I, Peter Nevins McBride, hereby submit this original work as part of the requirements for the degree of:

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It is entitled:

BIOMIMETIC CONSTRUCTS

HIGH-TECHNOLOGY TOWARDS ECOLOGICAL DESIGN

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BIMIMETIC CONSTRUCTS
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PETER NEVINS MCBRIDE
BIOMIMETIC CONSTRUCTS
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[BY]

Peter Nevins McBride

A Thesis Submitted to The Division of Research and Advanced Studies in partial fulfillment of the requirements for the degree of:

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Second Chair: Rebecca Williamson, Ph.D.
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Due to advances in large-scale rapid-prototyping technology, the terms ‘standard’ and ‘non-standard’ are increasingly being challenged in the lexicon of modern construction. Driven by the ever-expanding versatility of digital software, architects find themselves in a position of greater design freedom and less constraint from modular building materials, thus allowing for a paradigmatic shift towards an architecture focused on performative characteristics. The following investigation will engage these contemporary technologies to mimic basic processes and morphologies found in our natural environment that account for its inherent abilities of material conservation and systems integration. Software scripting techniques and research into the fields of biological morphology and behavior, digital design, and rapid-manufacture direct the creation of a morphogenetic generative process that decreases material usage within architectural structures and allows for informed speculation into the future of systems integration and the construction automation.
INTRODUCTION

“This century is going to be about biology”

No matter how far we trace historical lineage of architectural design, a direct, arguably genetic, attachment to the natural world can be observed. From Laugier’s hut to Palladio’s villas to Sullivan’s skyscrapers, all architecture is influenced by nature in one form or another. However, until relatively recently, architectural interpretations of this biological genius and beauty has been solely relegated to either the formal, the spatial, and/or the ornamental. Our society has come to a precipice concerning the dire state of our current global climate, and this thesis posits that the built environment needs to look beyond issues of aesthetics, and learn to behave more like living organisms, specifically in their inherent proclivity for material conservation, systems integration, and self-assembly.
The following investigation acts as a knowledge base for the speculative proposal of a biomimetic model for architectural optimization. The vast disconnect between architecture and the natural world are readily apparent, and this thesis work asserts that high-technology, specifically in the fields of computational design and computer numerically-controlled (CNC) manufacture, can function to bridge this gap. Though technical at times, this research document lays the groundwork for speculation into the future of performative architecture and construction methodologies and for the creation of a bio-inspired, experimental, and algorithmically-driven model for structural design that boasts significant material savings through its mimicry of plant cell morphology.

Chapter One, entitled ‘A Biomimetic Imperative’, begins covering the general waste and over-consumption abundant within our built world and lays out a broad argument for a biomimetic path towards sustainability and for the usefulness of thinking of architecture in terms of how it can function more like a plant. It posits that buildings should not be considered a single entity in itself, but as an integral part of a larger integrated collection of systems, in which all outputs of one system or process act as inputs for another. It continues with a further investigation into the growing field of biomimicry and a brief discussion on the available technologies that have come out of biologic study. From there it moves on, to discuss how the natural world has been exploited in architectural design largely for its aesthetic appeal,
rather than its sustainable behavior. Lastly, the chapter looks into the math of natural morphogenesis and how the complex morphologies inherent to many biological organisms are driven by relatively simple rule systems. This serves to make the argument that efficiency and complexity aren’t necessary mutually exclusive and lays out rule system that will later act as the basis for the thesis projects’ structural armature.

Chapter Two, entitled ‘Computational Design’, acts as the knowledge base as well as the justification for the digital translation of biological rules into computational script or code. It begins with a discussion of the modern notion of the ‘Digital Tectonic’ and how digital architecture is more concerned with the dynamism of topology than the constraints of typology. The writing then covers relatively popular methods in which progressive designers are using the this dynamism and the iterative abilities of the digital to take on the topic of sustainability. This section sets the stage for a discussion on a multitude of tools and techniques available to the digital designer, with an obvious emphasis on the ones that exceedingly lent to the creation of my final process and building. Ultimately, chapter two ends with a thorough description of the translation of specific biological rules into a dynamic script and the employment of these rules towards the creation of a bio-inspired truss.

The third chapter, aptly called ‘Future of Construction Technologies’, serves to layout research on additive manufacturing methodologies, and how these
technologies can be harnessed allow for a building-wide system integration. To preface this exploration I briefly review the history of CNC Technologies, and survey the current machines at work in the realm of Rapid-Prototyping and Rapid-Manufacture. From there, the discussion covers current research that is going on in the field of additive manufacturing and the concerns that one must take into consideration when traversing from small-scale rapid-manufacture to large-scale rapid-construction. Using the groundwork laid by the current researchers and companies involved in the large-scale additive manufacturing realm, whether they are working towards construction efficiency, building performance, or formal freedom, this chapter concludes by covering the many performative and formal advances that will come out of rapid-construction and laying out an informed speculative model for an automated additive construction process.

The final chapter, ‘Towards Biominetic Architecture’, linearly lays out the inputs and the processes involved in the creation of an urban headquarters for the Biomimicry Guild, a company involved in the integration of biomimetic technologies into our modern industry. Using the processes and technologies laid out in the three previous chapters, a design is created that, on many levels, attempts to bridge the gap between the biological world and architecture.

Simply put, the following thesis investigation searches for new methods of structural optimization in architecture. Existing in a disciplinary ‘grey-area’ at
the intersection of computer science, biology, and architecture, this research document will inform a biologically-inspired, algorithmically-driven structural system and speculate into the future of the construction process.

This investigation is significant for a handful of key reasons:

1. Architecture can benefit from 3.8 billion[i] years of evolutionary research and development. Looking to the biological world is a highly logical path towards sustainability, and architecture, with its predilection towards the synthesis of disparate fields of study, seems like a very logical place to institute these lessons. Though analogies only go so far to define an argument, architecture and biology, when reduced to their basic ideals, are not all that dissimilar - both are materially and organizationally based; both are concerned with morphology and structuring, and both are the product of multiple simultaneous systems. Through transformation of solar energy, air purification, integration of multiple complex systems, and general self-sufficiency, plants have been doing for millions of years, what the current sustainability movement hopes to do for our built environment. However, plants manage to accomplish this feat using only the most basic and inert earthly materials. The need for this investigation and ones like it stem from the deficient state of our natural environment today. If humankind ever hopes to reach a state of ecological equilibrium and stasis within its

fragile ecosphere, the way we inhabit the planet will need to mimic the
cradle-to-cradle cycling of energy and resources of the natural world.

2. Digital design allows for more precise modeling of complex systems. Digital techniques have proven themselves in the past decade to allow for a more precise, direct, and useful translation of metadata, or data that comprises data, into architectural application. This is most prominently seen in the use of environmental data to inform building facade strategies and forms, and this translational proclivity is a major asset in the ultimate goal of making the architecture function more like that of a plant.

3. Modern Construction is inherently wasteful. This study is important to discuss the future of construction methodologies. It is the place of the young designers to consistently challenge the current form of architectural and construction praxis. Speculation into the future of construction is important because construction methodologies are so closely intertwined with architectural design. Similar to the way in which progressive designs drive the creation innovative construction solutions, the feasibilities, economies, and materials involved in construction tend to drive the way in which buildings are designed. This study lays the groundwork for speculation into the future of construction processes, and proposes an automated model that minimizes material waste, allows for multi-system integration, and has the ability to efficiently and economically deal with complex and variable geometry. Moreover, with the capabilities of construction techniques and
technology quickly closing the gap with those of digital design software, the economic incentive to continue building with standardized materials fading. We are approaching a new era in architectural history, in which complex geometries will be able to be constructed by the same means and for the same cost as Euclidian geometries. These new technologies will open up endless possibilities for architectural design, but more specifically, it will greatly increase designers ability to optimize structural system through morphological processes that were formally constrained by standardized construction methodologies.

The ultimate goal of this thesis is to transform the currently tenuous and wholly analogical relation between nature and architecture into an operative system and use that system to produce a biologically-inspired structural armature that can be constructed with less overall material compared to traditional construction methods. In the process, it hopes to shed light on the endless potential that natural precedent, digital design, and construction automation hold for the progression of sustainable architecture.
We must draw our standards from the natural world. We must honor with the humility of the wise the bounds of the natural world and the mystery which lies beyond them, admitting that there is something in the order of being which evidently exceeds all our competence.

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VACLAV HAVEL,

president of the
Czech Republic
1.1 Shortcomings of our Current Built Environment
1.2 Biomimicry and Biomimetic Technologies
1.3 From Organic to Biomimetic
1.4 Morphogenesis and the Dynamics of Growth
1.5 Biological Structural System
The change can be felt throughout the design world. A significant shift - one towards an architecture of optimization - is beginning to affect the way in which architects are positioning their practices. As an industry, we have adjusted our lenses to focus primarily on the performative qualities of architecture and momentarily put aside our shallow preoccupations with style and appearance. This paradigmatic metamorphosis aims to locate architectural discourse within a more objective framework where efficient use of resources supersedes the aesthetic indulgences of works that previously came under the broad heading of Postmodernism. However, following the old

Einsteinian adage, “No problem can be solved from the same level of consciousness that created it”, many posit that simply readjusting and revising our current methodologies of design and construction will fall short in achieving the penultimate goal of a wholly sustainable built environment. Lasting change is going to necessitate a bottom-up transformation of the ways we think about architecture and architectural praxis.

We, as a species, have proven time and time again our limitless ability for waste and consumption. Most egregious is current state of our built environment. Though oil executives and Chinese fishing fleets are consistently being vilified by the media for the damage they have wrought on our environment, it is our buildings that are doing the major damage. Architecture’s seemingly genetic connection to archaic ideals from its industrialized past has left our generation with a contaminated present. With modern construction methods creating an average of 2.5 pounds of solid waste for every square foot of newly completed floor space and buildings accounting for sixty percent of total consumption of electricity\textsuperscript{ii}, it is obvious that changes in our built environment are imperative to the

success of future generations. And though there has been a major push for ‘green’ technologies in recent years, it is readily apparent that many of them are just re-branded versions of the same technologies that brought us into the current environmental crisis.

A common example is that of the compact fluorescent lamp (CFL) (Figure 1). This wonderful technology boasts a longevity several times greater than that of its predecessor, the incandescent, and consumes a quarter of the electricity. However, CFLs, akin to the many short-term ‘Band-Aid’ techs that have been forced upon us by popular media and by ill-informed legislation, simply function to shift the way we are polluting rather than solving the problem of pollution. Bills passed by the Senate in 2007 announced the complete phase out of incandescent light bulbs in the United States by 2012[iii], however no attention was paid to updating our antiquated electrical platforms to account for the truncated amperage needed to support this new bulb. Due to this government oversight (and/or corporate calculation), every consumer retail unit has been married to its very own electronic ballast to moderate amperage to the fixture. Consequently, the much improved life span and substantial energy reduction of a CFL is quickly offset by the amount of embedded energy used in the manufacturing

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[iii. Fix!!!! Library of Congress - http://thomas.loc.gov/cgi-bin/bdquery/z?d110:h.r.00006:
Moreover, this ‘upgrade’ is proving to be far more noxious than its recycled cardboard packaging would lead one to believe. Landfills are being inundated with abandoned incandescent bulbs, a portion of which were brand new or functioning, to make way for the next generation of ‘low-energy’ lighting. Similar to the predicaments caused by our ‘e-waste’, the lack of federal recycling regulations has relegated our landfills as the de facto storage facility for defunct CFLs, leading to the needless waste of solid-state ballasts (Figure 2) (the life solid-state electronics is relatively inexhaustible) and to the leaching of poisonous chemicals, including a significant amount of the notoriously deleterious neurotoxin, mercury, into our earth, our water table, and our air. However, compact fluorescent bulbs are not the problem. Though they are simply an example of how the promise of cutting-edge


v. At this point, only nine states in the U.S. have reasonable CFL recycling programs.

'green' technologies can be sullied due to a lack of substantial integration and transformation on multiple levels. Ideally, buildings should be designed with efficiency as a primary consideration from the bottom up, as opposed to the all-too-common practice of pasting green technologies on at the end of the schematic phase of design realization.

We, as architects, are just beginning to see the economic, social, and environmental benefit of structuring design process within a framework of energy and material conservation, and in doing this, we are abstractly mimicking the way the natural world has gone about designing for billions of years. Much like the evolutionary banishment into the realm of extinction that was wrought upon organisms with shortcomings in the field of conservation, this recent paradigmatic shift in architectural praxis will certainly result in fewer and fewer designs that do not articulate a performative intent to be realized. Similarly, many professionals have begun searching for technological and scalable abstractions or replications for naturally occurring solutions to deficiencies in their industries. The mining of nature’s relatively untapped evolutionary wisdom for applicable use within our industrial world has recently been filed under the apropos heading of ‘Biomimicry’, and the resultant bio-inspired technologies are allowing many to increase efficiency and do so in a highly sustainable manner.
FIGURE 3: Barbed wire.

FIGURE 4: Rose thorn.
Biomimicry, at its simplest, is the emulation of biological forms and processes. The etymology is derived from the Greek words ‘bios’, meaning life, and ‘mimesis’, meaning imitation[vii]. However, biomimicry does not entail solely the direct mimicking natural forms and processes, but it carries with it the connotation of natural abstraction. Much in the way barbed wire can be considered a manmade cognate of a rose thorns, biomimetic techs are not meant to be an exact copy, but reductive abstraction of a useful form or process found in nature.

Pioneer and champion of the Biomimetic Movement, and, by popular belief, the originator of the term ‘Biomimicry’, biologist Janine Beynus has been

touting the benefits of biologically-inspired design since the early 1990s.[viii] Her influential book (Figure 5), Biomimicry: Innovation inspired by Nature, has positioned her as the preeminent authority on the subject, led to the creation of two separate companies, and paved the way for more than a decade of influential and insightful dialogue concerning the way in which we, as a society, should frame our understanding of sustainability and the natural world.

She makes the assertion that evolution has left us with nature as the best solution to many of the problems we face within our industrialized world. A few of the principles of biological life described in Beynus’ book are that it self-assembles, it minimizes material waste, it adapts to cycles, it is always locally appropriate, it uses free energy, it can evolve, and it uses non-toxic materials[ix]. She follows the mantra that humans should see nature as a model, as a measure, and as a mentor[x]. She claims that this new type of sustainable design can be applied everywhere, from the materials industry to computer engineering.

The popularity of her book led to ultimately creating a company based

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around these concepts which she called The Biomimicry Guild (Figure 6). Beynus refers to the company as a chance to ‘bring biologists to the design table’, and the company has thus far been rather successful. All interested parties often gain insight from the perspectives of other disciplines. On a basic level, The Biomimicry Guild acts as sustainability consultancy, but their main goal is to show major industries that there are often multiple solutions to a problem and that it is often the case that some organism in our natural world has managed to solve it already. By acting as a conduit between these large corporations and the, often small, up and coming biomimetic technology firms, she serves to shed light on the wonderful technologies that are currently in production and make it harder and harder to ignore the significant profit stream coming out this small yet burgeoning collection of products and processes inspired by nature.

Many biomimetic technologies are already on the market or are being tested for their feasibility within our industrialized society and they are often more efficient and far less environmentally destructive solutions than had been previously considered. During a lecture at the TED Conference in
2005, Beynus uses her experience with a group of engineers from an urban infrastructure company to illustrate the notion that humans are the only creatures that have come up with solutions to problems that harm the environment in which they live. She touts the undeniable truth that “life creates conditions conducive to life”[xi], and goes onto chronicle her experience with these civil engineers that decided to come along on a Caribbean retreat hosted by the Biomimicry Guild in hopes of finding more sustainable solutions to some of their pressing problems by looking to biology. She recalls that one of their main problems was ‘scaling’, or the aggregation of large calcium deposits that occurred within most of the plumbing in their city. Their current “solution” involved excavation of clogged conduits and either the application of a noxious metal stripping cocktail or replacement of that section of pipe. Once they brought up this problem, Janine went onto describe how their problem had most likely been solved millions of years prior by the common abalone. Abalones, she explicated, self-assembled shells of a material called nacre, often referred to by its pseudonym, ‘mother of pearl’. Nacre is made up of calcium carbonate, the same mineral that was causing their scaling problems. She explained that shellfish excrete a protein template that attracts and crystallizes calcium in the seawater. The engineers quickly became more interested in the discussion and inquired, “Well, if these organisms are constantly crystallizing calcium from seawater,

why are their shells not infinite in size?”. Much as the abalone created a protein that stimulated the synthesis of calcium carbonate, at the end of the creature’s growth cycle, it secretes a protein that blocks further mineral accumulation. She goes on to tell them that a company has recently come to market with a product that mimics the function of this protein in order to prevent mineral crystallization, and thus corrosion[xii], in industrial machines and it does so in an environmentally-friendly way[xiii].

Biomimicry opens the door to technologies that have been proven ‘sustainable’ simply by the very existence of their precedent organism. We are at the beginning of a new era in that will redefine how we view and value nature. This century will bring greater import to what society can learn from nature instead of focusing solely on what society can extract from it. Though there is still an endless amount of natural wisdom that science and industry has yet to harness, there have been many inspiring advancement in the field of biomimetic technologies. By utilizing high-technology, we can begin close the seemingly irreparable chasm that has formed between modern society and the natural world though a close understanding of its inner working. The following only covers a handful of the many biomimetic technologies currently on the market or in late stages of development, but


it briefly mentions most of the ‘big ideas’ or areas of innovation that are currently being informed by biology. Each tech is not individually vetted for its usefulness within the realm of architecture, though it is very easy to imagine how they will one day fuel the future of sustainable design.

One process that many companies have begun to study is nature’s ability of self-assembly. The aforementioned material nacre (Figure 7), found primarily in the shells of mollusks, is a naturally occurring ceramic that has twice the density of our manmade ceramics, and is manufactured and hardened in seawater, rather than in the extreme heat of a kiln. Companies have begun to mimic this process on a small scale by inducing self-assembly of a thin, high density ceramic coating to form on electrical components at assembly using only the energy of evaporation[xiv]. Self-assembly has been looked at by a handful of communications companies, as well. Creatures have been discovered that are able to self-assemble highly complex communications components out of inert materials found in their salt water environment. Scientists have found that the brittle star is able to grow an almost distortion free lens as part of its exoskeleton, a feat that manmade technologies have never been able to do with a far larger palette of materials at hand.

Moreover, biologists have become, appropriately, very interested in a species of sea sponge that lives in the pacific that is able self-assemble a natural strands of fiber optics that transmit a clearer signal than our currently available technology and can be tied into a knot without breaking or distorting said signal (Figure 9). It is amazing to find these technologies being assembled in the bodies of relatively ‘simple’ creatures out of inert material found in sea water, when the man made cognates necessitate a thoroughly complex manufacturing process that involves the use of toxic chemicals. We know that there are only four polymer fibers that exist naturally: cellulose in plants, collagen in animals, chitin in insects and crustaceans, and silks in spiders’ webs, yet modern manufacturing utilizes hundreds of different polymers, most of which eventually find their way into a landfill. By considering the architectural implementation of


nature’s materials and methods of self-assembly, we are steering our built environment towards a sustainable future.

Another characteristic of many organisms that companies have started to look into is the ability to use carbon dioxide as a feedstock. In the natural world, CO$_2$ is not considered the global-warming cause and poisonous off-gas that its name connotes today. Many organisms, most notably plants in their process if photosynthesis, use CO$_2$ as a feedstock for biological processes. It is a very logical for companies to be looking for different ways of dealing with this gas rather than just pumping it into the air or into fissures in the earth. These solutions seem to be coming from the same train of thought that led to the dumping of our garbage into the middle of the ocean that continued up until twenty years ago. Currently there is a company called Calera© that claims, “We make coal and natural gas power plants and cement plants cheaper and cleaner than solar and wind by reducing carbon by more than 100%, in a scalable and economic way”[xviii], and they are managing this feat by mimicking a process that coral polyps have implemented for hundreds of thousands, possibly millions, of years. Similar to the way in which coral pulls carbon dioxide out of the water in order to build its a calcium carbonate skeleton, Calera© is using CO$_2$ siphoned from the burning of coal and natural gas and sequestering

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it by using it in the creation of cement.[xix] Companies such as this, are paving the way for a sustainable human ecology, in that the outputs of one system (energy production), act as the input for another system (building materials), and thus bring us closer to a systemic cyclical methodology for the future. These biomimetic technologies are very important due to the fact that using carbon produced by a separate process as an input makes them more than carbon “neutral”, it makes them carbon “negative”. Carbon sequestration technologies that use carbon dioxide as a feedstock are going to play a large role in our societal push for ‘clean’ energy. The shapes and forms found in nature have begun to inform biomimetic products in recent years. One company has mimicked the geometry of the bumps on a whale’s fin because they have proven to make them more aerodynamic, increasing the efficiency of their wind turbines.[xx] (Figure 10 & 11) Another company has started producing countertops for hospitals that mimic

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sharks skin, for studies have shown that the minute ridges that exist on the rough sharks scales do not collect bacteria, thus, eliminating the need for antibacterial soaps.[xxi] Moreover, surface materials and paints are now available that mimic the surface geometry of the lotus leaf that causes the surfaces to become self-cleaning.[xxii]

Along with solar cells that function like leaves and structural materials that can self-heal when they develop cracks, these are just of handful of the many promising technologies that are under development, but it is easy to see how these technologies will play a crucial role in making our lifestyles and architecture more sustainable. Most notably, biomimicry offers a new way for us to think about how we can design our built environment. It has become part of the accepted wisdom to say that the twentieth century was the century of physics and the twenty-first century will be the century of biology[xxiii], but it will be the role of the architect to delineate how biological lessons are translated into architectural form and whether or not they will lead towards a sustainable building stock in the future. Barring a few wonderful exceptions, historically we have seen natural forms used in architecture solely for its their ornamental beauty. However, we have

reached a plateau of technological advancement in which designers can begin to speculate how the built structure and architectural design can become more efficient by using nature to inform the way they are designed and the way they function. Respected architectural theorist Neal Leach claims that “Biomimetics - the study of what we can learn by replicating the mechanisms of nature - has...emerged as an important field of research.”[xxiv] If we hope to one day reach a level equilibrium with our natural surrounds and our planet, it is imperative that architectural design embrace this new functional way of looking at our natural environment. Architecture must look beyond its preoccupation with the aesthetic beauty of nature, and move its focus to its ability to sustain life.

Historically, nature has been a fundamental and recurring inspiration for architecture and for centuries the natural world has been used to augment architectural design. However, it is most often used in a strictly formal, ornamental, or metaphorical manner. The type of architecture that employs nature in this way is regularly lumped under the nebulous heading of ‘organic’ architecture. Though the word ‘organic’, as defined in the English language, denotes something characteristic of a living organism, it has been re-appropriated in art and architecture and rarely references anything that is akin to a biological entity. In addition, due to the consequent over-use of the word in the current trend to be ‘green’, its linguistic attachment to nature has become tenuous
at best. In order for architecture to truly connect with the natural world, a new architecture based in the study of biomimetics must be employed. Though nature has been used metaphorically, ornamentally, and formally in ‘organic’ architecture, ‘biomimetic’ architecture will utilize nature as a functional model to progress the overall sustainability of the design.

Frank Lloyd Wright was arguably the most famous architect to use nature as a metaphor for his design process. He proclaimed,

“An Organic Architecture means more or less an organic society. Organic ideals of integral building reject rules imposed by exterior aestheticism or mere taste, and so would the people to whom such architecture would belong reject external impositions upon life as were not in accord with the nature and character of the man who had found his work and the place where he could be happy and useful because of it... beauty seems to have made no sense for long at any time. I believe that time has come when beauty must make sense for anytime. I believe that time has come when beauty must make sense for our time at least... In this modern era Art, Science, Religion - these three will unite and be one, unity achieved with organic architecture as centre.”[xxv]

xxv. Wright, Frank Lloyd. Address to the Royal Institute of British Architects. 1939.
Though Wright forecasts a novel utopian future, his ‘organic’ architecture has little to with a real veritable connection to nature. He uses the notion of biology solely as a metaphor to justify his infamous insular design methodologies, rather that coherently making a true connection to biology itself. Though not very apparent in Wright’s proclamation, metaphors can be useful if used correctly. Metaphors allow one to quickly contextualize and familiarize a foreign or complex topic. The first cars were referred to as “horseless carriages” in order frame the strange loud mechanism within general comprehension. Modern computers still today use the terms ‘file’, ‘folder’, and ‘document’ in order to contextualize the concept computer storage. However, too often designers use metaphor as a basis from which to conceptualize a design. There are far too many complex interactions that must be considered to base design decisions off something as intangible and temporal as a metaphor. Especially when proposing an architecture of biology, it is the job of the architect to move beyond the metaphor and ground the project within a framework of objectivity. Killian Axel writes, in an article discussing the validity of models in architecture, that, “scientific processes are crucial in elevating design explorations of complex dependencies over guess work and provide results that can feed into the form and other aspects of architecture. Architectural design needs its metaphors but aspects these metaphors need to be translated into models that inform the architectural process in a much more rigorous and creatively
exciting way”[xxvi].

In addition, the process of mimicking natural forms for the purpose of ornamentation is a beautiful, yet undeniably wasteful way that biology has been (literally) applied to architecture. As far back as the Ancient Greeks, natural forms have been replicated as architectural decoration through painting, relief, and sculpture, of which the most excessive use of biologically-based ornament can be found in the Italian Baroque of the seventeenth century and, even more so, in the eighteenth century Rococo, most notably in Austria, Germany, and France. However, these monuments to the power of religion and government can barely be considered ‘organic’ architecture, for the grandiose decor no more defined the building than icing would define a Regionally Classicistic cake.

However, throughout the eighteenth and nineteenth century, research expeditions began that focused a new lens on nature and would serve as the foundation biological. This empirical research allowed the natural world to be categorized and systematized, as can be seen in Carl Linnaeus’ classification of nature and Darwin’s evolutionary tree of life (Figure 12).[xxvii] The natural sciences began to influence art and architecture as their popular interpretations, such as Ernst Haekel’s Kunstformen der Natur (“Artforms of

Due to the extensive proliferation of the empirical findings of these biological research expeditions, the flowing fluid forms of plants and animals became a the basis for much of the architecture created under the heading of ‘Art Nouveau’. Also, periodically referred to as Decorative Industrialism[xxix] when referencing the architectural style independently of the art movement, Art Nouveau employed an integrated and organic vocabulary to an create ornate and expressive designs in which the model of nature, most prominently of the plant world and the dynamics of botanical growth, is highly influential to its thematics. The structural systems, as well as the ornamentation, were often constructed of cast metal and made use of the industrial construction methods.

xxviii. Ibid. 13.
FIGURE 13: Ernst Haekel’s Artforms of Nature.
made popular by the automotive and maritime manufacturing industry[xxx]. Composed of iron and steel, this natural ornament could transform seamlessly from decoration to structure, as can be seen in the facade of Sullivan’s Carson Pirie Scott Department Store (Figures 14 & 17), or it can function simultaneously as both decor and structural armature, as is the case in Hector Guimard’s famed Parisian Metro entrances (Figures 15 & 16). Other prominent figures in the movement included Victor Horta and Henry van de Velde in Brussels; René Binet in Paris; and

Hermann Obrist and August Endell in Munich (Figure 18) [xxxii]. Though these projects are not scientific in method and are solely artistic interpretations of nature, the designs were conceptualized through a close understanding of plant morphology. In this understanding we can begin to move towards a biomimetic architecture. Architecture based in biomimicry similarly calls for an in-depth understanding of biological processes and forms, but it moves beyond that to question how that knowledge can inform sustainability and optimization of a building.

Although, from this era came arguably the first biomimetic architect, Antonio Gaudí. Throughout his illustrious, though limited, collection of works, it is easy to see that Gaudí was influenced greatly by the aesthetics of the natural world. From the ‘tree-columns’ at Parc Güell (Figure 19) to the undulating structure of Casa Batlló (Figure 20), Gaudí’s palette often referenced the
FIGURE 20: Casa Batllo. Barcelona.
natural world in his range of colors, his variability of form, and his almost
preternatural understanding of multidimensional geometric logic. Gijs van
Hensbergen, the author of Gaudí: A Biography, playfully recounts that the
young Antonio, based on his grades from his Catalan elementary school,
was a markedly inferior student for someone that was to grow up to be
revered for their architectural genius. However, he consistently excelled in
mathematics, with quite the proclivity for geometry[xxxii]. And although
he may not have been privy to the seminal work of D’Arcy Wentworth
Thompson[xxxiii], a pioneering mathematical biologist that will be covered
in Section 1.4, entitled On Growth and Form, he certainly developed a
keen understanding of the inherent connection between the structure and
form of nature and geometry.[xxxiv] His fixation with the natural models of
structural efficiency, aesthetics, and composition is well documented. From
the beginning of his professional career, Gaudí searched for architectural
inspiration in the both the plant and animal kingdoms, as well as “the
inorganic realm of crystallography”.[xxxv] Though this interest is readily
apparent in all his work, it initially manifests itself solely in a formal or a
decorative manner that could be considered as artistic abstraction, rather
than applying his depth of knowledge in natural morphology as design

xxxiii. D’Arcy Wentworth Thompson was a pioneer in the field of mathematical biology
and he will be covered in greater depth in Section 1.4.
principles. It was not until late in his career that he began work on his final, and most well-known project, The Expiatory Temple of the Sagrada Familia (Figure 22), that his design work can be called ‘biomimetic’. For this project, Gaudí wanted to incorporate the spirit of the Gothic, but do so with “freer expression” and truly exultant character. In order to do this, he felt that he had to ‘correct’ what he called the ‘errors’ of Gothic Architecture. By this he meant that he planned to rid his cathedral of the need for flying buttresses, which he referred to as ‘crutches’ (les muletas).[xxxvi] In order to take on this task, Gaudí studied tree morphology and gleaned from it an understanding of the growth angle, material distribution, and branching patterns, and he used that knowledge to design columns that draw loading stress from multiple points and transfers it uniformly down a single column (Figure 21). In this one design move, Gaudí was able to take biologic morphogenetic rules and apply them to the design of a column, thus negating the need for extra buttressing in the building. This type of bio-inspired innovation is the basis for Janine Beynus’ biomimicry movement, and is one of many sophisticated design decisions...
he made that harnessed the evolutionary genius gleaned from biologic
inquiry. Moreover, Gaudí believed in the importance of high technology
in the realization of his designs. His design process was characterized
by “a continuous and stimulating review and revision”, regardless of the
project’s level of completion, periodically altering designs to allow for
the incorporation of “current advances in construction techniques and
other technological discoveries”[xxxvii]. He even went as far to design
the towers at the Sagrada Familia in such a way that they could not
physically be constructed with the materials available during his lifetime.
He speculated that by the time it came to cap the towers, a much higher-
strength concrete would be available to form the thin tight curvatures that his
elevations called for[xxxviii]. Though nature’s predilection for energy and
material conservation has become a more popular topic of study in many
progressive design firms, this thesis investigation considers Antonio Gaudí
as one of the first, if not the first, biomimetic architects.

Possibly due to the consistently mixed reviews of Gaudí’s work or due
to the growing separation between divergent fields of study, regrettably,
there have been relatively few architects of note since Gaudí’s death that
can be considered ‘biomimetic’. However, the few that have followed
in his bio-inspired footsteps have been quite influential and have paved

the for the formal freedom and the cross-disciplinary interactions that we are beginning to become more common place within many of the more progressive architectural firms.

One of the more influential dominant voices in this group belongs to the German-born architect and structural engineer, Frei Otto. Otto is well known for his prolific research into the use of natural models as a source for architectural and engineering design, while keeping his focus directed on advancing construction applications[xxxix]. Much like Gaudí, Otto often employed novel physical-form finding experiments in his research, and has claimed in an interview with the periodical AD: Architectural Design that he uses as many as 200 different physical modeling methods at the University of Stuttgart, where he founded the Institute of Lightweight Structures.[xl] Much like the ‘biologists at the design table’ found at the Biomimicry Guild, Otto paired up with a leading biologist and anthropologist and founded a research group called “Biology and Building”. [xli] Currently they are looking into ways in which biological structures can inform a structural system that

can resist the “domino effect”\[xlii\] caused by tearing in skyscrapers. He posits that the skin should carry the loads of the building, much in the way it does in many exoskeletal organisms, and the skin should be comprised of a web of fibers. However, he claims that living skins are very different than the man made skins that are shaped by simple geometries. Irregularity of each element of the skin is the reason it is so resilient to tearing, his research suggests.\[xliii\] However, Otto makes certain to convey a lesson similar to that of Beynus’ Biomimicry: Innovation Inspired by Nature, when he warns, “It is necessary that we architects try to understand living nature, but not...copy it. This is one very important task for the future.”\[xlv\]

As Italian engineer and architect, Pier Luigi Nervi, and American architect and futurist, Buckminster Fuller, had laid the foundation for Otto’s research into the biological-technical structures and material organization, Otto has invested his life’s work into building a solid footing for the new generation of biomimetic architecture.

It is time to begin to design responsibly, and put concerns of building performance before that of building aesthetics. However, in order to bring

\[xlii.\] The term ‘domino effect’ in this context refers to the collapse of one floor in a skyscraper resulting in the subsequent collapse of every floor below it. The domino effect caused the ultimate collapse of the World Trade Center.


about the creation of a truly biomimetic architecture, there must exist a knowledge of the science as well as a knowledge of the technology that is needed to translate biologic principle into built form. Furthermore, it all must be synthesized within a framework of good design. Arup’s famed structural engineer to the stars, Cecil Balmond, parallels this sentiment in a cross-disciplinary colloquium:

I just want to say that architecture is very interested in biology, it always has been. Biology is intricate at many levels: it’s highly structural, highly dynamic and has all sorts of architectures in it. Nature has always been the paradigm for architecture. It is erroneous to think we can just copy these processes into architecture; we absolutely can’t and it’s dangerous. But having said that, my research is set up in the belief that science has great analytical powers, but architecture has great synthetic powers, powers of synthesis.[xlv]

Moreover, the Emergence and Design Group reminds us that we are currently living in a time of high-technology. Our computational power is progressing exponentially; our knowledge of the biological world increasing rapidly; and we find ourselves “...facing a very exciting moment where architecture can leave behind both mindless standardization, fetishism, and current hapless formal caprioles, and instead take on new significance through

intelligence, performance and beauty.”[xlvi] Designers have the technology and the skill to durably depart from the fraudulent iconoclastic veneration of nature that ‘organic’ architecture embodies. The future of biomimetic architecture will draw from nature’s ability to optimize and specialize and integrate. The formal nature of architectural structures will be imbued with principles of material conservation, and the construction waste that is customary to the use of standardized materials will be a thing of the past. Form will follow performance, and our built environment will evolve over time into a human ecology in which every architectural structure has an ongoing and continual relationship with every other element that makes up the built environment.[xlvi]

However, Beynus, Otto, and now, Cecil Balmond warn that it is futile and even “dangerous” to try copy biological processes directly into architecture. So the question remains - how can we as designers begin to be able to harness the genius of nature? And though there is not a single answer, nor even a single optimum approach to this question, understanding the rules that govern the organization of biological processes and the mathematical functions that drives natural growth offer much potential for translation


into architectural application. The current study of ‘biological emergence’ proposes that the systematic complexities that we see in nature are often the result of a small set of very simple rules or interactions. Following this logic, a specialized study into biological morphology, and more specifically morphogenetics, will be very useful in the process of translating biological wisdom into architectural application for structural design.

Morphogenesis means literally, “the beginning of shape”, and it is a field of study that how the formal nature of an organism develops over time. Eric Bonabeau defines this topic in his research compendium entitled, “From Classical Models of Morphogenesis to Agent-Based Models of Pattern Formation.” He states, “Morphogenesis is the development of pattern and form in living systems,” and, though the topic is considerably broad in scope, it is an important field to Biomimics and it should be an important field to architects. Much of the architectural design process is involved with the generation of

The role of an architect constantly involves the analysis of internal, external, and, oftentimes, metaphysical conditions and arrange them within a logical framework to drive a set of formal decisions. It is rational to posit that designers could benefit from a more clear understanding of how the natural world transforms its conditional inputs into physical form. Neil Leech, an authoritative voice in progressive digital design, affirms the assertion that architectural praxis could be strengthened through the integration of morphogenetic methodologies. “Used initially in the realm of biological sciences, the term refers to the logic of form generation and pattern making in an organism through the processes of growth and differentiation. More recently it has been appropriated within architectural circles to designate an approach to design that seeks to challenge the hegemony of top-down processes of form-making, and replace it
with a bottom-up logic of form-finding.”[li]

In short, with the current abilities of architects to impregnate code with multiple generative rules, there has been a large escalation of interest into the mathematical parameters that drive form, rather than the form itself. By breaking down the growth of biological forms into simple genetic rule systems, it makes it possible for designers to translate these rules into digital scripts and thus, an operative process that can inform architectural design.

For centuries, philosophers, scientists, and artisans, alike, have been arguing methods for the articulation and understanding of nature within a mathematical framework. From Plato and Pythagoras up to and through Seurat and Le Corbusier (Figure 25), an almost divine import has been given to the proportions derived from nature. However, the study of morphology inquires into the process involved in the creation of form, rather than the post-rationalization of form itself. A pioneer in the study of plant and animal morphology, poet and writer Johann Wolfgang von Goethe, “defined morphology as the study of forms; he combined the study of ‘Gestalt’, or structured form, with the process of ‘Bildung’, or formation, which acts continuously upon form.”[lii] And this focus on the dynamic nature


of form was continued into the 20th century, as can be seen in D’Arcy Wentworth Thompson’s influential work *On Growth and Form* (Figure 26). “D’Arcy Wentworth Thompson argued in *On Growth and Form* that the morphology of living forms has a dynamical aspect, under which we deal with the interpretation, in terms of force, of the operations of Energy.”\[i\]

His writing on the relationship between species and his work under the heading of ‘homology’ is still used as an important precedent in modern biological investigation. ‘Homology’ is very relevant to the integration of technology and nature because it intertwines the fields of mathematics and biology. Moreover, it has two different definitions depending on how they are contextualized. “To biologists it mean organs or body parts that have the same evolutionary origin but quite different functions. To mathematicians, it is a classification of geometric figures according to their properties.”\[iv\]

D’Arcy argues that two forms found in nature are related if one can deformed into another by transformation of Cartesian coordinates (Figure 27 & 28). These similarities between biologic forms is often referred to as “morphogenetic tendency”\[iv\], offer much insight into the parametric organization of our natural world. If one form can be transformed into

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**FIGURE 27:** Catesian mapping of hip homologous pelvis bones.

**FIGURE 28:** Fish with homologous morphologies.
another through deformation of a system coordinate, then it clearly is a system amenable to being modeled mathematically.

Biological morphology is dependent upon systems of basic rules that are affected by inputs to the system. These lessons offer a methodology for the creation of a structural system that integrates a certain dynamism, which will allow for its implementation across multiple architectural projects, while imposing the material optimization that is inherent in natural structures. The following section will cover the investigation into a biological precedent and the derivation of a basic set of rules that describe the geometry inherent in its structural organization. It will serve to elucidate how breaking down the formal nature of organisms into simple morphogenetic rule sets can allow designers to implement them within architectural design.
The biological precedent that will be referenced throughout the investigation is the giant lily pad (Victoria amazonica). (Figure 29 & 30) This giant species of water lily was chosen for its structural clarity and its spanning abilities. This structural system will serve to inform a digital translational model of the natural ‘homologies’ existing within this species morphogenetic geometry in order to creative architecturally relevant tools.

As can be clearly differentiated without an invasive examination, there is a clearly defined primary structure as well as secondary structural membranes that connect the vascular veins of the lily (Figure 31). Both systems follow a similar cellular logic, though the membrane functions two dimensionally and the primary structure functions three dimensionally. The pattern that drives the growth of the system is based on what has come to be known as

**FIGURE 29:** Artist’s Rendering of Giant Lily structure and it flowering body.
as ‘Voronoi’ patterns. These patterns are based on a decomposition of measured space into a set of discreet objects. As can be seen by the diagram (Figure 33), the pattern is reliant on the input of a point array, and depending on the arrangements of the points within the two-dimensional array, the system can create many of the tessellation patterns that we find in nature. This is because nature is based on a geometry that searches to minimize material usage and this system of spatial division divides space in such a way that it allows for the shortest possible boundary connections. As seen in this analysis of spatial division based on input arrays, the use of orthogonal geometries become more and more inefficient in comparison.

FIGURE 30: Giant Lily.
Top View.
FIGURE 31: Underside of Giant Lily.
to the biologically-based geometric system the more non-uniform the inputs become. In order to build more efficient structures for the future of architecture we must be able to harness this inherent genius for material conservation. Niel Leech agrees that “...nature itself can teach us important lessons about the efficiency of structural organizations.”[lvi] He goes on to reiterate that “Biology provides one of the major sources of inspiration for research into morphogenesis in architecture. Nature operates largely through a logic of optimization...”[lvii]

As is the case with most seemingly complex morphologies found in nature, this biological patterning follows a list of simple rules (Figure 32). Though our physical world exists in three dimension, for the purposes of understanding these natural geometries, it is helpful to initially limit them to abstracted two dimensional representations. As mentioned before, this mathematical system depends on the input of a system of points. The output of this generative process completely depends on the locations of the input points, which make it very useful in a dynamic system.

Step 1 - Within the array of points a single point must be selected for analysis.


Movement of any one vertex triggers a gradient of movement in neighboring vertices. Vertices that are close together try to keep their relative position. Vertices that are part of unstable lattices are more affected by forces. Vertices that are deep in the middle of the building try to move more closely to the rim (creating 'rooms'). Horizontal movement is more likely than vertical movements (creating 'floors'). Vertices are attracted or repelled by forces (creating random mutation).

II.  RULE-BASED SYSTEM OF SPRINGS

1. Points
2. Bisectors
3. Intersections
4. Boundary

Select one point in a set of points. Bisect all lines connecting point to all other points. Cell is formed by the of the local bisectors. Trace boundary and repeat for all other points in the set. Bise all lines connecting point to all other points.
Step 2 - The selected point is then connected to all other points in the array and the parallel bisectors of those line are extended into the 2 dimensional plane.

Step 3 - The boundaries for the cell is formed by the intersections of these local bisectors.

Step 4 - Once the boundary is defined, remove construction lines and repeat for all the point in the array.

Once this process is completed and spacial boundaries have been defined for all sets of point the process is over. What is left is a system of spaces that have been divided using the smallest possible spans and the least amount of acute angles or the decided input.

Moreover, because this system is able to adapt to an infinite number of different inputs and it has obvious the obvious ability of optimizing overall spanning length, it is east to see how this geometry could benefit how we design our built environment. Material savings alone make this type of system a valuable asset to the future of architectural design, but, even more so, it boasts the ability of being able to take more a randomized system of inputs and do so without interrupting a unified structure.

As can be in the following diagrams (Figure 32 & 33), the voronoi geometry serves to do better that the strictly orthogonal geometries when looking...
FIGURE 34: Diagram showing how orthogonal and voronoi geometries can divide discreet space depending on the input of a point array.
at the saving in the total length of spanning members, the average length of spanning members, and length of the longest spanning members. As can be clearly seen, the more nonuniform the input array becomes the better suited the voronoi geometry to take on the task of division of space.

By breaking this biological system down into basic rules, it allows it to transcend realms, from the biological and be used as a tool in the hand of the architectural designer. Methods of digital design have made seemingly esoteric fields of study such as biology to be more easily accessed and functionally translated. The following chapter briefly shows how a knowledge of digital design software and scripting techniques can take a biological rule
system and make it useful within the design of architectural structures.
For more than a decade, digital processes have taken part in making the unbuildable buildable. Early monuments to digital production, such as the Guggenheim in Bilbao designed by Frank Gehry and Lord Norman Foster's dome for the German Reichstag in Berlin, proved to the world the computer's ability to bring highly complex structures to reality. However, until recently this powerful tool was categorized within architectural practices exclusively as a representational or analytical device. As designers and architects have become more technologically savvy, a trend towards integration of the computer into the design process has occurred. Kostas Terzidis, author of Algorithmic Architecture, lectures on the notion that "digital is a process, not a product."

And there certainly is merit in the argument. Different design programs were developed with very specific constraints prescribed within available design softwares. In order to get away from the ideal of the computer as a solely representational means, it is up to the designer to have the technical abilities to work outside and around the constraints prescribed within available design softwares. Much of the criticism of digital architecture lies in the argument that the architecture is largely affected by the software platform in which it is created. And the software platform is very much determined by the constraints (both established and implied) prescribed within available design softwares.
written privileging certain capabilities over others. For example, Revit, one of the more celebrated and prevalent competitors in the world of Building Information Modeling (BIM), creates digital models embedded with information from the physical world. A wall in Revit, is not simply an extruded plane, but it exist as a layered entity, containing the properties of common construction materials (i.e. stick-built construction, fiberglass insulation, and gypsum paneling). This type of modeling software, though it does allow for much improved systems integration, it greatly constrains the design process. BIM often favors design efficiency of design creativity. Complex geometries and nontraditional material systems become extremely hard to engineer within BIM, and thus the designs are often reworked to fit within a more Euclidian construct. On the other side of the spectrum, is a piece of software called Maya, that offers far more freedom of design. Initially known for its popularity in the video game and film industries, Maya quickly became a mainstay in progressive architectural design circles searching for a greater degree of formal articulation within architecture. Moreover, the software is ‘open source’ and could thus be changed and specialized to the user’s needs. The initial shock of all this geometric flexibility, completely detached designers from the architecture’s materiality and physicality and incited the onset of what is now commonly, and often resentfully, referred to as ‘blobitecture.’ And though these two software platforms are polar opposites within the spectrum of digital tools, it still elucidates the notion of architectural design being driven by the chosen architectural tool. Because
of this, the future of digital design will lie in technical capabilities of the architect. Digital design will rely on the architect to take on a partial role as computer programmer. For the most success within digital design will come from those who augment and specialize existing softwares to meet their needs and the needs of their clients.

The process of augmenting digital design software is most common done through a process called ‘scripting’. Scripting is a term used to refer to the writing of computer code, however, within the architectural field, this coding is usually relegated strictly to a single design software.

In order to use scripting to take our previously laid out two-dimensional system and transform it into a ‘script’ that will be useful in the design of useful structural systems, the two-dimensional system must be translated into three dimensions. This will be done by inserting vectors in the place of lines. Once we do this the rule systems changes as follows:
Movement of any one vertex triggers a gradient of movement in neighboring vertices. Vertices that are close together try to keep their relative position. Vertices that are part of unstable lattices are more affected by forces. Vertices that are deep in the middle of the building try to move more closely to the rim (creating 'rooms'). Horizontal movement is more likely than vertical movements (creating 'floors'). Vertices are attracted or repelled by forces (creating random mutation).

II. RULE-BASED SYSTEM OF SPRINGS

II. ITERATION
Movement of any one vertex triggers a gradient of movement in neighboring vertices.

Vertices that are close together try to keep their relative position. Vertices that are part of unstable lattices are more affected by forces. Vertices that are deep in the middle of the building try to move more closely to the rim (creating 'rooms').

Horizontal movement is more likely than vertical movements (creating 'floors').

Vertices are attracted or repelled by forces (creating random mutation).

II. RULE-BASED SYSTEM OF SPRINGS

II. ITERATION

**FIGURE 36:** Graphs show that the voronoi geometry is better suited to deal with nonuniform inputs and could lead to material savings in structural systems.
FIGURE 37: Rhinoscript translation of 3-Dimensional Voronoi system.

Option Explicit

Public Vector Functions: Various

Function Four: Generate Blocks from plane and performs a boolean intersection

Function Five: Finds maximum diameter of point array

Function Six: Calculates time needed for solution
By mapping out the three-dimensional translation visually, it allows it to be translated into computer code, thus making it part of generative system that can inform the future of a more sustainable, more waste-conscious architecture in our future. With the institution of large scale rapid-construction, technologies in the realm of additive manufacture are going to bring about a change the way we understand how architecture is built and rid the construction field of the waste that we now see through the use of standardized construction materials. That savings compounded by the material saving that we will find through the institution of natural models, such as this one, will pave the way for our a truly sustainable future.
FIGURE 38: Example of script dividing 3-Dimensional space
With these new and long-awaited freedoms the stage is set to realize the construction of a biologically-inspired architecture that is designed to take advantage of 3.8 billion years of evolutionary research and development[lviii] towards optimizing material and energy distribution. Dennis Dollens agrees that, “architecture deserves to be re-conceptualized in a biologic frame, not merely in a frame of materials, systems, and aesthetics.”[lix] The utilization and integration of natural morphologies and processes into the architectural design process

holds incredible potential for the future of sustainable design, and this generation will have the tools to bring those applications out of the theoretical realm and into physical reality.

This generation will witness an interdisciplinary collaboration resulting in a change from metaphor to model, from ‘nature’ as a source of formal inspiration to ‘nature’ as a mine of interrelated dynamic processes that are available for analysis and digital simulation.[lx] Also, this research is important for it will add to the ongoing debate over the effect of ‘the digital’ the role of the architect and further discussion of the notion of ‘digital tectonics’, and, furthermore, because the subject matter is relatively novel. New questions bear new answers, especially in a field as readily and optimistically synthetic as architecture, or as Allen Cunrow more pointedly wrote in his poem Landfall in Unknown Seas, “simply sailing in a new direction you could enlarge the world.”[lx]


FIGURE 32: p. 54 – 2-D Voronoi Rule System (author)

FIGURE 33: p. 55 – Voronoi system deployed in nature (author)

FIGURE 34: p. 57 – Voronoi vs. Orthogonal geometry diagram (author)

FIGURE 35: p. 58 – Voronoi vs. Orthogonal geometry graphs (author)

FIGURE 36: p. 64 – 3-D Voronoi Rule System (author)

FIGURE 37: p. 66 – Breakdown of 3-D Voronoi Script (author)

FIGURE 38: p. 67 – Example: 3-D Voronoi Script (author)
BOOKS


Renner, Gábor, and Anikó Ekárt. “Genetic algorithms in computer aided design..”


**PERIODICALS**


ELECTRONIC AND MISCELLANEOUS


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