ABSTRACT: *Materials are essential for the realization of architecture. However, the architectural design studio has historically privileged activities like drawing and scale model-building instead of full-scale material explorations. Today's environmental concerns, coupled with emerging discoveries in science and technology, offer compelling incentives to incorporate material thinking more integrally into today's studio pedagogy. A sequence of graduate-level studio courses taught at the University of Minnesota School of Architecture has provided a platform for heuristic experiments in material-focused student learning. This article offers case studies of three studios in which students generated material-based design narratives in connection with the natural and physical sciences. Assessments of opportunities, challenges, adaptations, further thinking, and potential broad impact of the methods used follow studio and project summaries.*

KEYWORDS: Materials; Design; Architecture; Studio; Fabrication; Biodesign; Pedagogy; Heuristic; Interdisciplinary

Learning from Matter: Exploring Materials and Natural Systems in the Graduate Architecture Studio

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INTRODUCTION

Architecture is born when a concept assumes physical form in the environment. However, the contemporary architectural studio fails to make this phenomenon tangible. Today's architecture studio evolved from influential art-based educational models such as the École des Beaux-Arts and the Bauhaus. Although both platforms established particular connections to the physical world, ensuing decades have witnessed increased digitization, automation, specialization, and abstraction in architecture—resulting in a distancing between concept and reality in the studio as well as in practice. For example, in the Bauhaus curriculum, architecture students regularly experimented with materials and a variety of physical media while considering the bau (building) as the central focus. Yet today, the process of designing buildings is mostly an abstract, computer software-driven exercise. Although students still make physical models and consider natural processes in their designs, the common pedagogical approach encourages "out-of-thin-air" conceptual development with little consideration for the intricacies of material and environmental behaviors as starting points for design inspiration.

Although contemporary architectural design pedagogy and practice typically downplay the roles of materials and natural systems, particularly at the outset of a project, these

can be useful generators of novel solutions to common architectural problems. Our long-term goal is to inculcate in students a deep appreciation for the natural world based on the direct study of natural phenomena, including both biological and abiotic systems. By aligning the educational experience more closely with natural and tangible behaviors—in other words, a broader reality—we aim to enhance students' ability to find novel and creative solutions that are highly attuned to the needs of our physical world.

BACKGROUND

As Janine Benyus suggests in her seminal book Biomimicry, architects, designers, engineers—all of us, really—would do well to "quiet our cleverness." Especially in the early stages of solving an investigation, instead of striving for a smart approach or innovation from the start, she suggests, we would benefit from taking time to listen and observe, quietly. In this way, strategies might emerge more slowly, and ideas evolve, from a deeper understanding of situational specificity. Benyus, of course, implores us to learn from biology, from the specific behaviors of particular species of flora and fauna developed over millions of years of evolution. The vast richness of planetary biota provides almost infinite nourishment for the growth of novel solutions that are light, benign, and regenerative.

That we might ask students to be less clever sounds absurd for a school of design. It is surprising to most students at the onset of a new design studio. However, this is precisely the approach to which we introduce our upper-level design students at the University of Minnesota. Especially for those accustomed to top-down design approaches where a blank piece of paper or a stack of unadulterated modeling materials is the starting point, that an unexpected idea might emerge from remixing, borrowing, mimicking, or partnering with biological species is unsettling. If one goal of architecture school is, as we believe it to be, to unsettle its students, to encourage them to see the world in a new, unexpected way, or to turn broadly-held assumptions inside-out, then observational analysis of, and partnership with, biology is pedagogically invaluable.

CURRENT STATE

Two recent trends motivate our pedagogical approach. One is an elevated awareness of the natural world, both as a vast collection of inspirational models and as a vulnerable system in need of responsible stewardship. During the 20th century, natural paradigms rarely factored into design methodologies; yet today, nature guides the work of many design and other disciplines. Architects, engineers, scientists, and artists regularly investigate the workings of biological organisms, either with the intent to emulate (mimicry) or synthesize (design) better outcomes. These organisms' relationship to their environment provides clues concerning our own circumstances. For these reasons, students should have opportunities to conduct in-depth examinations of natural systems for producing compelling and imaginative designs.

Another trend is the accelerating arc of technology and the increased number and variety of materials that now exist for design applications. Researchers speculate that the burgeoning diversity and quantity of materials today represent a wholesale change in technological development. In The Advanced Materials Revolution, author Sanford Moskowitz hypothesizes that advanced materials represent "the central technology, the 'straw that stirs the drink,' of technological change in the late twentieth and twenty-first centuries." We argue that such change necessitates that students explore a wide array of materials, more directly than is typical, to ascertain their rich design potentialities.

PEDAGOGY

To assume that we, trained as architects, hold all the knowledge necessary to research and understand biological systems and material science is presumptuous if not patently arrogant. For students to create design processes in which they can meaningfully learn from or partner with natural systems, they must first develop the capacity to collaborate. Real and effective collaboration can seem, especially at first, to invoke a loss of control—a scenario in which the student no longer feels as though he or she is the master designer. In the context of a design studio, we view this loss of control as an asset rather than a liability for several reasons.

First, we believe that the challenges we face as a discipline and planet are so big, messy, and fierce, that a sole researcher, author, engineer, scientist, or designer cannot hope to address them on his or her own substantially. Interdisciplinary, team-oriented design strategies are more innovative, novel, and firmly wedded to the context of a problem than conventional design strategies. Second, we believe that when students work in interdisciplinary teams, they develop a keen sense of empathy. They learn to understand those with whom they collaborate in a profound way, and they recognize that meaningful work grows as much from careful listening and understanding as it does from authoritatively asserting. Finally, we believe that when students see their work in the context of other disciplines, they come to appreciate their own unique skills and ways of thinking in more tangible ways. They understand not only the value of their collaborators' contributions but also the value of their own. This lesson builds confidence and contextualizes their contributions.

THREE STUDIOS

This article conveys the overarching strategies of this pedagogy in three thematic studios, which we title "Learning from Life," "Learning from Matter," and "Learning from Living Matter." "Learning from Life" refers to the study of natural organisms and systems as models for architectural application. It includes biomimetic, biodesign, and abiotic design approaches. The relevant studio course is ARCH 5250–Hypernatural: Architecture's New Relationship with Nature, based on the book we co-authored by the same title. "Learning from Matter" concerns the study of physical materials—both biological and abiotic—as a primary means of generating design concepts. Students conduct heuristic, open-ended material explorations that lead to conceptual insights—thus inverting the conventional design process. The relevant course is ARCH 5250–Generative Matter: Procedural Material Design in Architecture. "Learning from Living Matter" represents a combination of the first two themes. In ARCH 8255–Third Coast Studio: Transcalar Resilient Systems, students conduct physical experiments using their biological models—in this case, invasive plant species—as material feedstocks that inspire new structures and processes. In our retrospective survey of these studios, we will evaluate pedagogical aims, student works, successes and limitations, and opportunities and challenges.

LEARNING FROM LIFE

"[Werner] Sombart pointed out, in a long list of contrasting productions and inventions, that the clue to modern technology was the displacement of the organic and the living by the artificial and the mechanical. Within technology itself this process, in many departments, is being reversed: we are returning to the organic; at all events, we no longer regard the mechanical as all-embracing and all-sufficient." — Lewis Mumford, Technics and Civilization, 1934

Figure 1

Our Hypernatural studio speculated on the changing relationship between the designed environment and the natural world, along with the opportunities that arise from this transformation. In this course, we first presented students with several precedents from aligned and peripheral fields of study, where biological research yielded innovations. For example, we discussed scientists who craft photosynthetic cells made from trees, engineers who encapsulate stratified clouds within buildings, architects who design structures that simulate the phototropic behavior of plants, and artists who grow rooms made of mineral crystals. It was in this pilot course that we first introduced students to the hypothesis that biological and abiotic systems might hold the keys to valuable insights around technology and design. Moreover, we argued that work guided by a sophisticated knowledge of natural systems has the potential to counteract the increasing fragility and degradation of the natural environment.

In this studio, students interrogated potential relationships between architecture and natural systems. They started by researching a chosen system—either biological or non-biological. Design proposals unfolded from this initial exploration. Throughout the course, students alternated between two modalities—design synthesis and natural systems research—to develop an architectural construct that evolved from the combined input of the designer and the authorial will of a natural system. The course explored how a partnership with nature might yield unexpected, novel solutions to difficult architectural problems; a scenario in which the designer takes on the role of project strategist, relinquishing a degree of control over his or her work.

PREMISE

In this studio, it was necessary to develop rigor concerning conceptual approaches. Generally, nature-focused design work falls into two categories: mimicry and design. Mimicry emulates a natural model using other materials or systems, whereas design works with the natural model directly (e.g., bioengineering). Despite the clarity of these terms, they are too broad for precise use.

Instead, we established a set of approaches based on natural phases of growth, development, and interaction with the world. There are two subsets: the first concerns abiotic systems, and the second concerns biological systems. Abiotic system approaches may be categorized in terms of properties, processes, and phenomena. Properties concern the intrinsic structure of things, such as the predictable shape of icicles. Processes address natural growth and change "during construction," such as the self-assembly of crystals. Phenomena describe a system's response to its environment in realtime, such as wind-driven sand formations.

Biological system approaches are similar yet are unique to life, and may be classified as behavioral, genetic, and epigenetic. Behavioral design (pre-construction) emphasizes particular characteristics and patterns gleaned from prior studies, such as the movement habits of silkworms. Genetic design (construction) concerns intrinsic properties, such as the functional gradient structure of a lobster shell. Epigenetic design (post-construction) pertains to how a system responds to environmental cues, such as the mimosa pudica flower that closes when touched.

After finalizing the selection of their champion biology, student teams clarified which approach they intended to pursue—as indicated in the following examples.

PROJECTS

The first team, four M.Arch students in the 2015 studio, was primarily interested in crystalline growth. As discussed above, this topic falls under the category of abiotic-processes. After conducting many exploratory studies using different crystalline compounds, the group began to fabricate a collection of structural modules using sodium tetraborate decahydrate (borax) crystals. The students became fascinated with the transformative properties of a particular compound: borax-infused polyester batting (a porous fabric). In its initial stage, the hybrid was soft and pliable—but once placed in boiling water, the borax formed a thick, rigid shell with surprising compressive strength. When the students shaped the material around sections of tubing in the boiling water, they created fixed, self-supporting cylindrical modules. Surprisingly, the team subjected the modules to compressive tests and found that each borax-infused fabric module could support over 400 times its own weight. With this building block suitable for masonry construction, the team built a small, open-air enclosure scaled for one or two occupants [Fig. 1]. A critical insight concerned the time-constraints of the process: each module required six hours to complete, based on the speed of crystal growth. Thus, students had to consider the critical path for their installation's construction based on the inherent properties of the material process.

In an example of a biotic-genetic design approach, another student team studied the sessile barnacle and its growth process. These intriguing organisms, which are champions of packing efficiency, attach themselves to surfaces where they develop protective plates that continually move radially outwards until they encounter an obstacle. The team developed this unique growing behavior into a new form of additive manufacturing: they custom-built a unique 3D-printing table informed by studying time-lapse videos of barnacle growth. In their version of "barnacle printing," they squeezed dry mixtures of plaster and mortar onto a horizontal surface from a pump located below. They then injected the powder with periodic, strategically aimed streams of water. The student team recognized that barnacles not only spread out radially but also grow taller in relatively confined spaces. So, the tighter they are packed, the taller they grow; the looser they are packed, the shorter they grow. Capitalizing on this contingent system of taller, thinner organisms in tight quarters and shorter, wider organisms in more generous quarters, the team developed a process in which variation in nozzle spacing produced cylindrical modules of varying heights and diameters. Rather than altering the height of their units based on the allotted area, they chose to determine height in response to light. In their final proposal, program and desired light character drove the size and depth of three-dimensionally printed skylight modules. [Fig. 2]

Another team investigated the ways that certain species of cuttlefish use their skin to manipulate light. The organisms the students analyzed camouflage themselves by mimicking colors, patterns, and textures in their environment—an approach we categorized as biological-epigenetic. What is truly fascinating is that the cuttlefish replicate areas in their surroundings beyond the range of their eyes. This phenomenon occurs because their skin effectively sees, based on the use of opsin, a light-responsive protein found in the human eye. Cuttlefish skin changes its structure and depth with a collection of tiny bumps that manipulate light in realtime. Inspired by this strategy, the team devised a system of dynamic apertures that employ a self-folding procedure to regulate light [Fig. 3]. When darkness is preferred, the cells remain flattened. However, when light and view are desired, the apertures unfold in a spiraling, upward motion. They become volumetric light tubes, adding dimensionality to—and providing shading for—the overall surface. This example demonstrates the advantages of students investigating biology to solve architectural problems. If they had been charged with designing a dynamic aperture without studying natural models, they likely would not have arrived at such a novel and insightful solution.

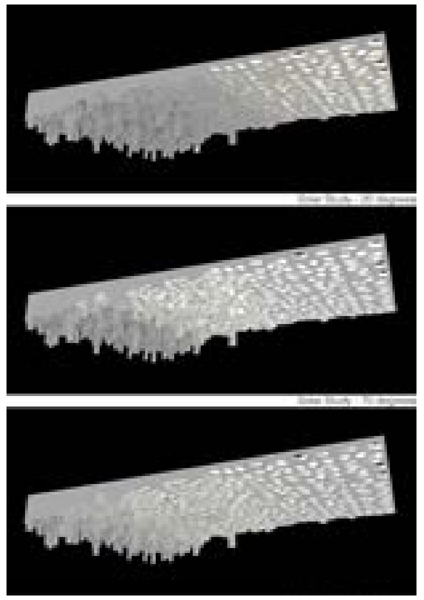

Figure 2

Figure 3

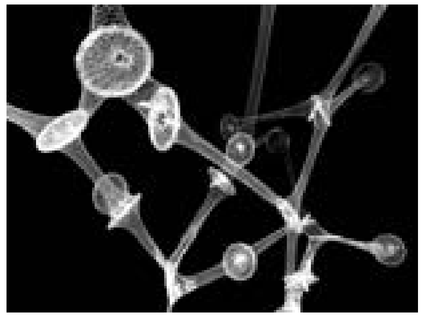

Figure 4

LEARNING FROM MATTER

"With typical buildings, details are decided upon in the final stages," says Japanese architect Kengo Kuma. "The site is chosen, then form, and lastly the details. By then, there is less time for the details—only standard details are considered because of the limited time."

A common regret in both academia and practice is the lack of adequate time to investigate materials for a design project. From our experience, students often come to a typical final review lamenting the lack of development in their material concepts and details. The reasons for this deficiency are simple: students are expected to focus on too many priorities, or the framework of the studio shifts material concerns too late in the timeline.

We wanted to try a new approach. Teaming up with University of British Columbia Associate Professor of Architecture, Blair Satterfield, we developed ARCH 5250–Generative Matter: Procedural Material Design in Architecture. The idea was to invite the students to design "backward," which is to say, to prioritize material criteria over all others in terms of importance and timing. We charged teams with selecting widely available materials as a starting point, and through multiple stages of heuristic inquiry, students transformed these products into entirely new tools for design.

PREMISE

In this seven-week design studio, students explored how materials, imbued with particular properties, react uniquely to circumstance. While any material can be fashioned into nearly any shape to accommodate almost any function, we premised this studio on the idea that materials embody certain tendencies that suggest particular directions for design and fabrication. Through careful consideration of these properties, a designer can develop material-specific behavioral rules. When material behavior intersects with a tool, a circumstance, or an environment, a rich matrix of outcomes emerges. We can manipulate materials in unlikely ways, with unlikely tools, and capitalize on under-examined material behaviors to yield surprising results.
This approach requires students to embrace uncertainty and unpredictability, and in doing so, it challenges conventional attitudes about design authorship in the physical environment. Students learned to question the value of creative control by privileging an alternative design process; one in which final appearance emerges unpredictably as

an outgrowth of behavior and circumstance, rather than their own authorial will.

The studio began with a simple assignment. We asked students to select a common material and marry it with an uncommon manufacturing technique. Without indicating any specific architectural objective, such as a building program, site, or circumstance, we launched the material explorations. Given the freedom to select any material, several students picked unexpected substances such as ice, salt, wax, and hot-melt adhesive. We then asked them to form small teams based on shared interests.

PROJECTS

The team "Oh Knit" explored the domestic activities of knitting, cooking, and gardening, and the gender-based stereotypes with which they are associated. Together, the students began their project by working to master a few basic domestic techniques. Then, they combined these techniques in unique ways to yield a delicate tensile structure filled with a growing medium that later turned into a living surface of networked lines and nodes. Specifically, the project emerged from the unlikely combination of mechanically woven nylon monofilament and a home-cooked bioplastic consisting of glycerin, starch, and water. Using a system of woven monofilament and rigid connectors, the students formed elongated parabolic tubes through a careful process of heating and stretching [Fig 4]. The tubes were layered with pliable, translucent bioplastic containing tiny seeds, which then sprouted and took root in the contained growing medium. The project deftly balanced the technical and programmatic requirements of the studio with a project narrative that subtly challenged traditional roles in design and construction often associated with particular genders. The students highlighted that knitting and cooking have strong cultural associations with the domestic, feminine role of homemaking; yet these methods can profoundly impact, in unexpected ways, the traditionally male-dominated disciplines of architecture and construction.

A project called "Cold Form" was inspired by two familiar material processes in a region that commonly experiences harsh winters: ice harvesting and salt-based road de-icing. The students began experimenting with rock salt and ice, visiting frozen lakes to extract ice blocks and manipulating them with different amounts and grain sizes of salt. The team devised a means of subtractive manufacturing in which they placed varying quantities and types of salt in various locations on the top surface of an ice block. A diverse network of spatial cavities emerged in the ice as a result. The size and placement of these voids were partly anticipated, but also somewhat unpredictable in nature. To set the form in a more permanent material, the group poured hot-melt adhesive (EVA) around the affected ice. Recognizing the capability of this porous, translucent material to filter sound and light, the students proposed a building module that would function as an acoustic and light diffuser. They created a prototype infill panel for a window exposed to a large amount of glare, located in an acoustically live space. They also developed proposals for immersive environments in which the Cold Form blocks could tune the sound and illumination in a space with a high degree of specificity. [Fig. 5]

Figure 5

Figure 6

The team "Wood Foam" explored the productive use of wood waste as a method for extending wood's capacity to sequester and store carbon in the environment. According to California-based CalRecycle, "Wood waste is, by far, the largest portion of the waste stream generated from construction and demolition activities." Capitalizing on the millions of tons of waste the Environmental Protection Agency says we generate annually from the construction and demolition of our buildings in the United States alone, this student team developed a unique way to transform wood waste into useable, millable, cuttable, rigid wood panels. The students fabricated these panels by combining wood pulp with ordinary, everyday ingredients like baking soda, yeast, and sugar to create foams. They then dried each module into a rigid sheet with varying thickness and density. The resulting material compares favorably to typical petroleum-based structural or insulation boards in terms of technical performance, but with entirely biocompatible ingredients. [Fig. 6] Interestingly, the chemical aeration process that the students developed was completely tunable, meaning that they could engineer each wood foam panel to embody particular thermal, light-transmissive, and ultraviolet light-responsive characteristics, depending on the add-mixtures, curing time, curing temperature, and humidity conditions. Further, the panels could embody multiple functions in their variable cross-sectional arrangements, like serving as structure in one area, while helping to transmit light in another, and providing insulation at the same time throughout, thus reducing the need for many of the more toxic materials typically used in wood wall construction.

LEARNING FROM LIVING MATTER

In "Anthropogenic transformation of the biomes, 1700 to 2000," geographer Erle Ellis and co-authors trace the extensive influence of human development on global terrestrial systems, marking the reversal from a majority of wildlands to a majority of human-dominated landscapes today. The current supremacy of "anthromes" over biomes has resulted in an omnipresent built environment that has precipitated climate change, biodiversity loss, resource depletion, and fracture-critical design. Despite this circumstance (or perhaps because of it), the built environment is now viewed as a critical agent in establishing a more environmentally responsible future. Coastal

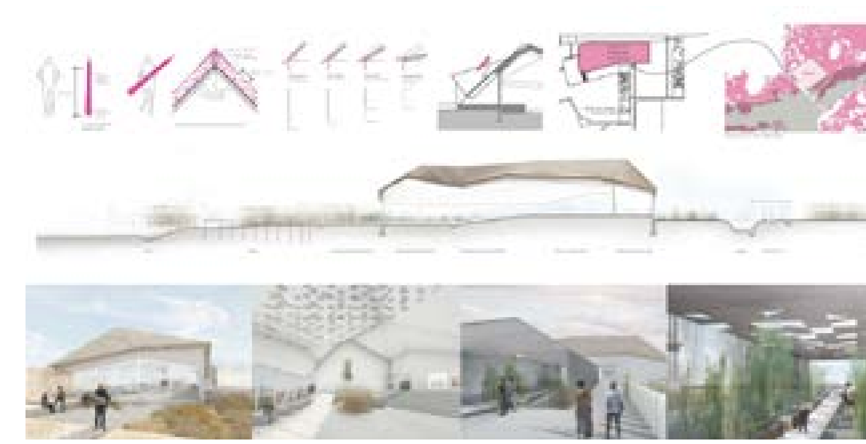

Figure 7

development is particularly scrutinized due to its often adverse influence on littoral ecosystems as well as its vulnerability to the hyper-dynamic qualities of the land/water interface. The Great Lakes coastline likewise exhibits signs of significant environmental stress due to human-caused habitat degradation, toxic and nutrient pollution, and invasive species proliferation.

The Third Coast studio, co-taught with University of Minnesota Assistant Professor of Landscape Architecture Karen Lutsky, focused on the interdisciplinary development of an invasive species research site set along the international waterfront of the Detroit River. Studio investigations began with the question of a resilient detail—an interrogation of resilient design at the material scale. Design work then shifted into a broad research phase and ultimately culminated in the development of a final, material-rich project. Throughout the studio, we invited interdisciplinary teams of architecture and landscape architecture students to work in broadly multi-scalar and multi-temporal capacities, consider unexpected methods for engaging natural systems, and develop novel approaches to materiality—including various phases of material life.

PREMISE

Foundational to this studio was an exercise called the resilient detail, where students explored the formal and conceptual opportunities afforded by a developing an architectural detail from plant matter. Beyond the scale of a material joint, students equally considered the scales of time, growth, and decay, as well as the ecological and social systems implicated by their detail. Understanding the detail at not just the intimate scale but also at the system scale, students could speculate on how the generation, assembly, and disposal of a material—all on the same site—might form a closed-loop system, intricately wedding the landscape to its architecture.

Students arrived at this trans-scalar approach by first researching a plant species considered invasive. They explored their species by chopping, grinding, peeling, shredding, weaving, dissolving, cutting, assembling, fastening, and otherwise destroying their material to learn about its underlying behavioral tendencies. From this starting point, we asked students to develop a material logic, to allow the species to push back on their hands, as the designers, so that their detail emerged as something unexpected—something they would never have conceived willfully. Students developed both a palette of material assembly variations and an approach to systemizing the material by stacking, assembling, connecting, arraying or spanning.

Finally, students chose a prototypical site on Belle Isle in the Detroit River based on its relationship to their invasive species. We asked the students to transform their invasive species from a liability to an asset, from a blight to something that improves the site. Program emerged from a consideration of how an invasive species would be actively grown, harvested, transformed to a resilient detail, and ultimately, allowed to decay, providing nutrients for the future growth of the site. As such, students always viewed materials as cyclical and alive; never permanent and stable.

PROJECTS

One team selected the fast-spreading and robust perennial grass, phragmites or

Figure 8

Figure 9

common reed. Known for snuffing out native vegetation and lowering the biodiversity of local plants, phragmites can form a thick and dense matte of impenetrable growth up to fifteen feet high, making it impossible for certain native plants and animals to survive. Variations of phragmites are native to Michigan and North America, but the team focused on a non-native variety of phragmites considered invasive and threatening to the wetlands and the Great Lakes coastal shoreline.

Capitalizing on phragmites' fast-growing nature and its material strength, along with its resilience even after harvesting, the team developed a Water Reed Research Center along the shore of Belle Isle in a wetland area where the plant thrives [Fig. 7]. Along this littoral zone, the team proposed a systematic planting of grass to reduce waterfront erosion. The center would evolve, in phases, starting with the simple act of seasonal planting and regular harvesting. Weaving through the dense thickets of phragmites, the team developed a simple, elegant boardwalk network that supported itself on mature, living phragmites, where visitors could experience the sublime spatial qualities produced by fields of the grass. In other areas, the team proposed zones for harvesting the grass to then use in the construction of a roof and walls for a research and visitors center. Relative to the charge of the studio (to develop a resilient detail), the team successfully developed a cyclical disassembly and reassembly system that supported the material sustainability of a building and infrastructure over time, harvesting newly grown phragmites to replace areas that decay with age. The project capitalized on the fast-growing, resilient nature of a plant we consider invasive (an ecological liability), turning these negative and problematic attributes into positive ones that could only be fulfilled by this particular species (an environmental asset).

Another team studied the black locust, a resilient hardwood tree. This tree is fast-growing, resistant to rot, extremely adaptable to almost any soil type, thrives in wet or dry soils, and, like many plant species considered invasive, can generally flourish in locations where other trees and plants cannot. Beyond these qualities, it is known for its tolerance to urban pollution, drought, and extreme temperatures. As a natural hardwood, black locust has traditionally been harvested for decks, outdoor furniture, fence posts, flooring, and siding.

This team of students saw the potential for a symbiotic relationship between humans and the black locust. The tree is an excellent absorber of CO_2, prevents erosion, and provides robust hardwood for construction. Meanwhile, the conditions often associated with human habitation, like nitrogen-poor soil, drought, and even pollution, are ones in which the black locust thrives. Understanding this rich opportunity for mutually beneficial exchange, the team developed an urban Black Locust Research Center [Fig. 8]. Their facility used a combination of an existing site (an abandoned sawmill), robust permanent materials like brick and stone, and newly harvested black locust procured onsite. Zones of live black locust, each a different age, organized the site and provided visitors with a didactic understanding of the plant. Elevated boardwalks weaved in and out of the black locust groves, the reused sawmill, and the newly constructed research facility. This path allowed visitors to experience the center both internally and externally, to understand its research functions and its subject of study, and to experience the black locust tree sectionally, from its intricate rhizomatic root structure to its creamy white flowers that bloom every spring.

Another team selected Eichhornia crassipes, commonly known as water hyacinth, as its model invasive species. A free-floating aquatic perennial, the water hyacinth is among the fastest-growing plants—up to five meters per day. The plant is native to South America but is now widely distributed in many other parts of the globe. It is now considered a significant invasive species. Unchecked, water hyacinth can completely cover bodies of water, and it forms thick mats that can support peoples' weight.

Intrigued by this capacity, as well as the fact that the plant grows better in areas of human disturbance, the four-person team imagined living dock infrastructure that would ebb and flow with the seasons (with edge controls to stop the organism's spread). They studied the various parts of the water hyacinth—the bulbous stalks, the roots, and stolons (runners)—to understand how the plant performs individually as well as collectively. The team simulated scaleable bubble and tube components to emulate this behavior architecturally, creating a lightweight circulation network over water with minimal resource utilization. [Fig. 9]

CONCLUSION

Opportunities

Today, architecture and other creative fields face an uncertain, volatile, and sometimes alarming world. Accelerating resource depletion, species extinction, widespread pollution, and climate transformation are now elevated and recurring concerns. Because buildings comprise nearly half of all resource use, those responsible for their realization are complicit in their negative environmental consequences. However, despite progress made in ecological awareness and policies, much more work is necessary. For architects, there remains a glaring lack of knowledge about resource flows, including harvesting, chain-of-custody, and ecological footprint implications. There is also a dearth of expertise concerning how to partner with natural systems in mutually beneficial ways.

However, if architects were well-versed in these issues, much progress could be made. Erin McDade, Architecture 2030 Senior Program Manager, notes that two fundamental accomplishments occurred during the 2015 United Nations' Conference of Parties (COP21). The first was the historic signing of the Paris Climate Agreement. The second is less well known but no less significant: "In addition to the historic signing, COP21 made history by hosting its first ever Buildings Day in recognition of the crucial role that the building sector must play in reducing global CO2e emissions," she writes. In other words, buildings' contribution to nearly half of the greenhouse gas problem is now seen as an opportunity. Architects now have a chance to demonstrate meaningful leadership in this global cause.

Challenges

Educating architecture students to be sufficiently prepared for this role is a tall, if not impossible, task. The necessary skills must be developed over time in both academia and practice. We view our graduate design studios as one part of many requisite experiences for gaining this expertise. Our primary goal has been to provide students direct and meaningful encounters with materials and natural organisms, knowing that deep hands-on involvement will make a more significant impact, and leave longer-lasting memories, than learning in the abstract.

That said, there are challenges to this type of studio teaching. One is a question of relevance. Some architecture faculty may question what borax crystals, ice-melt salt, or water hyacinth plants have to do with educating graduate-level students in a professional program. A related concern is disciplinary knowledge. If students are spending time studying biology and material fabrication, when will they satisfy all of their architecture accreditation requirements? Another challenge is the unconventional approach of beginning with the material "answer" as a means of pursuing architectural questions—a kind of backward process rarely seen in the discipline.

Yet the forward process—the typical "problem first, then solution" method—disregards the realities of the scientific method. In many fields, breakthroughs are often achieved by connecting diverse bodies of knowledge in unlikely ways—not by pursuing a direct, hyper-specialized line of questioning. We believe that first-hand, interdisciplinary experiences with materials and natural systems as design drivers produce students who are better prepared to make critical contributions to the profession.

Adaptations

Over ten years ago, we first offered a graduate elective studio as an experimental study on potential relationships between biology and architecture. Since that first studio, the syllabus for which Biomimicry author Janine Benyus helped craft, the course has evolved pedagogically. Where we placed early emphasis on mimicking biological organisms and their behaviors to inform design work (a building skin that pulls water through itself like the capillary action in the giant sequoia tree, for example), current studios emphasize operating on, partnering with, and "sub-contracting" with the biological organisms themselves.

By focusing on the tactile qualities, performance benefits, and behavioral operations of biological and non-biological natural systems, we have found that students are liberated from trying to duplicate sophisticated operational processes. In the earliest studios, not documented in this essay, students rarely moved beyond a superficial understanding of their precedents because they always encountered a knowledge barrier. Even when they partnered with experts outside the discipline of architecture, like biologists or botanists, their systems for replicating biological processes, which are developed through millions of years of evolution, were often rudimentary and superficial. In a short design studio—although students developed elegant, thoughtful architectural proposals and the pedagogical approach stretched them to think synthetically, develop new design processes, and ask relevant questions—the resulting work was usually an unbuildable speculation that would likely have taken teams of engineers, scientists, designers, and researchers years, if not decades, to work through in any convincing way.

The three studios we describe in this essay represent a purposeful shift away from emulation of natural systems and towards a partnership with them. In the first studio, Hypernatural, we still allowed some students to work in a biomimetic way, to develop methods of making and building inspired by a researched natural system. However, we also encouraged some of the students to work more behaviorally, to grow their materials, and to allow partnering organisms to produce their enclosures. In the second of the three studios, Generative Matter, we shifted entirely to material systems that are grown and made from biological and abiotic natural systems, focusing students' attention on opportunities for behavioral adaptation and control. In the final course, the Third Coast Studio, we further encouraged students to partner with biological organisms, but in this case, we urged them to understand these organisms systemically as landscape architects or ecologists do.

Further Thinking

This purposeful shift represents a subtle but essential distinction. When students create work that is analogical (this thing is like that thing), the process can only take them so far. More importantly, what we have realized is that the analogical design process keeps them in complete control of their work. The benefit of partnering—whether it be with a biological organism, a natural system, an interdisciplinary collaborator, or a colleague—is that it builds in the student a capacity to relinquish control and, more importantly, increases empathy. When students ask a biological organism to construct a detail, or a joint, or a surface for them, they can never expect to control the outcome precisely. The final result is contingent and not predetermined.

This understanding of contingency, of complexity, of the systemic connectedness of the world, is a shift not only for students but for architects. When we as designers give over control, when we can no longer predict, with real certainty, the outcome of our work, and when we grow more comfortable with these unanticipated results, we start to see tangible benefits. For one, the work is more novel and surprising. We are often not as creative as we think we are, and as designers, our work takes on predictable patterns. Another benefit is that when we leverage the intelligence of local, biological experts, our work is more tuned to context—to the nuances of place, climate, and resources. A third benefit is that when we give over control, we reposition our authority in a way that has more agency than that of a traditional designer. In such a scenario, we take on the role of design strategist. We no longer design the thing in a traditional way but instead set up the system that designs the thing. We are no longer the sole author, but we assemble the team that provides the authorship. We no longer consider the building as a one-off creation, unaffected by what came before it and what will come after it. Instead, we evaluate it within a larger ecological context, as being part of a broader ecosystem in which its birth feeds off the buildings that came before it and it, in turn, feeds the buildings that will come after it.

Indeed, there are liabilities to such an approach. Architects are notorious control freaks. We get very uncomfortable with giving over control. There are legitimate reasons for this, related to liability, the performance and comfort of our buildings, and the satisfaction of our clients. This approach also requires a substantial mind-shift in the design process. When we design the systems that design the thing rather than designing the thing, we approach our work in a very different way. Most architecture offices are not ready for this. But, we argue that this shift may be what is precisely necessary for architecture to remain connected, impactful, and relevant as a discipline.

Potential Broad Impact

In conclusion, we argue that the architectural profession currently has an odd relationship with the natural and material worlds. Both are critical to architecture's existence, but practitioners relate to both in a mostly conceptual, disconnected fashion. Architects rely on the selection and application of building products, for example, yet very few develop their own. They also depend on establishing a beneficial relationship between a building and its site, including various biological and abiotic systems, yet very few have in-depth expertise about ecology. To be sure, architects have to juggle many priorities and areas of knowledge. Nevertheless, if they can emphasize material and environmental issues from the outset of a project, engaging experts as needed, the architecture that results can be much better attuned to today's significant challenges and opportunities.

For many years, and increasingly in the recent past, architecture has siloed itself, building solid, thick walls between itself and other disciplines, between itself and nature, between itself and the growing pool of people for whom their services are irrelevant. This siloing was not always the case. Historically, architects have enjoyed meaningful, necessary relationships with makers, clients, and other disciplines. Now, however, architecture is at a critical crossroads. If it refuses to ventilate the boundary between itself and the world in which it exists, both literally and metaphorically, it runs the risk of growing obsolete. Conversely, if it becomes more willing to partner meaningfully and legitimately with people, organisms, and systems, productively losing control along the way—or perhaps more accurately, resituating control—it might find itself more central to conversations around many messy, pressing problems facing the planet today. Paradoxically, by giving over control, architecture as a discipline and practice stands to gain more than it can imagine.