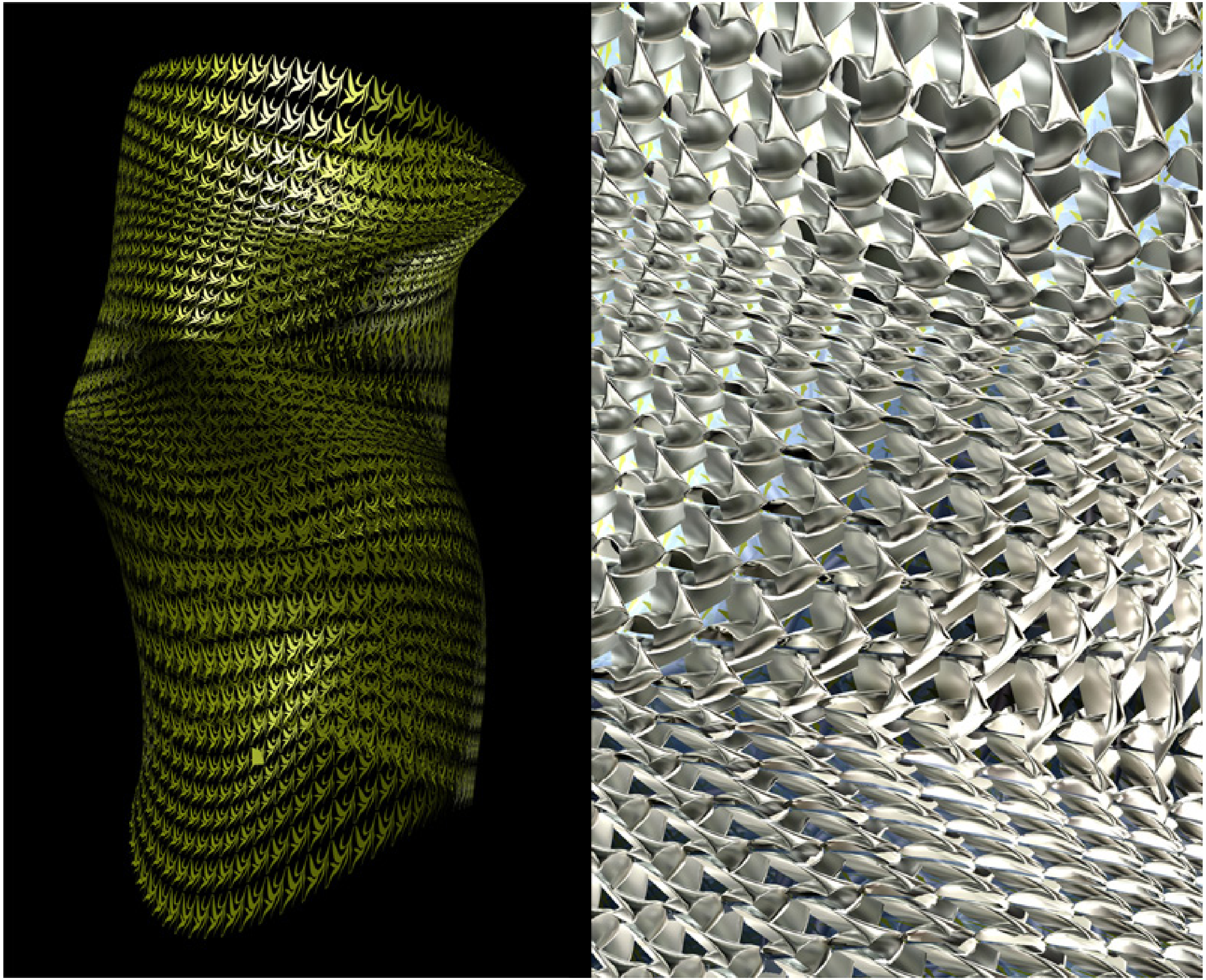

Fig. 11. Los Angeles Tower. Two Parametric Details. Left: 2D leaf form populated over the warped cylinder of the tower's body in a first step for (Right) ParaCloud generating an interlinking, 3D monocoque based on the folds of the leaf used on the left.

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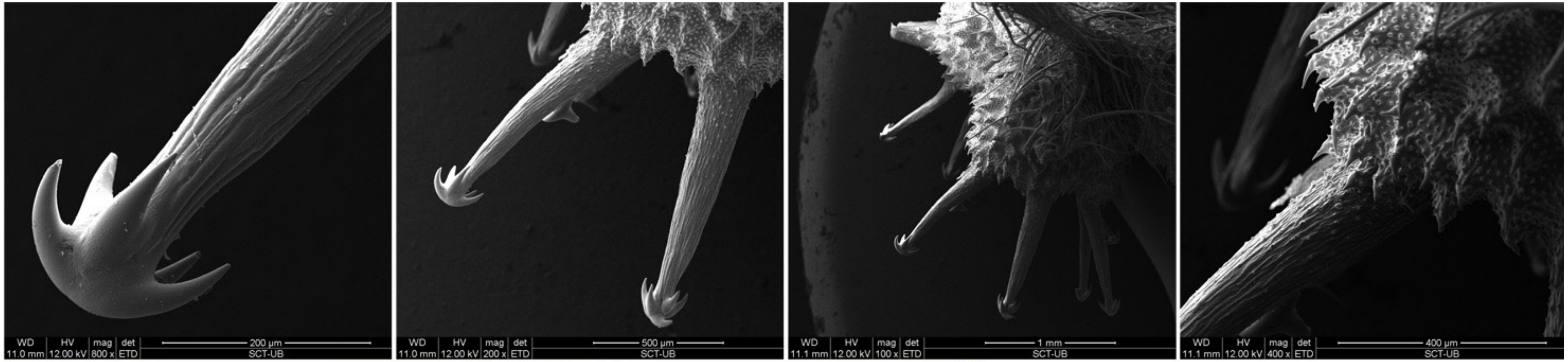

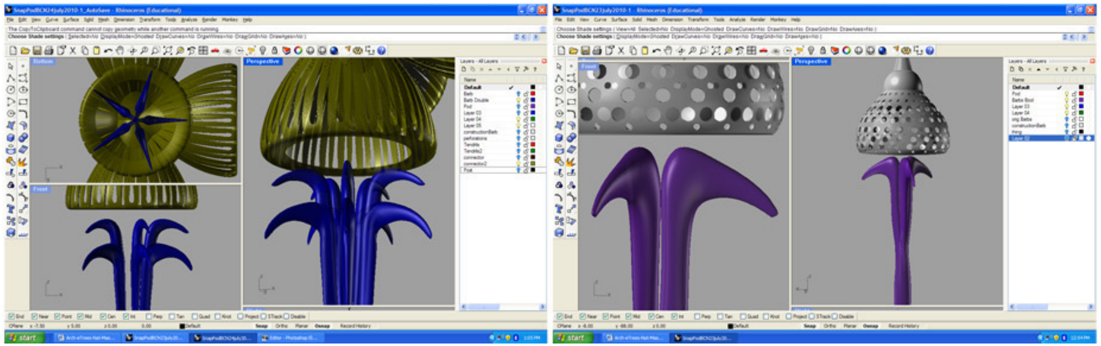

Fig. 12. *Lappula occidentalis*. SEM (Scanning Electron Microscope) images used to investigate surface morphology and barb anatomy for developing interlinking, impact/friction connectors; followed by Rhino screen-shots, concept drawings for connector barbs and receptors. Part of ongoing design research for structural connectors based in barb morphology. (I made the SEM images on 2 August 2010, at the Serveis Cientifico-tècnics de la Universitat de Barcelona, with the supervision of Alberto T. Estevez and the support of the BioDigital Architectures program, Universitat Internacional de Catalunya-—to Alberto and the universities, many thanks).

underside. This was useful programmatically and morphologically because it distinguished between upper surface and lower surfaces, and their biological functions—something two-sided panels are enhanced by doing. Using images from electron microscopy to analyze the stomata, one sees individual cells tasked with opening/closing a leaf's pores. A ring of compressor cells activated with low-pressure turgor movement, shrink or expand around a central pore-cell. The resulting pressure (or lack there of) causes the pore's mouth to open and close, allowing it to inhale CO_2 or exhale O_2—a biological mechanism worthy of study as plausible, bio-mechanical surface vents. For the idea of hybrid breathing and self-venting buildings (*Fig. 11*), leaves provide a physiological model far less intricate than, for example, models based on mammals' lungs or fish gills. Even considering complex life support for leaves—the reception of minerals and water from roots, the conversion of sunlight, and the manufacturing of carbohydrates, is comprehensible in very basic terms. My suggestion is to try and incorporate stomalike functions in walls; to mimic a leaf and begin learning how to combine selected, multiple functions from their life cycles [Benyus, 1997]. To use Beckett's words from *Westward Ho* "Try again. Fail again. Fail better."

SNAP-AND-HOOK CONNECTORS

Scientists process information from microscopes seeking discovery as well as confirmation of various hypotheses. Designers could process some of the same information with equally legitimate, if differently directed results. With information from microscopy (and other imaging technologies), designers might translate visualized, natural

Fig. 13. Almond Shell, *Prunis dulcis*. 2010. Structural inspiration from the relationship between inner and outer surface textures and the interconnecting, truss-like, structure between them.

information to architecture, thereby re-envisioning molecular, cellular, and morphological nature for use in fresh ways and contexts.
Sometimes I use a microscope for ideas to transform plant mechanics or morphology into design elements. One ongoing project utilizes electron microscope images of thorns, burrs, and barbs to design and prototype loop-and-hook connectors.
Velcro, for example, was visualized from burdock seed-barbs sticking to the clothes of Swiss engineer, George de Mestral. Since his 1941 extrapolation, de Mestral's loop-and-hook system has become almost globally ubiquitous. Yet, there are thousands of other seed-barbs that could inspire products for connecting building parts together.
In two recent SEM (Scanning Electron Microscoe) investigations I have looked to the barbs of *Salsola kali* (tumbleweed) and more surprisingly to *Lappula occidentalis* (Western sticktight) (*Fig. 12*). The sticktight images revealed a network of barbs, stickers, and tricomes (plant hairs), complex and aggressively bellicose, populated across irregular surfaces and stems.
Densely arrayed, the plant's morphological defense and propagation devices far surpassed my expectations for snag-and-hook connectors—additionally suggesting design surfaces parametrically populated with morphological functions. The images moved me from the idea of point-to-point connections to surface-to-surface bonding as well as stirring ideas for stippled acoustic and aesthetic surfaces.

ALMOND SHELLS AS MONOCOQUES

Biomimetically related to barbed surfaces (often mechanisms of seed dispersal), but shifting to a seed's endocarp, this long-running, design research began with the low-tech observation that almond (*Prunis dulcis*) shells have different inner and outer surfaces—polished inside, reticulated and rough outside. Interestingly too, in terms of substance and unity, the shell surfaces are materially the same as their connective woody structure. These filamentous membrane structures are strong, lightweight, and performance oriented. Break an almond shell in half (depending on species, it may take a nutcracker to do it), its cross section is an obvious engineering triumph and a model for a truss, panel, or rigid membrane—beautiful and complex—akin to bone structures (*Fig.*

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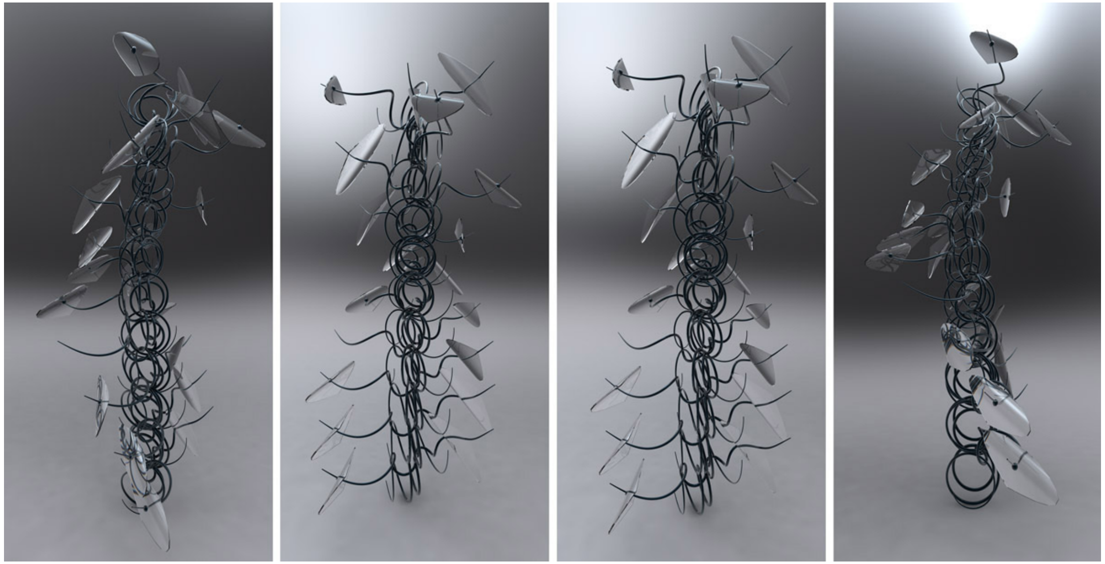

Fig. 14. STL eTree with Glass Leaves. 2008. Using an exoskeletal eTree (no central support armature), this structure became part of a series simulating glass leaves as surface scales.

13). I've learned that almond seeds breathe and off-gas through their shell pores—and, realized that the shell's inner and outer surfaces, working in unison, and are architectural spaces (incubators) for *Prunis dulcis* babies. Thus, for my studio and teaching, the shells have become important specimens for case-studies and research involving double curvature structures, iterative structural bracing, homogenous materialization, and membrane perforation.

The shells influenced the monocoque panels of the Los Angles Tower and more recently, aspects of the AgaveCube (*Figs. 5, 9*).

I think of them as design's equivalent to botany's *Arabidopsis* or biology's genetic test fly, *Drosophila* and imagine them nourishing a long list of idea-to-design prototypes.

CONCLUSION

Architecture was naturally born of minerals and plants, imagination and observation—of nature—and it is from nature's forces that bioarchitectural inspiration can now stream, fueling ideas for extrapolation—ideas for re-embedding architecture in nature and for regarding design as a natural act. Bioarchitecture development requires inventing new architectural paradigms—understanding them as naturally evolved—thinking of architecture as nature and nature as collaborative with building. A parallel strategy fosters teamwork between design, science, and industry thereby encouraging designers to involve themselves with laboratory, industrial, and manufacturing research.

Biology and technology will define our buildings' increasing abilities to interact with nature. Such buildings are likely to first be nurtured, their functions guided, from software, computation, environmental sensors and mechanics, later from life. In this scenario, software and scripting become interpretive tools for generating, analyzing, and integrating design into nature. Equally important, is looking at nature and assessing methods for building, thinking, designing, and visualizing—motivated by what nature grows in, around, and through us.

Presently branches, leaves, flowers, and seeds are pushing me in alternative directions. In 2007 I began digitally populating parametric panels onto irregular surfaces, trying to understand how iterative, software scaled elements could be hybridized with natural properties. I was testing components for façade panels

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with deformable skins first based on a 2D abstract leaf from and then with 3D folded panels. These self-supporting units, abstracted from leaves and seeds, needed a parametric program with iterative abilities in order to link and scale the big number of panels, each a different shape, required to cover the project's surface. For example, the Los Angeles Tower's (*Fig. 5*) exterior was generated from an eTree whose branch tips defined a point cloud that, in turn, was used to generate an irregular glass cylinder. The cylinder surface then defined the building's facade matrix; and that matrix was populated with 2,000+, leaf and almond shell (derived) panels (*Fig. 11*).

Buildings, cities, and their infrastructures are going to be environmentally beneficial, contributing to cleaner air, their skins functioning like leaves, alerting us to pollution and allergens, their bioluminescent surfaces illuminating and broadcasting public information. Architectures will be adjusting, folding, accommodating, and reorienting themselves to reduce solar gain in hot periods and heat loss in cold. Further, they may aerodynamically reconfigure in response to shifting wind loads or rain direction. And, I see the eventuality of buildings contributing to carbon sequestration and targeted photosynthesis. In an urban context, bioarchitecture may cohabitate in restored urban watersheds, while, at the same time, nourishing conditions for future parks, wetlands, and urban farms.

If we consider design as part of nature, we need to begin reconceptualizing architecture as natural and, consequently, realigning design as an expression of nature in education and design practice. Using the tools of technology, science, and nature to give buildings and cities biological properties, architectures may be reanimated as environmental assets, rather than liabilities. We may look to biodigital generation and fabrication as one route from toxic, formulaic architecture, seeing them instead as drivers of architectural speciation. Furthermore, before bio-architecture or reforested cities can be tested or publicly and professionally considered, before residents and viewers can react to biologically living structures, there have to be examples or prototypes to consider, debate, and refine. We must attempt to build in order to test... try, fail, fail better.

This text and its illustrations are a set of related ideas realized as drawings and models for

contemplating nature, architecture, digital nature, and the integration of botanic functions into constructed, urban infrastructure. In an elemental way, the work samples ongoing experiments in generative biodesign from plants and software (*Fig. 14*). The work also illustrates potential directions for environmentally related design linking to botany and biology, hereby-encouraging research for biotic, bionic, and hybrid architectures (*Fig. 1*). In a poetic sense I hope my studies are digital-seeds for a next generation of ideas and designs synthesizing architecture and nature.

NOTES

Drawings made by Plants

1. Circumnutation, Darwin's word for plants circular [spiral] movement.

The circumnutation drawings in Darwin's *The Power of Movement in Plants* were instrumental for my understanding of environmental variations experienced by growing plants. Whereas algorithms may capture phyllotaxic information: branch, leaf, and flower sequencing and spiraling, and while allometry may document proportional relationships—growth ratios; Darwin's drawings very clearly show nature's deviation in growth caused by external (non-genetic) factors such as light. So, while genetic instructions drive growth distribution and proportions, the drawings illustrate that the environment determines aspects of morphological variation.

Darwin's drawings track movement in the X and Y planes and are seen from a top, Z, view. The drawings were made from a device Darwin invented that directly attached a needle to the plant. As the plant moved, it scratched its path on a smoked glass, thereby etching its route. Darwin, or his son, later transcribed it to paper. Other factors, including wind, temperature, soils, predators, and moisture can be understood to affect the rate of growth and could be charted in similar ways. Additionally, these drawings illustrate an important principle, that environmental conditions cause shape variation that partly defines the difference between one plant's form and another's.

I also like Darwin's drawing device—it's an invention allowing plants to draw their own growth patterns. And, at another level—the drawings show scientific work documented in a simple and clear manner—3D movement accurately rendered in 2D. From this, someone interested in setting up a range of plant investigations could do so in the best traditions of DIY citizen-scientists.

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