Fall 10-1-2019

Fractals as Basis for Design and Critique

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by

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A dissertation submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy
in
Systems Science

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Portland State University
2019

Abstract

The design profession is responding to the complex systems represented by architecture and planning by increasingly incorporating the power of computer technology into the design process. This represents a paradigm shift, and requires that designers rise to the challenge of both embracing modern technologies to perform increasingly sophisticated tasks without compromising their objective to create meaningful and environmentally sensitive architecture. This dissertation investigated computer-based fractal tools applied within a traditional architectural charette towards a design process with the potential to address the complex issues architects and planners face today. We developed and presented an algorithm that draws heavily from fractal mathematics and fractal theory. Fractals offer a quantitative and qualitative relation between nature, the built environment and computational mechanics and in this dissertation serve as a bridge between these realms.

We investigated how qualitative/quantitative fractal tools may inform an architectural design process both in terms of generative formal solutions as well as a metric for assessing the complexity of designs and historic architecture. The primary research objective was to develop a compelling cybernetic design process and apply it to a real-world and multi-faceted case study project within a formal architectural critique. Jurors were provided a platform for evaluating design work and weighing in as practicing professional architects. Jurors' comments were documented and discussed and presented as part of the disserta-

tion. Our intention was to open up the discussion and document the effectiveness or ineffectiveness of the process we presented.

First we discussed the history of generative and algorithmic design and fractals in architecture. We begin with examples in ancient Hindu temple architecture as well as Middle Eastern architecture and Gothic as well as Art Nouveau. We end this section with a discussion of fractals in the contemporary architecture of Frank Lloyd Wright and the Organic school.

Next we developed a cybernetic design process incorporating a computer-based tool termed *DBVgen* within a closed loop designer/algorithm back and forth. The tool we developed incorporated a genetic algorithm that used fractal dimension as the primary fitness criterion. We applied our design process with mixed results as discussed by the jurors whose feedback was chunked into ten categories and assessed along with the author/designer's feedback. Generally we found that compelling designs tended to have a higher FD, whereas, the converse was not true that higher FD consistently led to more compelling designs.

Finally, we further developed fractal theory towards an appropriate consideration of the significance of fractals in architecture. We articulated a nuanced definition of fractals in architecture as: *designs having multi-scale and multi-functional representations of some unifying organizing principle as the result of an iterative process*. We then wrapped this new understanding of fractals in architecture to precedent relevant to the case study project. We present and discuss fractals in the work of Frank Lloyd Wright as well as Dean Bryant Vollendorf. We expand on how a theory of fractals used in architecture may continue to be developed and applied as a critical tool in analyzing historic and contemporary architecture a well as a creative framework for designing new architectural solutions to better address the complex world we live in.

Dedicated to Dean Bryant Vollendorf

Acknowledgments

I would like to thank, first and foremost, my mother and father, Winnifred Flynn Driscoll and John Cuervo Driscoll for their love and support throughout this long process. Wayne Wakeland has been a guiding light from the first day I walked into the Harder House and he has been more than *necessary* and *sufficient* for getting me through. Martin Zwick has been an invaluable resource on this project. Special thanks also to Melanie Mitchell who was instrumental in teaching me the tools I have put to use here and introducing me to the world of complexity science. I would like to thank my committee, Joe Fusion, Annmarie and John Jacques and Antonie Jetter. John was on DBV's thesis committee long ago and I have been astounded at the serendipity of his involvement with this project. Thanks also to the jurors who kindly participated in this project. Gary McCowan has been invaluable in this work for the past decade with his tireless advocacy regarding the legacy of DBV. I would also thank James Walter Schildroth, apprentice of FLLW and friend of DBV, who has been a steady hand in assessing the implications of this work. Tom Dolan deserves special thanks for the countless hours we have discussed DBV and Organic Architecture. Special thanks also go out to my friends who have helped me work through the fragmented convolutions of this project – Ed Cecere, Kirby Urner, Glenn Stockton, Peter Duffy, Brian Kardon, Amy Rowles, Susan Griskonis, Goffmachline Razin Khan.

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Glossary

The following definitions are given in regard to their usage in this dissertation.

Algorithmic design: Using computer-based tools and/or AI to generate solution to design problems.

Box-counting dimension: A graphic technique for determining the fractal dimension of an irregular object.

Critique: A critical review of a Pin-up by a panel (jury) of experts (architects).

Complexity: Organized synergistic behavior that emerges from a large number of interacting parts with no central control

Cybernetic: combination of man and machine with regard to some regulatory system.
Design: A human being's creative solution to the constraints of some compositional or architectural project.

Design process: The levels, steps and phases that are involved in a design.

Generator: 1. A repeating shape in a fractal. An organizational principle used to create and unify designs.

Genetic algorithm: A computer-based search heuristic using biological evolution as a metaphor.

Fitting: Making the output of an algorithmic design a realistic design solution.

Fractal: 1. Self-similar and multi-scale patterns. 2. Patterns having multi-scale self-similarity as the result of an algorithmic process. 3. Designs having multi-scale and multi-functional representations of some unifying organizing principle as the result of an iterative process.

Fractal dimension: A fractional dimension between 0 and 2, a measure of basic attributes of fractals.

Model: General term for the algorithm we develop and how it is used in the design process.

Organic Architecture: The school of architecture influenced and advocated by Frank Lloyd Wright.

System: Complex organization of parts and relations.

Systems theory: The body of quantitative and qualitative theory collected and applied to studying systems.

Theme - development - variation: An underlying organizational scheme in art and architecture that is applied to a project in numerous ways and most importantly, at multiple scales. The theme provides unity to a work and is related to "generator."

Pin-up: A presentation to a panel/jury of in-process or final presentation drawings and a description of a design.

Vollendorf Method: A didactic exercise for creating a composition using 3 lines on a page.

1.0 Introduction

"Why have cities not, long since, been identified, understood and treated as problems of organized complexity? If the people concerned with the life sciences were able to identify their difficult problems of organized complexity, why have people professionally concerned with cities not identified the kind of problem they had?" (Jacobs, 1961)

1.1 Motivation

In 2011, the United Nations reported that 3.6 billion people are living in urban areas, and this is expected to grow to 6.3 billion people by 2050 (World Urbanization Prospects, 2012). Today, 51% of the world population is living in urban areas and this comprises 3% of the world's surface (World Population Data Sheet, 2012). People are not only moving to cities but cities are moving to them, as cities become more bloated–swallowing towns and hamlets that once surrounded them. At the same time, we are facing unprecedented natural disasters. At the time of this writing we have seen intense wildfires in California, hurricanes and floods that have devastated Houston and Puerto Rico as well as major earthquakes across Mexico – and this is just the western hemisphere. Limits to growth are inevitable as the carrying capacity of the planet is tested beyond anything we have seen before. Many indicators such as peak oil, drought, climate change, top soil depletion, bio diversity loss, ocean acidification, and so on, are having an effect on societies worldwide and especially in the third world. Buildings alone account for 39% of CO_2 emissions in the United States. This is larger than any other sector (U.S. Green Building Council, 2019).

Buildings and cities in as much as they represent the problem are also a potential solution in many ways. Research into the science of cities has shown that densely populated urban environments are generally more efficient the larger they become (West, Bettencourt, 2010). A key question is, can architects and planners leverage this important aspect of urban dynamics? If so, they could perhaps design better buildings and infrastructure and consequently a more sustainable built environment for the pressures we face in the 21st century. A key to answering this question is provided by Jacobs' prologue above and involves identifying the problem we face as one of *organized complexity,* or perhaps, the notion of a *complex system* would be more apropos. The real-world problems that architects address every day involve complex systems related to ecology, culture, economics, precedent, life-cycle, energy/resource use, materials, tectonics, etc.

The design profession is responding to the complex systems represented by architecture and urban planning by increasingly incorporating the power of computer technology into the design process. This represents a paradigm shift, and requires that designers rise to the challenge of both embracing modern technologies to perform increasingly sophisticated tasks without compromising their objective to create meaningful architecture and address the larger issues inherent in our built and natural environments.

This dissertation investigates using computer-based tools applied within a traditional architecture context towards a design process with the potential to address the issues at hand. Computer-based tools are often considered as analytical and discriminative and less often as generative. Here we reverse this emphasis and put computer-based tools within an aesthetic framework and incorporate theoretical notions such as intention, meaning, making, creativity, vision and so on. This flipping of the paradigm can be thought of generally in terms of *sense-making* versus *change-making*. Making *sense* of the world requires a discriminative approach that looks for correlations in data and builds predictive models. How we make *change* in the world, however, involves generative models that can produce novelty and create meaning.

Computer-based tools used in a generative way have the potential to profoundly affect our physical environment. Managing the sheer amount of data available in our modern world has propelled the development of computer technology and architects and planners have come to rely to a large extent on computational approaches for analyzing spatial data. Such approaches are quickly becoming more than computational machines for crunching numbers. Machine learning techniques such as neural networks and genetic algorithms are advancing to such a degree that they can be used to create form as well as analyze it. For our purposes here we will refer to tools at this level with the tag "artificial intelligence" (AI) to serve as a placeholder for such technology. These developments are increasingly relevant to our built environment and architects would be well advised to consider this technology and its implications in terms of addressing the complexity inherent in design at this stage in history.

Architecture has traditionally been the province of designers trained in architecture but not necessarily in computer science, yet the tools of the architect are becoming increasingly computer-based. Conversely, computer scientists are often not trained in design and yet their work is having a large effect on how buildings are designed and consequently on our built and natural environments. Computer-based tools have a large impact on architecture and city planning but, until recently, have effectively bypassed the design field and consequently the enormous historic precedent inherent in architecture. Many tools are now available for the architect which not only have redefined how architects design and represent buildings but also suggest a new paradigm of design science and evidence-based design that applies rigor and analysis to the design process.

We have seen in architecture that the incorporation of computer-based tools is gaining momentum as architects use them solve the “wicked” problems our built environments represent, but AI itself remains largely a black box in the architect’s world. It is important to integrate AI as a toolset within the context and culture of architecture to more adequately address the problems we face – internalizing the externalities – while at the same time it is essential to retain the vital aspects of architecture such as precedent and the creativity of the designer. The question then becomes not simply how can we apply new computer technology to architecture, but rather, how can we do this and retain the spirit of architecture and meaningfully address the urban and environmental issues we face? To paraphrase the architect and educator, Dean Bryant Vollendorf, we stand on the shoulders of those that came before us so we can see further into the future.

We present an algorithmic design process in this dissertation that draws heavily from general systems theory (GST) and specifically fractal theory. Next we offer in sections 1.2 and 1.3 a brief introductory background on key concepts relevant to this dissertation. We will delve more deeply into these ideas in Chapter 2.

1.2 Systems Theory

GST

A background to architecture with regard to general systems theory (GST) is provided in this section. GST is used as a framework for this thesis because of its comprehensive and trans-disciplinary agenda. GST is envisioned by Bunge (Bunge, 1977) as a *scientific metaphysics* and offers an array of processes and tools for engaging large unwieldy problems. Boulding writes, "General Systems Theory is a name which has come into use to describe a level of theoretical model-building which lies somewhere between the highly generalized constructions of pure mathematics and the specific theories of specialized disciplines" (Boulding, 1956).

One hope for solving the wicked problem that architectural and urban design represents involves a shift in paradigms from reductive thinking to a more comprehensive approach that internalizes within the model difficult aspects of design problems that are often ignored – such as the larger environment and ecology. Solutions to the global challenges we face require an approach that treats the problem not as one that can be "maximized" per se or reduced to a small number of variables. A systems approach consists of multiple perspectives and looks at problems from the bottom up (holistic) in all their messy and haggard details as well as from the top down (wholistic) as ensembles of elements and relations (Linstone, 1984) (Lendaris, 1986). This dichotomy is also related to cornerstone ideas in information theory such as order and entropy as well as contemporary philosophy, such as Deleuze and Guattari's notions of "mesh-works" and "hierarchies." A similar dichotomy is offered in architectural criticism such as Christopher Alexander's seminal paper, A City is not a Tree (Alexander, 1964). A systems approach attempts to look at relations such as these as general and "stuff free," capable of being applied to a wide variety of systems. George Klir offers a common sense definition of a system as simply a set of things and relations, S = (*T, R*). (Klir, 2013).

System

Epistemologically a system, as defined by George Lendaris, is a defined focal unit or whole that consists of defined sub-units or elements as well as a defined supra-system or larger context. These three aspects can be thought of as: the supra-system perspective *B*, the unit perspective *C* and the sub-unit perspective *D*. (Lendaris, 1986). Essentially, any focal perspective is nested within a higher and lower level. In an open sense, this pattern can expand upwards and downwards indefinitely, in a closed sense, there is some limit to the expansion or contraction. We apply this general framework in the closed sense within a context of architecture and design when we develop our design process in Chapter 3 as well as our discussion on the use of fractal algorithms in architecture generally.

Systems approaches are particularly suited to the complexity inherent in the practice of architecture and design. Herbert Simon, in developing hierarchy theory, makes a distinction between *complexity* and *complicatedness*. To Simon, complexity represents a system with many levels and parts or sub-systems coordinated within some framework. The behavior of such a system is often simple or well organized, whereas, complicatedness represents a relatively simple structure with fewer or no hierarchical levels but many parts and often having very complicated behavior (Simon, 1996). An example of *complex* behavior may be the vehicular circulation patterns in New York City with its four tiered system of vehicular modes consisting of interstate highways, local highways, avenues, and streets which represents a hierarchical underlying structure that allows for a complex problem to have relatively simple behaviors, whereas, an example of *complicatedness* may be traffic patterns in densely populated cities with only one or two types of streets.

CAS

Following Jacobs' lead, we assume the nature of design at the urban level and ecosystems level to be *problems of organized complexity* and start by defining a complex adaptive system (CAS): a system capable of adjusting its behavior to suit new conditions and composed of many parts and relations that cannot be understood from understanding the parts alone. CAS is related to systems that are self-organizing, emergent and fractal as will be discussed next.

CAS are “adaptive” in that they are capable of changing over time relative to an environment or, in a word, l*earning*. CAS are often discussed in relation to living systems as neg-entropy or open systems far from equilibrium with large throughputs. CAS as living systems are observed to follow scale-free or power law distributions. For instance, Kleiber's Law has been widely discussed in the literature (Enquist, Brown, 2005) as an attribute of biological scaling (allometry). Geoffrey West has written about this extensively and recently in his book, "Scale" (West, 2017). For these reasons, cities are beginning to be thought of in terms of CAS and a similar methodology has been applied to the study of urban dynamics (Bettencourt, 2013; Batty, 2007). Generative design in architecture is also borrowing concepts from CAS and applying them to the design of buildings. Emergence has been particularly influential in generative design in architecture (Weinstock, 2010) as have fractals (Ediz Cagdas, 2007, 2009; Gürbüz et al., 2010).

Scale Invariance

Power law distributions have been observed in a wide variety of phenomena in both nature and artifice. Power law distributions are scale-free distributions and are linear on a log/log graph – as you zoom in on them they are always the same. Per Bak is one of the leading theorists in this domain and has developed a rich body of theory around scale-free distributions in nature such as the notion of self organized criticality (SOC). Some natural phenomena such as earthquakes and avalanches have been observed to *self-organize* to a critical point attractor and to exhibit scale invariant behavior over time (Bak, 1987).

Fractals

Scale-free (power laws) distributions are related to fractals. Fractal dimension (FD), also known as Hausdorff dimension, is the power relating the initiator (r) to the generator (N) – in Mandelbrot's terminology – which can be expressed as $N = r^{FD}$ or, $FD = \log N / \log r$. We will discuss in subsequent sections the use of the exponents for such power laws in terms of FD which is used for analyzing fractals. Fractals are found in dynamical systems and chaotic systems (May, 1976). Most importantly for this dissertation, fractals have been shown to be relevant in research into general urban patterns and in architecture as well as generative and algorithmic design. This research thread also includes new approaches to understanding biological and urban scaling through the application of fractal geometry (West, 2017, 2005; Bettencourt, 2013).

In today's increasingly complex world, where we face a motherlode of wicked problems, systems approaches have undergone a renaissance of sorts. Important multi-disciplinary research into complex systems is ongoing. Fractal geometry is an important aspect of complex systems research, and has been incorporated as one important measure of complexity in the form of Hausdorff dimension, also called fractal dimension (FD). Fractal theory provides additional tools for assessing complexity as will be discussed in Chapter 2. This is a key reason we have chosen fractals as the focus of the present research and experiments. In addition to analyzing complex systems, the word *fractal* refers to geometric objects that can be visualized, designed and used as the organizational principle in the design process. For these reasons we argue that fractals represent an appropriate theoretical and practical framework on which to base our research.

1.3 Parametric, generative and algorithmic design

Brick and mortar architecture is concerned with many inter-related sub-systems such as structural systems, mechanical systems, electrical systems, plumbing systems, glazing systems, waterproofing systems, etc. The physical and ecological context for a building might be thought of as a supra-system in Lendaris' systems framework. Architects must integrate all these various systems together into one relatively integrated whole if a building is to function properly.

Architects often employ a general organizational system to help integrate a design. Designing with a proportional system or modular one is a general technique for organizing the inherent complexity of a building, and has been used since time immemorial. Frank Lloyd Wright was especially fond of designing relative to what he referred to as a "unit system." Some contemporary architects have attempted to develop meta-systems – systems of systems – towards a more unified approach to managing the sub-systems within a building within an integrated whole. One such approach was developed in the 1960s by Ezra Ehrenkrantz called School Construction Systems Development (SCSD) (Boice, 1965). Increasingly today, architects are reliant on computer-based systems to manage the complexity inherent in the problems they face.

Computer-based systems include computer modeling, computer aided design (CAD) and building information modeling (BIM). These types of software are currently developing in a variety of ways and fall under the general heading of *parametric design*. Parametric design is an encoding of rules with adjustable variables. Parametric design allows designers to utilize various modifiable modules to help solve architectural problems within an analytic framework. These problems are increasingly multi-variate and data driven, that is, problems which require mathematical analysis and computation-based search heuristics.

Algorithmic and generative design is a further advancement of computer-based systems that goes beyond simple parametric design in that they are used generatively to create novel form. The germination of algorithmic and generative design relates to GST such as the cybernetic project of the 1950s (Ashby, 1961; Wiener, 1961) as well as Simon's Sciences of the Artificial (Simon, 1996), and research regarding evolutionary processes and computation such as John Holland's pioneering development of genetic algorithms (GA) (Holland, 1992). GAs and evolutionary programing are examples of generative systems, and they have given the architect powerful new tools to study and invent form. Galapagos is one such tool and represents an out-of-the-box genetic solver plug-in for the BIM Rhino/Grasshopper, tailored specifically for architects and urban designers (Rutten, 2013, 2010).

1.3.1 Design Process

Design technology has in some ways paralleled early developments in cybernetics. Archer and others developed models of design processes in the 1960s which reflected parallel developments in systems approaches such as the systems morphology models introduced by Hall (1969). Alexander's approach to architecture and urban planning as a *pattern language* has been influential to a generation of both designers and software engineers and has influenced the development of computational based "architectures" such as object oriented programing. These concepts are directly related to BIM and algorithmic design. BIM utilizes parameterized objects that provide a quick and easy ways to update a three dimensional model globally to solve specific design problems. Models may also be exported in a variety of ways, for instance as traditional construction documents, 3D printed models, or directly to automated manufacturing systems and so forth. Objects are also available from manufacturers as downloadable libraries representing, to a degree, ready-made design solutions. These can be fit together virtually like patterns. BIM has introduced a platform where architecture, manufacturing and construction have begun to be integrated in a way that never would have been possible before the advent of computer-based technology.

Some architects have taken the potential of digital technology in different directions, creating virtual spaces that employ algorithms to connect architecture and context in “intelligent” ways such as the work of the architecture firms Morphosis and Asymptote, and the work of artist/architect Marcos Novak (Judelman, 2004). Generative design, fractal geometry and the use of automated manufacturing processes have been influential to Joris Laarman and his designs for furniture (Doubrovski, 2011). Generative design and fractal dimension have been developed as a method for designing efficient and robust structural forms (Rian, 2016, 2018, Kiani, 2016; and have also been used to analyze and create neighborhood plans as well as individual schematic designs of residences (Gürbüz et al., 2010); Ediz, Cagdas, 2007). This last example is the closest work related to our dissertation.

1.3.2 Meaning

To make things more complex, architecture is also charged with the socio-technological dimension. This includes the behaviors and needs of people which have a pragmatic side in the sense that a building represents habitable and healthy space as well as a sensitivity to historic and cultural context. This dimension we define in this dissertation as a supra-system. This category suggests a more ephemeral dimension in terms of "creativity," "meaning" and "beauty," to name a few weighty terms. This abstract and symbolic dimension is important to mention because it highlights the metaphysical aspect of architecture. To borrow from linguistics, architecture has a *pragmatic* and *syntactic* side as well as the *semantic*. As such, the problem architecture attempts to solve is very difficult to define in concrete terms and must include the intent of the designer which is subjective and intuitive and falls squarely within the realm of aesthetics. Some theorists have attempted to discuss meaning in architecture using information theory (IT). (Baird, 1969). "Meaning" and IT have been awkward bedfellows, as we discuss here and more in Chapter 3, yet offer much insight into qualitative and quantitative approaches. For instance, IT as a means for assessing a semantic system has met with significant pushback, with critics pointing out that the term *information* and how it is used in certain contexts does not imply meaning (Arnheim, 1971). Arnheim is skeptical of advocating quantitative approaches in assessing design and emphasizes the need for the "finger pointing" critic (Arnheim, 1977).

1.4 Preview of subsequent chapters

The algorithmic design concepts and processes touched on above offer much promise to help architects and urban planners to better analyze and solve the complex problems they face. In Chapter 2 we offer a more thorough review of contemporary algorithmic design and literature. We focus on fractals applied to architecture history as well as contemporary approaches in algorithmic design and the work of Frank Lloyd Wright and the tradition of Organic Architecture. In Chapter 3 we investigate FD as a design aid for architects. We define the Vollendorf method and apply it to "proto-cybernetic" design process. We develop and present a tool termed DBVgen which incorporates the Vollendorf Method and a genetic algorithm using FD as a fitness criterion. The design process using DBVgen is applied to a proof of concept (toy) problem. Selected jurors comments are presented and discussed. In Chapter 3 we also apply the design process to a real world architecture project in response to a request for proposals (RFP) from the City of Ithaca, NY. Selected jurors comments are presented and discussed. In Chapter 4 we investigate and present a fractal algorithmic interpretation of the work of FLLW and DBV and relate this interpretation to our approach in the case study project. We also discuss the potential of fractal algorithms as an organizational principle in architectural design. In Chapter 4 we discuss further the background and precedent for the research in terms of fractal algorithmic design and the work of FLLW and Dean Bryant Vollendorf (DBV). Chapters 2, 3 and 4 represent related but separate papers to be published in appropriate venues. Consequently, there are some repetitive paragraphs needed for the chapters to be self contained. Chapter 5 is a synthesis and conclusion to the entire dissertation.

End of Chapter 1

2.0 Review of algorithmic design and fractals applied to historic and contemporary architecture

2.1 Introduction

Solutions to the global challenges we face undoubtedly require a wholistic/holistic approach and one that looks at the situation from multiple perspectives and from multiple disciplines. We focus on architecture and the potentials and challenges offered by algorithmic design and fractal geometry. Design presents an important leverage point in how we affect our built and natural environment, and new computer-based technologies enhance this leverage significantly. Peter Senge offers an interesting thought problem with the analogy of a ship at sea. Senge asks, who has the most control of a ship? Is it the captain or crew or perhaps the engineer in the engine room or maybe the navigator? The answer is the *designer* of the ship (Senge, 2006). Buckminster Fuller offers a slightly different analogy to a ship in terms of the trim tab on the rudder (Fuller, 2008). The trim tab has seemingly little to do with the overall working of the ship yet it has in fact a powerful influence on the overall heading even though it is a small and seemingly innocuous part. From a systems perspective this represents an important leverage point – where a small change in a part may have a large effect on the whole. We focus on this idea not only as an analogy but literally as mereology and its general relationship to the whole reflected in the part aspect of fractals. In this chapter we review fractals as represented in (organic) architecture historically as well as contemporary computer-based approaches in algorithmic design. We keep an eye towards the potential offered by algorithmic design and the creativity of the architect as a key leverage point (trim tab) that has the potential to alter the direction we are headed.

2.2 Background

Section 2.2 presents a short background on the history of generative computer-based tools and their current state-of-the-art implementations.

2.2.1 Algorithmic design / generative design

As touched on in the previous chapter, modern algorithmic design and generative design grew, in part, out of research in cybernetics of the 1950s. Figures often associated with systems theoretic approaches and artificial intelligence (AI) in the early days are: Alan Turing, John von Neuman, Ross Ashby, Norbert Weiner, and Herbert Simon, to name a few. Algorithmic approaches to invention and creativity were extensively studied by Genrich Altshuller in the 1950s and incorporated into a system of problem solving known as TRIZ (Altshulle, 1996). Around this same time, another computationally based approach for dealing with complex non-reducible problems was being developed by Fritz Zwicky termed morphological analysis (Ritchey, 2006). A number of threads might be traced from this starting point. For our purposes here we are interested in the development of genetic algorithms and fractal geometry as they apply to algorithmic design.

Singh in "Towards an integrated generative design framework" highlights five techniques which are currently being used in architectural design. These are shape grammars, L-systems, cellular automata, genetic algorithms and swarm intelligence (Singh, 2012). The thread we explore originates with Turing and von Neumann and weaves through the development of the field of artificial life (AL) by figures such as Christopher Langton's self replicating CA loops, John Holland, and Melanie Mitchell's work into genetic algorithms and evolutionary computing as well as the exploration of algorithmic patterns in nature by the botanist Aristid Lindenmayor and, most importantly, we focus on the iconoclastic work of Benoit Mandelbrot and his relatively single handed synthesis of mathematics and theory into the field he termed "Fractals."

Modern algorithmic design practitioners are influenced by the early pioneers mentioned above. John Frazer has applied concepts such as evolution and morphogenesis to architectural design. Frazer developed the Evolutionary Digital Design Process at the Architecture Association as part of his work in morphogenesis in the mid 1990s. Frazer describes his work as a process driven methodology that has the potential to address larger (global) environmental concerns. Frazer taught with Gordon Pask who introduced cybernetics into architectural theory in the 1960s through Stafford Beer and Von Neumann’s “Universal Constructors” which Pask developed as 3D building block prototypes (Frazer, 1995, 1997). Michael Weinstock is also an important contributor to generative architecture in terms of emergence. His work draws from biological as well as the historic development of cities and culture. Weinstock draws from a macro view of geology, biology and urban forms (Weinstock, 2010).

Other research in architecture has been influenced by Turing's early work in reaction diffusion processes (Turing, 1952) as well as Lindenmayer's L-systems (Lindenmayer, 1968). Paul Coates et al. reference this work as being influential to their development of "shape grammars" to breed structures that respond to physical constraints in the environment such as light and wind (Coates, 1999). Coates utilizes a form of genetic algorithms that uses L-systems as parse trees which evolve relative to an objective function. Combining genetic algorithms and L-systems is a parsimonious approach to exploring what Coates terms, "spatial morphogenesis" (Coates, 1999).

Precedent in architecture and evolutionary design is investigated by Zarzar and earlier by Gero. Zarzar develops the notion of "d-genes" and focuses on the architecture of Corbusier and Calatrava, analyzing form, structure and the evolution of design principles such as Corbusier's five points of modern architecture (Zarzar, 2003). Gero does research into the architecture of Frank Lloyd Wright (FLLW) and the paintings of Mondrain. Gero develops a GA to abstract rules from a number of FLLW window compositions and Mondrian paintings and then uses the GA to develop new designs that are a hybrid of both architect and artist (1998).

Patrick Schumacher addresses the paradigm shift in the design community relative to these new tools and concepts. Schumacher writes in "The Autopoiesis of Architecture" that:

"Beyond such obvious surface features one can identify a series of new concepts and methods that are so different from the repertoire of both traditional and modern architecture that one is justified in speaking of the emergence of a new paradigm within architecture. New design tools play a crucial part in making this possible, establishing a whole new design process and methodology" (Schumacher, 2011 Volume 2, Chapter 11).

Trends in research are towards *biomimetic* approaches combining evolutionary computational methods with morphogenetic processes inspired by nature, where form is generated by computer technology, incorporating the rules and constraints of fabrication (Menges, 2012, 2013). GAs are becoming commercially available for practitioners such as the Genr8 plugin for Maya as well as the Galapagos plugin for Grasshopper which is a used as a visual programming aid for architects within the BIM software Rhino. Galapagos and Grasshopper offer access to non-programmers that allows for GAs and other algorithmic design tools to be experimented with in a variety of ways.

We touch on three such applications next. Galapagos has been used to optimize spatial adjacencies for complex building programs (Boon, Griffin et al. 2015). This project optimizes a three dimensional layout for 50 programmatic spaces, essentially creating a bubble diagram that an architect may then use for schematic design. Galapagos has been used for daylighting and shading studies (Gonzales, Fiorito, 2015) as well as to find novel solutions to structural problems (Danhaive, 2015). Galapagos has also been used to generate new fractal forms for urban environments using cellular automata (Devetakovic, 2015).

The brief background above reviews the coming together of architecture and computer science towards a new evolutionary design approach that combines the creativity of the designer with the computational power of computers to simulate natural processes and apply them to architecture. This process draws heavily from nature and has been termed variously: biomimetic design, generative design and algorithmic design. We use the term *algorithmic design* to the degree possible to refer to this general approach to design

2.2.2 Genetic Algorithms

The advent of search algorithms that are inspired by biological evolution is a story of co-evolution developing independently in the United States and Germany in the 1950s and 1960s. In both cases, principles of biological evolution such as natural genetic variation and natural selection were applied to computer programs to solve parameter optimization problems. In Germany “evolution strategies” were introduced by Rechenberg and later Schwefel which could be used to solve real world engineering problems such as the design of airfoils (Back et al., 1991).

John Holland developed Genetic Algorithms (GA) which are attempts at formalizing evolutionary and adaptation processes in nature and applying them to computer systems (Holland, 1975). Genetic algorithms were an abstraction of organic evolution replacing chromosomes with bit strings and using the operators: crossover, mutation and inversion to "evolve" populations based metaphorically on sexual reproduction. In a GA, populations evolve over time relative to some fitness criteria (Mitchell, 1998).

Evolutionary programming was another line of research which was also developed in the 1960s. Here, a finite-state machine representing a given solution is mutated according to a state-transition diagram to develop more fit individuals (Fogel, Owens, Walsh, 1966). Additional work has been done by Koza (1992) termed genetic programming (GP). GP uses a different method that is intriguingly fractal in form. GP begins with parse trees (hierarchical node graphs) consisting of nodes representing various mathematical operators, variables, and logic gates: [+, –, *, / , A, X]. Trees are then randomly cut at a node and inserted into other trees, or subtrees may be removed and replaced with other subtrees and recombined over many generations relative to a training set on some data. Koza claims such a system is capable of *automated programming* and has demonstrated GP's effectiveness within a variety of domains. be equal at best, or less effective (O'Reilly, Oppacher, 1994).

The preceding background illustrates just a few of the many GAs that have been developed. As Mitchell describes, specific GAs are as numerous as the problems they attempt to solve (Mitchell, 1998) and in this sense do not represent a universal search algorithm but rather a heuristic approach or process that can be tailored for specific applications. GAs have been widely used not only for discriminative data analysis but also as generative algorithms. Following the previously mentioned pioneering work of Karl Sims in Chapter 2, GAs have been incorporated by designers in a variety of ways. Artists such as Rooke, Unemi and Hart followed in Sims' footsteps using expression based algorithms similar to Koza's genetic programing model and many contemporary visual artists have followed this earlier work (see Romero, 2008). 3D GAs have also been developed with a variety of approaches such as geometric (lattice) deformation by Wattabe and sequences of polygonal operators by McGuire (Romero, 2008). Latham and Todd developed the PC mutator system at IBM UK's Scientific Centre with individual projects as well as commercially available software (Romero 2008). Hemberg and the Emergent Design Group (EDG) at MIT developed Genr8 in 2001 which is based on artificial life and evolutionary computation and developed as a plug-in for the modeling and animation software Maya (Hemberg, 2006, 2007). EDG is an interdisciplinary group that attempts to bridge computer science and architecture in the nascent field of generative or algorithmic design. Hemberg et al. describe six different projects which use genr8 (Hemberg, 2008) Shape grammars and GA's have been explored with a prototype tool called Shape Evolution to design hypothetical buildings (Chouchoulas, 2007).

2.2.3 Cellular Automata

This section describes cellular automata research and application in architecture (CA). CAs are interesting because they offer a simple way of expressing what algorithmic design is. CAs offer insight into the sheer variety and surprise embedded in simple codes iterated again and again as will be touched on next.

CAs represent a system where simple rules govern local interactions yet global or emergent behavior may arise in the absence of any governor or central processor. Mitchell and Crutchfield used GAs to perform density-classification tasks on CAs such as determining if the initial configuration contains majority black or white cells. Rules evolved by the

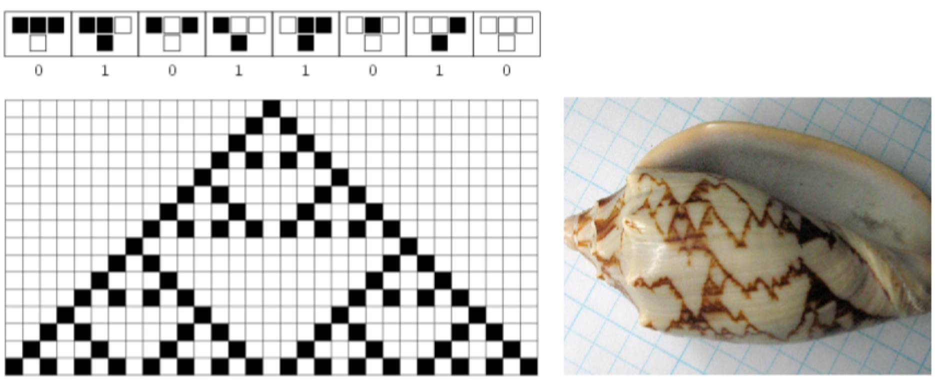


Figure 2.2.3.1. Elementary cellular automata (left) with simple rules creating a Serpinsky triangle fractal juxtaposed to an organic shape (right) with similar patterns, (Wikimedia Commons).

GA have been discussed in terms of computational mechanics relating to concepts such as, “particles” and “particle interactions” (Crutchfield, Mitchell, Das 1996). CA strategies are seemingly evident in nature (Figure 2.2.3.1) and have been an area of fascination for researchers interested in artificial life beginning with Turing's work in morphogenesis (Freeman, 1986).

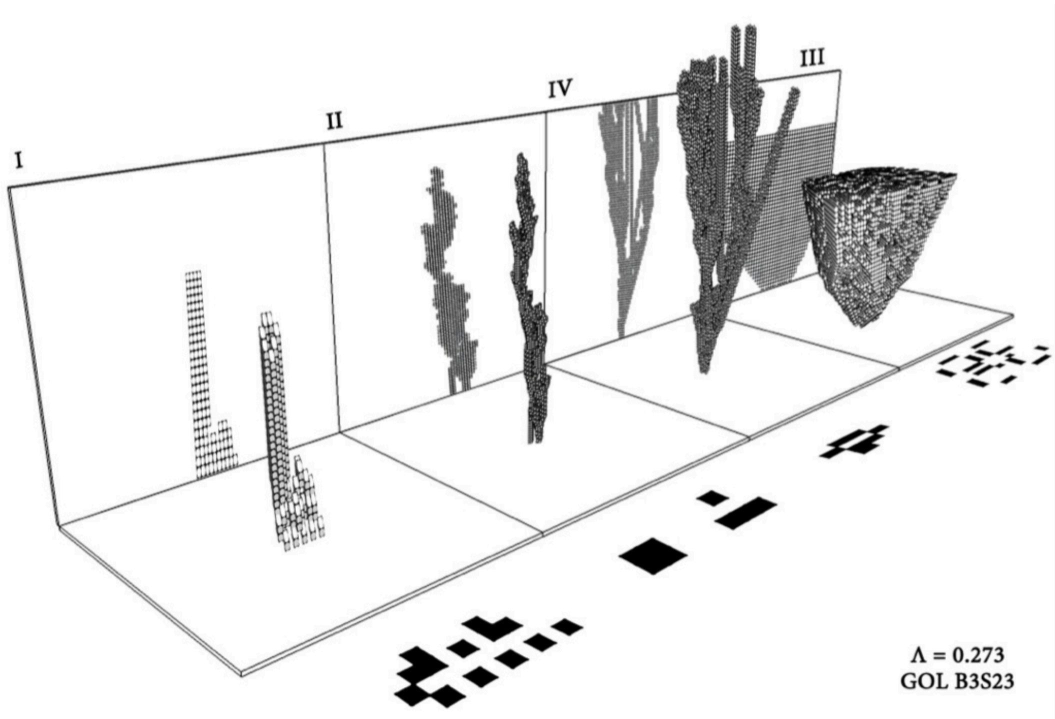


Figure 2.2.3.2. Cellular automata algorithmic design models (by author).

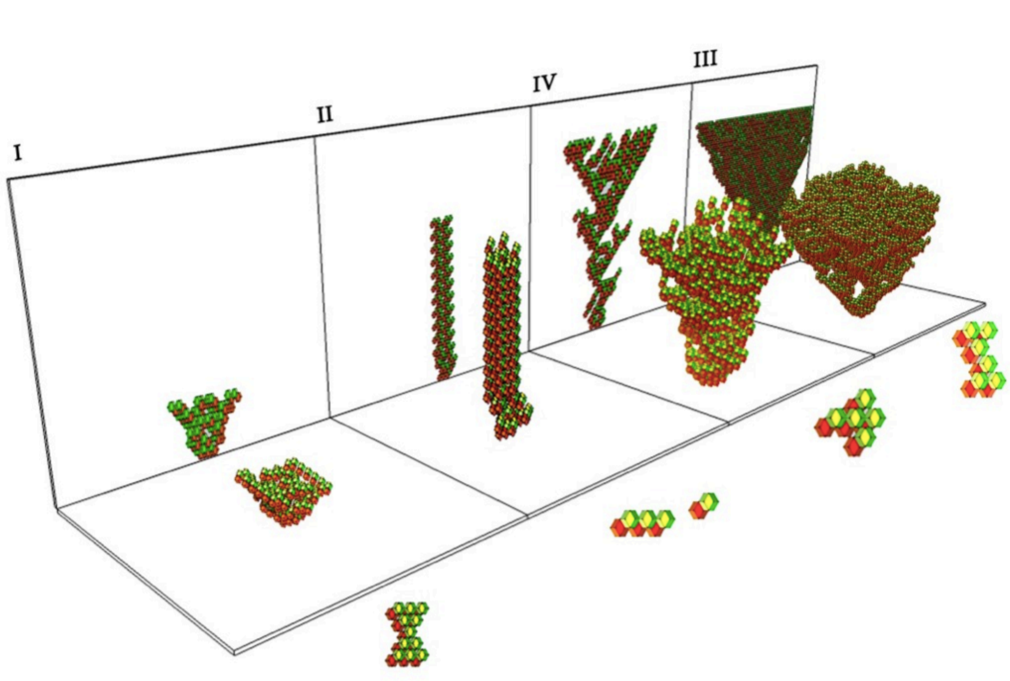


Figure 2.2.3.3. Cellular automata algorithmic design models using a hexagonal module (by author).

CAs have also been applied to architecture and urban modeling. White investigates the development of a cellular automaton to model the spatial structure of urban land use over time (White, 1993). Schelling applies CAs to models of human neighborhood segregation (Schelling, 1971).

The author has also experimented with applying CAs to architecture. Figure 2.2.3.2 represents a CA system using orthogonal modules and Figure 2.2.3.3 is one using hexagonal modules. The models were created by layering successive iterations of CAs on top of each other, thereby creating a 3D form. A large number of rules were investigated and many types of sculptural forms resulted with attributes similar to John Conway's Game of Life (Conway, 1970). These forms became the basis for a hypothetical project in Portland, Oregon.

2.3 Fractals

Fractals have significance in many fields and are an active field of research. From developing efficient principles in programing biological form in genetic design (Weibel, 1991), to building nanoscale fractal architectures in gold (HianáTeo, 2010), to universal theories in physics (El-Showk, Poland et al., 2014), fractals are receiving much attention at present, yet fractal geometry and fractal algorithms have long been employed in architecture. With mathematical tools at our disposal it is now possible to analyze the fractal qualities of this architecture. Along with GAs, fractals have a strong association with nature and life. As we will discuss, fractals are an important aspect of algorithmic design as well.

Benoit Mandelbrot famously applied fractals to the measurement of the coastline of Great Britain. If you measure Britain's very jagged coastline with increasingly smaller instruments, first at the level of kilometers, then with a meter stick, and even at the level of centimeters and below, you will continue to see a self-similar jagged structure. As you use smaller and smaller measuring devices, the length you measure approaches infinity (Mandelbrot, 1967). This phenomenon was first studied by Lewis Fry Richardson who realized that when measuring the border between France and Spain there was no converging measurement but rather the length of the boundary was relative to the precision of the measuring device he used. Richardson plotted length measures against the resolution of the corresponding metric and noticed a linear relation when plotted logarithmically. This later inspired Mandelbrot as well as the contemporary physicist Geoffrey West who refers to the convoluted or ever-folding nature of this phenomenon as 'crinkliness' when he writes:

"Crinkliness, later to become known as fractallity, is quantified by how steep the slopes of the corresponding straight lines are on Richardson's logarithmic plots, the steeper the slope the more crinkly the curve. The slopes are just the exponents of the power laws relating length to resolution..." (West, 2017).

Before Mandelbrot, fractal functions were thought of as the "monsters of mathematics" and little was developed regarding their properties although key figures such as Gaston Julia laid the foundation stones for Mandelbrot. Today, fractals are a popular research topic in mathematics with regard to dynamical systems and deterministic chaos.

In the literature surrounding fractals in architecture a strict definition of a fractal is somewhat challenging. Regarding fractals and chaos theory, Ediz and Cagdas write, "Fractals lie at the foundation of the self-similarity concept which appears with Chaos. The term fractal comes from the Latin 'fractus' which ... is taken to mean piece, break, broken, fragment, fractional, and disorder [sic]." (Ediz, Cagdas, 2007). Rian et al. offer, "A non-strict definition of a *fractal* is a shape or a figure that encapsulates the copies of itself at the infinitely different level of scales [sic], which means it is recursively self-similar as well as rough at every magnifying level." (Rian et al., 2018). Lorenz further clarifies, "Fractals are defined by their characteristics – self-similarity, generations by iterations, rough surfaces, infinite complexity, dependence on starting parameters and common features with nature – but often the only way to describe Fractals is through their Fractal Dimension [sic]." (Lorenz, 2009).

The term "Fractal" is used above in two general senses, (1) a self-similar *pattern* or *shape* at multiple scales and (2) a *process* that defines the pattern – the former is an instantiation of the latter. The first definition is an object in space and the second is a process in time. Combining these two senses, a good working definition of a fractal is –

patterns having multi-scale self-similarity as the result of an algorithmic process. A fractal is a scale-free, non-Euclidean geometry of some kind (fractal iterate) that is the outgrowth of some operations (mathematical transformations such as re-scaling and rotation). However, a more nuanced definition of fractals begins to emerge when applied to architecture. In architecture, a fractal is not necessarily limited to a self-similar *shape* only but more a self-similar motif or theme or, in the most simplistic sense, a self-similar *idea*. Dawes and Ostwald touch on this notion when describing the role of invariant patterns in Christopher Alexander's work, "the creator's perspective represents a global view of the language that is consistent with Alexander's conceptualization of design as a scale-based cascade of decisions." (Dawes, Ostwald, 2018).

Fractal iteration in architecture is more loose and freeform perhaps than what we think of as the rigorous fractal geometry in mathematics. Fractal geometry in architecture often transforms or develops in different ways and as per a designer's individual approach, or as architects like to say, a designer's "hand." In architectural design as in music composition, an idea is sometimes explored in terms of theme, development and variation where design options are explored within particular constraints. Fractal geometry in architecture has this "variations on a theme" or ètude feel to it. A third definition of fractals when applied to architecture emerges as *designs having multi-scale and multi-functional representations of some unifying organizing principle as the result of an iterative process*.

Ediz touches on these points and applies them to generative design by using an analogy to jazz improvisation, "A key is the reference point for improvising. It is like a structure or DNA code. One has to be at least intuitively aware of the individual notes within that key. In generative design, the fractal dimension is the "key" that determines the potential variations of a specific shape or pattern" (Ediz, 2009).

Fractal geometry in architecture is not strictly scale-free but repeats at a finite number of scales (levels) and is more eccentric and freeform than the rigorous fractal geometry in mathematics such as the Mandelbrot set. Fractal geometry in architecture may transform or develop in unpredictable ways as per a designer's individual approach, or as architects like to say, a designer's "hand." Architecture generally employs fractal geometry within a context of *theme, development and variation* as is discussed in later chapters.

2.3.1 Fractals in architecture history

This section focuses on the relationship between fractals, and historic architecture. Long before Mandelbrot formalized the mathematics of fractals, architects were making use of self-similar forms at multiple scales. Architecture is perhaps unique in the arts in that a geometric pattern can represent something at many different spatial scales – from the pattern or motif in window muntins to the general layout of the plan and even on up to the organization of the urban form. This idea follows patterns found in natural objects. The leaves of a fern are composed of smaller replicas of themselves for instance (Fig. 2.3.1.1)

Figure 2.3.1.1. Fractals in the leaves of a fern. 3 distinct self-similar levels are evident (Wikimedia Commons).

Fractals are an ancient component of architecture and were considered a sacred cosmological aspect of architecture. Figure 2.3.1.2 shows a Hindu temple completed circa 1030 C.E. Patterns such as these were defined in Vedic texts on vaastu (architecture) and could be thought of as recursive algorithms that were that were written down such as the following...

"The layer of prahara (projection) will be above the chadya (eave of the roof). This is to be repeated again and again on the spire over the spire. A fraction of the prahara is to be constructed and again the spires are to be constructed. Each of the upper spires will be sprouted out with a measurement equal to half the size of the lower spire"

(Quoted from Trivedi, 1989).

Fig. 2.3.1.2. Kandariya Mahadev Temple, Madhya Pradesh – Photograph by RM

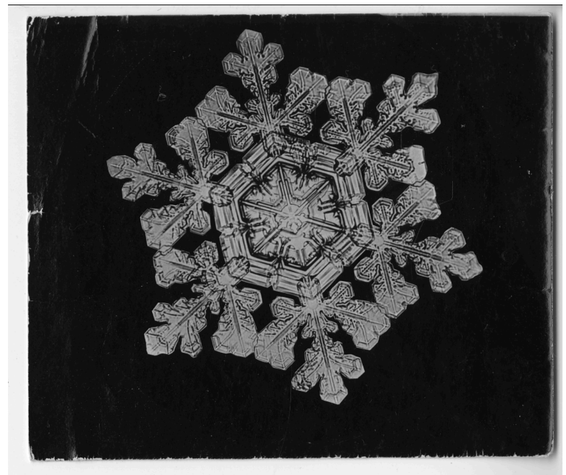


Fig. 2.3.1.3. A "Dendrite Star" photomicrographed by Bentley, W., Smithsonian Institute, (1890).

It is noteworthy for our purposes here, that such designs were not specifically detailed in drawings but were general "instruction potentials" that allowed for buildings to emerge. The plan view of the building called a mandala, literally "polygon" could be expressed vertically in elevation in myriad ways. Interestingly, Indian temple architecture has been related to a ideological system where the whole is contained in the part. "The strict adherence to the directional alignment of the buildings and its enclosed functions is one of the consequential derivations of the site envisaged as a cosmological grid of the Vaastu-Purusha-Mandala" (Patra, 2009). This architecture suggests that an emergent and fractal model co-exist in the form, much as a snowflake has infinite variety yet follows a hexagonal geometry (Fig. 2.3.1.3).

Trivedi writes, "The Vastu-parusha Mandala, is not an exact blueprint of the temple but a 'forecast,' a marking of the potential within which a wide range of possibilities are implied. The *mandala* is an ideogram, while the temple is a physical manifestation of the concepts it embodies" (Trivedi, 1989). Iasef Rian et al. extends this research significantly in his analysis of Hindu temple architecture. The simple fractal basis of its underlying order yet complex instantiations (Rain et al., 2007) offers convincing massing models in their paper, "Fractal geometry as the synthesis of Hindu cosmology in Kandariya Mahadev temple, Khajuraho".

Fig. 2.3.1.4. Detail of Red Mosque in Safed, Israel, 1276. (Wikimedia Commons).

The figure (Fig. 2.3.1.4) shows drawings on the 15th century Topkapi Scroll found in Turkey. These drawings represent a quarter of a dome in plan. The dome is composed of a tiling pattern that forms three-dimensional shapes or *muqarnas*. Muqarnas are often seen in Islamic architecture and are used to transition from a square to a circle or from an orthogonal layout to a dome in the vertical dimension. Fig. 2.3.1.5 shows an example of how this technique was used to ornament the corbeling of an apse when transitioning from orthogonal to circular shapes. Notice that each individual unit is a smaller version of the larger apse itself. Additionally, the muqarnas are often adorned with smaller tiling patterns, creating another level of self-similar detail. Similarly, the apses, domes, colonnades, etc. could be repeated to create an entire building or serve as the organizational principle for a number of buildings in a complex. Kiani et al. analyzes fractals in Iranian architecture from three scale perspectives including a discussion of fractals and muqarnas (Kiani et al., 2016). Ediz and Ostwald use fractal dimension to study the facade of the Süleymaniye Mosque using what they describe as the most extensive fractal analysis to date. Their method is to determine the FD of the major facades of the building at three primary levels of scale which they refer to as the form, ornament and material levels. They conclude the mosque represents primarily a complex formal idea that relies little on ornament or material (Ediz, Ostwald, 2012).

Another rich domain for the application of fractal analysis to design is in Gothic architecture. Samper and Herrera analyze a number of Gothic cathedrals in terms of their fractal attributes. This research assesses the ruggedness or convolutedness of the form which is used as a strategy for approximating curve shapes with orthogonal materials, e.g., stone. (Samper, Herrera, 2014). This is a similar technique as we saw in the Hindu temple example above. An orthogonal plan or 'mandala' is extruded vertically and gradually becomes more of a dome shape as the structure grows taller. This idea is related to a cosmological program linking the earth to a square shape and the heavens to a circular shape (Trivedi, 1989).

Ediz et al. points out that the whole reflected in the part ideology represented in Gothic cathedrals is evident in some column capitals which are miniature versions of the entire building (Ediz et al., 2007)

In addition to exploring the use of fractal geometry in analyzing architectural precedent, authors have also interpreted fractal geometry and made various assertions regarding its theoretical significance to design. Al Goldberger discusses a dichotomy between the Romanesque and Gothic styles which he characterizes with fractal dimension and links to the fractal qualities of the brain itself. He makes this bold claim in ‘Fractals and the Birth of the Gothic, reflections on the biological basis of creativity’ (Goldberger, 1996). We conjecture on this idea more in Chapter 5.

A cursory background into fractals and architecture would be remiss without mention of the brilliant work of Antonio Gaudi. Figure 2.3.1.8 shows a recent photograph of Sagrada Famila in Barcelona, Spain. The great cathedral Gaudi designed and which broke ground in 1882 is still being built today. The fractal qualities of this building are represented in the self-similar shapes that seem to grow from a central idea or motif and build on each other like a grand symphony culminating in the massive central tower which has yet to be built (Figure 2.3.1.9).

Fig. 2.3.1.9. Sagrada Famila nativity facade 2017 (Wikimedia Commons).

2.3.2 Contemporary architecture and urbanism

Although multi-scale self-similarity has been evident in architecture for a long time a mathematical model was only recently proposed by Benoit Mandelbrot (Mandelbrot, 1967, 1979, 1983) although what he termed *fractal* had been studied in certain mathematical circles prior to him – most notably by Gaston Julia who published ‘Memoire Sur L’iteration des fonctions rationnelles" in 1918 (Julia, 1918). However, the advent of modern computing gave Mandelbrot the ability to iterate the Julia Set and see these *monsters* in all their glory for the first time (Mandelbrot, 1967, 1979). Mandelbrot researched and appropriated many mathematical models, beginning with Lewis Fry Richardson who had discovered that the measurement of certain natural features like coastlines was relative to the scale at which it was measured. A tool, which Mandelbrot borrowed from Felix Hausdorff, is a method for determining the fractional dimension of an object or *fractal dimension*. Another method Mandelbrot used for approximating the fractal dimension of real objects such as coastlines or mountains uses a graphic technique involving discs or *boxes* at different scales to cover the object in question and plot the number of boxes required to cover an object against their scale. The slope of the logarithmic plot is equivalent to the fractal dimension. This technique is referred to as box-counting dimension (BCD). This method is used and critiqued in later chapters.

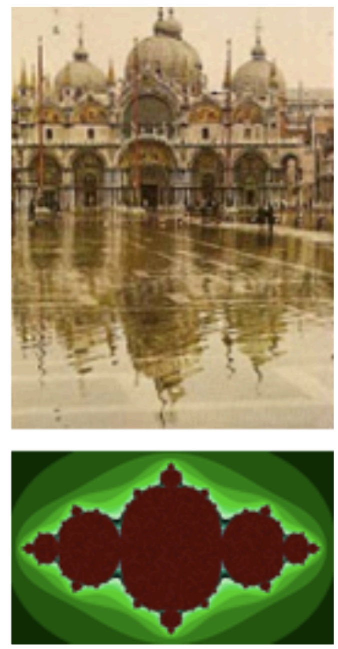


Fig. 2.3.2.1. Above: San Marcos church in Venice, Italy reflected in the flooded piazza. (Wikimedia Commons) Below: San Marcos fractal named after the church above (image by author).

Mandelbrot focused primarily on natural objects and general physical phenomena but was also curious about applying fractals to architecture (Fig. 2.3.2.1). Fractals and their mathematical counterparts have become increasingly popular in analyzing architectural precedent and are beginning to be applied to the creation of form from a designer's perspective as we discuss extensively in subsequent sections.

2.3.2.1 L-systems

Another important tool in fractal analysis that describes forms in nature with regard to their generative algorithms are L-systems. L-systems were developed by Aristid Lindenmayer to describe plant taxonomies and can also be used to describe certain fractals generally. L-systems are a basic grammatical language consisting of a semantics and syntax. Semantically, alphabetical symbols refer to certain procedures and syntactically, sentences are formed consisting of strings of symbols. Sentences then refer to 'meta-procedures' which operate on the entire string, such as a re-scaling (Lindenmayer, 1968).

L-systems and fractal explorations began to develop alongside computer technology in the 70s and 80s. As computational power increased, many intriguing phenomena in nature and mathematics were made available for exploration through advances in computer technology. Lindenmayer, Mandelbrot and others opened the door to a vast realm of forms that in some cases had literally never been seen before.

2.3.2.2 Iterated function systems

In addition to L-systems, Iterated function systems (IFS) are another technique for defining a fractal algorithm. Basically, an IFS provides a framework for creating fractals which uses vector and matrix algebra to define affine transformations such as scaling, rotation and translation. Matrix transformations can be expressed in terms of matrix multiplication and vector addition. IFS can be incredibly detailed and diverse, almost indistinguishable from natural forms (Figure 2.3.2.2).

Figure 2.3.2.2. IFS used in gaming rendering (Tamas Melykuti. artsta-

2.3.2.3 Fractal dimension and box-counting dimension

Fractal dimension

Fractal dimension is one of the metrics used in analyzing complex systems (Mitchell, 1996). An interesting question we focus on here regards how fractal dimension might be used to create design ideas and, ultimately, how these ideas might influence architecture and the design of cities. For instance, could the efficiency of cities be improved through the intentional use of higher FD form? We do not attempt to answer such questions here, rather we develop a process and applied case study towards this goal. In a sense, we run the model backwards to see how this might inform not the analysis of spatial data but the *generation* of spatial data. This shift also corresponds with a shift from assessing form to creating form. We specifically use FD as a general metric for guiding the creation of design variants which then are incorporated into a traditional design charette.

As we have mentioned, FD is a useful coarse-grained metric for analyzing complexity. Fractal measures can identify non-linear relationships in data and scale invariant behaviors. Fractal dimension has been used for feature selection when analyzing data sets (Traina, 2000). Kotowski et al. has conjectured that entropy measures and specifically fractal dimension can be used to characterize classes of genetic algorithms and their properties in terms of convergence. Fractal dimension has been used to model the trajectory of genetic algorithms and is proposed as a new method for constructing GAs and optimizing them (Kotowski, 2008).

FD offers a measure for assessing the self-similarity of a branching pattern such as those discussed above. Self-similar patterns have detail at many levels and fill the picture plane in a way that a Euclidean object does not. In general, a self-similar fractal object obeys the following relation:

Eq. 2.3.2.2 $$N = \varepsilon^{d}$$

Where *d* is the fractal dimension (or fractional dimension) and *r* is the number of segments in the initial object, called the *initiator*, and *N* is the resulting number of elements produced, called the *generator*. Fractals typically have fractional dimensions; that is, dimensions that lie between whole integer values. A fractal (fractional) dimension is more like a measure of density or a rate of growth towards infinity than a conventional description of space. The exponent *d* is the Hausdorff dimension. You can solve this equation for *d* by taking the logarithm of both sides and re-arranging:

Eq. 2.3.2.3 $$d = \log N / \log \varepsilon$$

Fractal dimension for a geometric fractal like the Koch Curve shown in Figure 2.3. is the ratio of the initiator (ε) to the generator (N). The initiator is a straight line that is divided into an equal number of segments (3 for Koch Curve). The generator is the number of line segments in the repeating geometric shape superimposed on the initial segmented line (4 for the Koch curve). Fractal dimension = log N/ log ε. So in this sense, the Koch curve has a fractal dimension of log4/log3 or 1.26186...

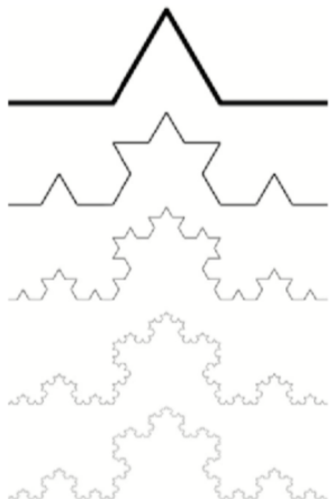


Fig. 2.3.2.4. Koch curve with 5 iterations (image by author).

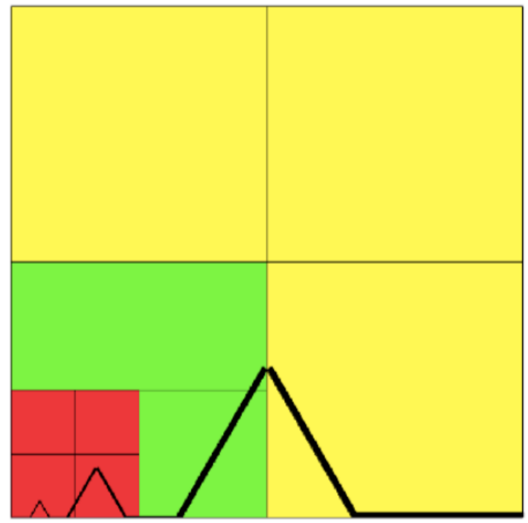


Fig. 2.3.2.5. Partially iterated Koch curve and box-counting (image by author).

Box-counting dimension

Next we discuss box-counting dimension (BCD) more thoroughly. Fractal dimension can be approximated heuristically using BCD and is useful for irregular objects such as rivers and trees or in this dissertation for not strictly repeating orthogonal compositions. BCD is determined by covering the object with different size boxes and counting how many cells contain the object compared to the overall number of cells in the grid. In Figure 2.3.2.5 you can see that a smaller grid requires less area to cover the shape. Notice how smaller iterations of the shape require fewer boxes to cover them, for instance, the red grid can cover the shape with 1 box; whereas, the green and yellow grids requires 2 boxes to cover the shape.

Box-counting dimension is often used to measure fractals that are not defined with pure geometry but rather consists of idiosyncratic shapes such as those found in nature and in complex, hard-to-characterize forms such as cities. Box-counting dimension is determined by first overlaying a grid on an image and counting how many lattice sites or 'boxes' are necessary to completely cover the shape. Additional grids at ever decreasing or increasing scales are overlaid recursively on the shape. The coordinates of the log of number of boxes N_ε and the of log of their scaling ratio, $1/\varepsilon$ are recorded in a scatter plot. The scatter plot is a graph with *log* $1/\varepsilon$ along the x-axis and *log* N_ε along the y-axis. From the scatter plot a *best-fit line* or sum of least squares linear regression is drawn (see Figure 3.3.6, plots). The slope of the best fit line is the fractal dimension of the shape and should approximate the Hausdorff dimension. As discussed, box-counting dimension is a technique for determining the fractal dimension of an irregular object. In the equation below, N is the number of boxes at some scale ε.

Eq. 2.3.2.6

$$D_0 = \lim_{\epsilon \to 0} \frac{\log N(\epsilon)}{\log \frac{1}{\epsilon}}$$

2.3.3 Fractals in urbanism, architecture and art

Systems perspectives in architecture and urban dynamics were pioneered in the 1960s and 1970s by environmental scientists, urban theorists and architects such as Jay Forrester, Donella Meadows, Jane Jacobs' and Christopher Alexander. From one historical perspective, important antecedents to systems approaches in architecture track Lewis Mumford and Frank Lloyd Wright and the development of an "organic" approach in architecture design, history and theory.

The city as a problem of 'organized complexity' was identified by Jane Jacobs as a response to the new urbanist craze in New York between the 1930's and 1960's (Jacobs, 1961). Many have taken up the yoke of identifying what makes our built environment healthy and vibrant, most notably Christopher Alexander. Alexander describes a mathematical model of urban dynamics in, Notes on the synthesis of Form (Alexander, 1964) shortly after Jacobs publishes her seminal, 'Death and Life of Great American Cities.' Alexander later develops his work into a set of scalable design ingredients he terms a "pattern language" (Alexander, 1977). Alexander also implements his *patterns* in a variety of architectural and urban settings using real-world urban planning problems (Alexander, Neis, 1987).

Current systems approaches are evident in the work of researchers across multiple disciplines including architecture and physics. A notable architect engaged in analyzing the complexity of cities and their fractal geometries is Michael Batty (Batty, 2007). Batty has been associated with the Santa Fe Institute alongside physicists Geoffrey West and Luis Bettencourt who are also interested in urban dynamics.

Michael Batty has explored the relationship between fractals, natural phenomena and the form of cities. Batty has used fractal geometry to try and explain the complexity of cities. Much of his research is covered in ‘Complexity and Cities’ (Batty, 2005). Others have used fractal geometry to research the growth of cities such as Sara Encarnacao et al., ‘Fractal Cartography of Urban Areas’ (Encarnacao, 2012) who discusses five types of urban environments in Lisbon Portugal based on their fractal dimension. The present author has also looked at the relation between fractal dimension and various attributes of cities, City Population Dynamics and Urban Transport Networks (Driscoll, 2013).

Fractals are useful in analyzing chaotic behavior where traditional geometric techniques are not particularly helpful. Fractals hold much promise for analyzing infrastructure in cities and architecture. Such infrastructure may have fractal characteristics such as transport networks, electrical grids, plumbing lines etc. as well as the configuration of: building plans and elevations, lots, blocks, neighborhoods etc. Buildings themselves may have fractal properties in their: wiring, plumbing, HVAC, spatial layouts and physical structure. Analyzing cities and buildings using fractal dimension is an active area of research as has been discussed above.

One study of many is discussed here briefly. The railway system of Paris has been shown to have a fractal dimension of 1.47 (Benguigui, Daoud, 1991). The tracks have a definite center at the Ile de la Cite and radiate to the outskirts of the city with bifurcation, where the tracks split into two. The overall morphology is dendritic and looks like behavior we see in natural and simulated branching structures such as diffusion limited aggregation (DLA) which Batty has focused on as well.

The authors of the Paris study suggest that the fractal quality of the transport network reflects the underlying fractal character of the city at large. “It is known that the transportation system conditions the development and growth of cities, with a strong feedback. Thus, it is not unreasonable to envision the railway network as a ‘picture’ of the town. This is the reason why we think that Paris itself, that is, the built and occupied area, has most probably a fractal character” (Benguigui, Daoud, 1991).

Geoffrey West offers a more theoretical approach to applying fractal geometry in nature and urbanism (West, 2005), Louis Bettencourt has developed this idea more in relation to urban dynamics (Bettencourt 2013). West and Bettencourt study scale-free behavior in a variety of settings. West theorizes that fractal geometry is efficient in distribution and uptake systems and therefore selected for in biological evolution. West and Bettencourt’s work began by attempting to define a mechanistic explanation for Kleiber’s Law pertaining to biological allometry and other long tail distributions such as Zipf’s Law. Zipf’s law (among other things) approximates the covariance of populations of cities with their rank within individual countries (Zipf, 1942). Zipf's law is an inverse proportion between frequency and rank, so subsequent ranks of 1, 2, 3, 4, 5, etc. have populations of 1, 1/2, 1/3, 1/4, 1/5 etc. A power law relationship also exists for biological scaling originating with the work of Max Klieber. This log-linear relationship correlates body mass (horizontal axis) to metabolism (vertical axis) over 27 orders of magnitude with a scaling exponent of 3/4. West's theory relates this law to the fractal geometry of vascular systems (West, 2002). Additional power laws have been discovered relating many variables in city dynamics and remain an active area of research. Bettencourt has applied West's ideas to cities and urban infrastructure globally. Some scaling laws Bettencort et al. have discovered in cities when compared to population density are roads, electrical cables, plumbing pipes, number of gas stations and post offices which are sub-linear and patents, income, real estate and crime which are super-linear (Bettencourt, 2013).

The conclusion Bettencourt reaches is that cities are more efficient the larger they become. A key aspect that may explain this is the same one West offers to explain Klieber's law, namely the geometry of their infrastructure. West and others have argued that these mechanisms are fractal and this helps explain economies of scale and why larger organisms are more efficient than a simply scaled up version of a smaller organism. Fractal networks that are self-similar at many scales can fill space more densely with less overall edge length. The adage attributed to the architect Mies van der Rohe, *less is more* succinctly describes the properties of fractal networks whether they are vascular systems or city streets or the lengths of electrical conduits or HVAC ductwork in a building. This idea is oversimplified here in some ways but it does hint at a parsimonious approach to coarsely gauging the complexity of a system in terms of its multi-scale self-similarity. West's theory has been met with controversy on multiple fronts, including the legitimacy of the power laws the theory is based on (Dodds et al., 2001). A note of caution here is important to stress. Another adage of Mies', "god is in the details" could be applied to ubiquitous power laws but in the reverse, "the devil is in de-tail." This means that sometimes outliers may be lost or considered irrelevant in long-tail distributions due to error distributions in linear regression. Studies have shown previous linear regression techniques in biological scaling to be generally valid but new methods have been proposed based on the specific data being analyzed (Xiao, 2011).

2.3.3.1 Fractal analysis/genesis in urban design and architecture

Fractal based approaches within generative design processes have been used to both analyze and create urban environments and individual buildings. Ediz and Cagdas and Gürbüz et al. have developed a tool (CADaFED) to analyze the FD of existing urban conditions and use the FD (as well as other parameters such as lacunarity) to create new urban environments and architecture that match the FD of the existing fabric. This approach claims to preserve attributes of the original neighborhoods (Ediz Cagdas, 2007, 2009; Gürbüz et al., 2010). Gürbüz et al., write, "The aim of the research is not only generating new form alternatives but also considering [sic] the continuity of traditional architectural and urban patterns which faces deterioration." (Gürbüz et al., 2010).

Fractals and FD have also been more recently applied to building structure in several studies (Kiani, 2016; Rian, 2016, 2018) involving load modeling as well as demonstration construction projects. Such studies use fractal geometry and fractal metrics to search for novel forms with provocative architectural as well as measurable physical properties. Rian et al. write, "Accordingly, the *relative size value* (*w*) which is a factor of the fractal dimension, is an effective geometric variable that can manipulate the structural strength of a structure [sic] which is based on the Takagi-Landsberg surface (Rian, 2018).

2.3.3.2 Fractals and art

A parallel use of fractal geometry as a means for assessing man-made objects is undertaken by the physicist Richard Taylor from the University of Oregon who used fractal dimension to evaluate the authenticity of drip paintings attributed to the painter Jackson Pollock (R.P. Taylor et al., 2006). Taylor et al. has analyzed 50 Jackson Pollock paintings and determined using box-counting dimension that the artist typically achieved a FD of 1.7 (Taylor, 2007). This measure, and other similar fractal measures developed by Taylor and his team, have been shown to be a signature of the “hand” of Pollock and suggest a remarkable ability by the artist to create scale -invariant self-similarity by eye without the use of computers. Taylor et al. refer to this as *fractal expressionism* to differentiate it from fractal art produced by computers (Taylor, 2007). Taylor's work has been tested and elaborated on by Jim Coddington et al. (Coddington, 2008).

2.3.4 Fractals in American Organic Architecture

As discussed above, West and Bettencourt have helped develop a new "science of cities" where scale-free relationships in biology and cities have been related to fractal geometry. An architecture historian often cited in this work is Lewis Mumford who was interested in cities from multiple perspectives and writes about them in biological terms. Mumford was influenced by FLLW and his use of material, form and integration of the architecture with nature. Together, FLLW and Mumford popularized the term “organic” as it relates to architecture and worked closely together developing this notion. Mumford writes, “On Richardson's solid foundations (Sullivan) laid the cornerstone of the new Organic Architecture. Sullivan was the link between two great masters, Richardson and Frank Lloyd Wright; and with the development of Wright's architecture the last stage in the transition was born: modern architecture in America was born" (Mumford, 1933). FLLW called his school "Organic Architecture" and its practitioners continue to adhere to it’s design philosophy.

For the past few decades, researchers have begun to study complexity in architecture as characterized by fractal dimension. The fractal qualities of various architecture including the work of FLLW was begun in earnest by Carl Bovill and continues as a rich research agenda (Bovil, 1996; Eaton, 1998; Harris, 2007, 2012; Joye, 2007, 2011; Ostwald, 2001, 2016). Again the juxtaposition between FLLW and Organic Architecture and the modernists is a common thread. Yannick Joye has linked complexity in architecture to nature, suggesting that a certain range of fractal dimension relates to our evolutionary development and the natural landscapes that were favorable to our survival and well being: ‘Fractal Architecture Could Be Good for You’ (Joye, 2007). Fractal geometry has been used increasingly over the last couple of decades to analyze individual buildings and the architectural ideas associated with them with a focus on the work of Frank Lloyd Wright (FLLW) and American Organic Architecture. Bovill published a book titled, ‘Fractal Geometry in Architecture and Design’ in which he analyses two significant works by FLLW and Le Corbusier respectively using box counting dimension. In Bovill’s analysis he concludes that FLLW work is more complex than Corbusier’s and in some ways more related to nature than modernist architecture (Bovil, 1996). FD is used by Ostwald et al. to analyze five residential designs from three architects, Eileen Gray, Le Corbusier and FLLW. The average FD of the designs is 1.378, 1.481 and 1.543 respectively. Ostwald et al. suggests these results indicate that, "Gray's architecture is much less visually complex than Wright's. This supports the standard reading of the method arising from Bovill's work and it agrees with qualitative views of these architect's works recorded in architectural histories" (Ostwald et al.. 2008).

2.3.4.1 Frank Lloyd Wright

Eaton, Joye and separately Harris analyze the fractal characteristics of FLLW's Palmer House (Ann Arbor Michigan) but reach different conclusions (Eaton, 1998; Harris, 2012). These differing views highlight some of the disagreement in the literature regarding fractals and fractal dimension. When referencing Eaton's work and the use of fractals in FLLW's architecture, Joye writes, "Initially, the geometry governing his architecture created with the aid of such modules remained Euclidean. In later works, however, these elements were sometimes so organized that they gave the building a remarkable fractal organization. The Palmer House seems to be the culmination point of this evolution. Here, one geometric module – an equilateral triangle – is repeated in the ground plan on no less than 7 different scales" (Joye, 2011). Separately, Harris analyses the Palmer House and reaches a different conclusion regarding the fractal character of the design. Harris interprets the design as a series of iterative operations that result in a fractal pattern. The pattern Harris presents is not entirely self-similar. This is an analysis more of FLLW's process and provides insight into how FLLW conceived of the organizing principle which generates the form and pervades its fractal character. We argue that this is a significantly different treatment of fractals and fractal dimension in the analysis of the architecture of FLLW when we discuss algorithmic techniques in architecture in Chapter 4.

2.3.4.2 Dean Bryant Vollendorf

Many of Frank Lloyd Wright's apprentices and acolytes have continued the design philosophy he promoted and was termed, "Organic Architecture." The architect and professor Bruce Goff (1904 – 1982) was a significant adherent of FLLW's organic philosophy of architecture and influenced many students during his tenure at the University of Oklahoma from 1942 until 1955. Dean Bryant Vollendorf (DBV) (1929 – 2008) was influenced by FLLW and Goff, having been born and raised in Sheboygan, Wisconsin in 1929 surrounded by the work of Mr. Wright, and later spending significant time designing and teaching in Norman, Oklahoma within Goff's still vibrant orbit. DBV also apprenticed for and later headed up the Florida firm of the prominent architect John Randal McDonald who is often compared to FLLW and worked within his dictums. DBV eventually settled in the Carolinas and became an important hub for Organic Architecture there, designing and teaching many students beginning in 1971 (from personal correspondence) and influencing such architects as Jim Fox, Gary McCowan and Stan Russell. DBV is best known for his extensive body of bold renderings and meticulously detailed drawings. DBV's architectural work ranged from prefabricated homes to signature free-form concrete structures that show him moving beyond FLLW and Goff to develop his own unique and original approach to design we will describe at length in terms of its unique example of fractal design in architecture in Chapter 4. DBV also developed a didactic model which we term the "Vollendorf Method" and discuss in terms of algorithmic design and fractal organizing principles in Chapter 3. DBV's work highlights key aspects of this dissertation. Selected projects which show a progression towards a comprehensive language of form applied to different "performance needs" and at multiple scales is discussed in Chapter 4 and presented in, 6.0 Plates within this dissertation.

2.3.4.3 James Walter Schildroth

James Walter Schildroth (JWS) is a prominent Organic architect with a long history of outstanding design spanning almost 60 years and still going strong today. JWS was an apprentice at Taliesin beginning the year FLLW died in 1959. From Taliesin he continued his architectural education at the University of Oklahoma at Norman, beginning in 1961 (http://www.schildrotharchitect.net/autobiography.html). This was within Bruce Goff's powerful impact at the school that Goff had founded. One of the first courses that all architecture students were required to take was Architecture 8, an introduction to design course which should be understood within the context of FLLW's teachings.

One of the projects for this course was to design a series of "points." Points were of 3 types, geometric, mobile (curvilinear) and composite. The points were then used recursively to create a composition that was in the grammar of the individual point used for that feature (Figure 2.3.4.3) (Plate 6.2, 6.3). This was before the term fractal had been invented. The concept was expressed mereologically in terms of parts to wholes in a similar way as FLLW expressed it, the core principle being that the whole is embedded in the part and vice versa. There is a strong connection to the work and teaching of Bruce Goff. Figure 2.3.4.4 shows a design for a player-piano roll by Goff that presents a similar organizational principle used in the composition.

2.4 Summary

In this chapter we reviewed fractals with regard to architecture historically and some contemporary approaches in architectural criticism and urban analysis. We also touched on how fractals have been used to create designs, especially in Organic Architecture and the work of Frank Lloyd Wright. We also position algorithmic design within a context of general systems theory. We present a thread of development that includes the early work of cybernetics as well as computer-based models which have been loosely based on natural processes. We explored the development of genetic algorithms and their relationship

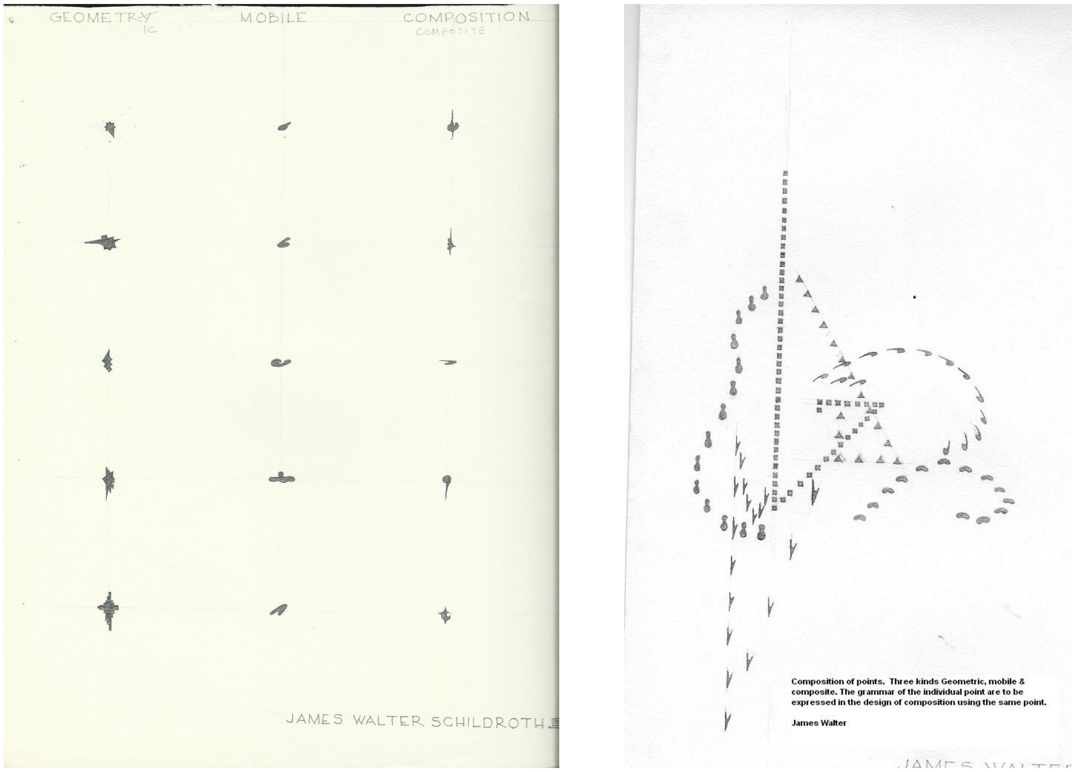


Figure 2.3.4.3. Student project. James Walter Schildroth, 1961. (Used by permission).

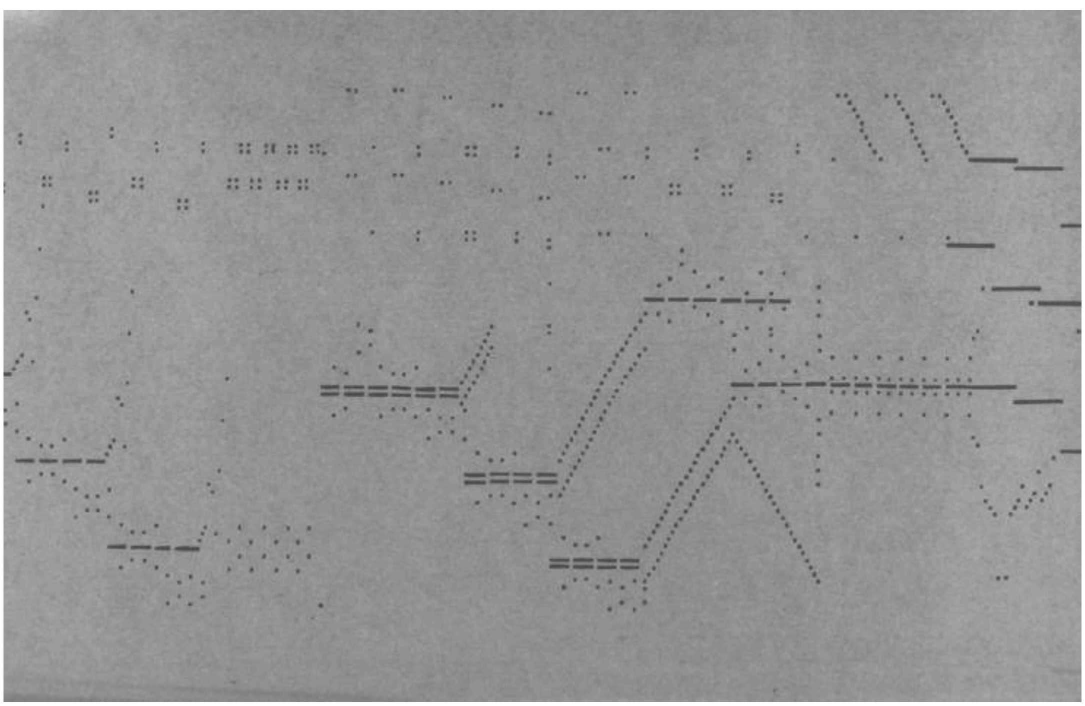


Figure 2.3.4.4. Custom cut player-piano roll composition by Bruce Goff (Art Institute of Chicago Digital Archives).

to design and the creative process as well as cellular automata and L-systems. Along with GAs, fractal geometry and analytic techniques and representation systems were reviewed relative to the algorithmic design process we develop in the subsequent chapters.

We find that a significant connection exists between the contemporary application of fractals in urban analysis and the tradition of Organic Architecture as developed by FLLW and others. We also offer a definition of fractals in terms of architecture that strives to clarify some key properties. We stress that in addition to self-similarity at multiple scales a good definition must include the algorithmic component of the process that produces fractal "iterates." We explore this idea more in Chapter 4.

2.5 Next steps

We have touched on a new approach to analyzing and designing buildings using fractal geometry. We have begun to apply this terminology and mathematic rubric to the history of architecture and have demonstrated its current development in contemporary algorithmic design. Much work remains to be done in terms of assessing precedent with the new terminology and with quantitative methods that have only recently been developed vis-à-vis computer-based tools.

End of Chapter 2

3.0 Fractal dimension as a fitness function in a genetic algorithm applied to design: Toward a fractal cybernetic design process morphology

3.1 Introduction

In the spirit of Mario Bunge's definition of systems science as, "an exact and scientific metaphysics" (Bunge, 1973), we present here an algorithmic design process as an amalgam of creative design and mathematical precision. We present a cybernetic design methodology and juried critique by professionals in the field of architecture. The design process presented was applied to a mock architectural problem as well as a real-world problem. The audience for this chapter are architects with some interest in applied computation. This is a standalone chapter intended for publication in a theoretical journal. We introduce an approach representing a new algorithmic design methodology based in part on what we term the Vollendorf Method. As part of the methodology a genetic algorithm is trained with fractal dimension as the fitness criteria. A human being (author) is the creative designer. A third component to the methodology presented is a critical review by a panel of architects who act as jurors. Pin-up #1 presents the design process and the design of the algorithm, and Pin-ups #2 & #3 focus on praxis with a case study design response to a formal request for proposals (RFP). The case study explores in more detail the algorithm's potential application to a complex architectural problem, including context, scale and program. We present the design process, graphic presentations from the pin-ups and selected comments by the jurors followed by a discussion along with conclusions and next steps in this line of research.

3.2 Background

Below is a background on the key aspects of the design process and case study projects for this chapter. Each of the main aspects of the design process and algorithm we develop is discussed in depth in the sub-sections which follow. In the next paragraph we offer a brief vignette of the basic idea so that the reader will be familiar with some of the language and concepts when delving deeper into the more expository sub-sections.

We introduce a cybernetic process and algorithmic tool termed DBVgen which consists of a genetic algorithm (GA) which uses fractal dimension (FD) as a fitness criteria in collaboration with a human designer. The cybernetic aspect of the process refers to the dual aspect between man and machine. An algorithm in this context is defined as a simple computer program consisting of iterative rules. The designer modifies or "tunes" the algorithm's output in the design modification subprocess. A fractal is a recursive geometric object that has a self-similar theme that occurs at multiple scales or levels of magnifica-

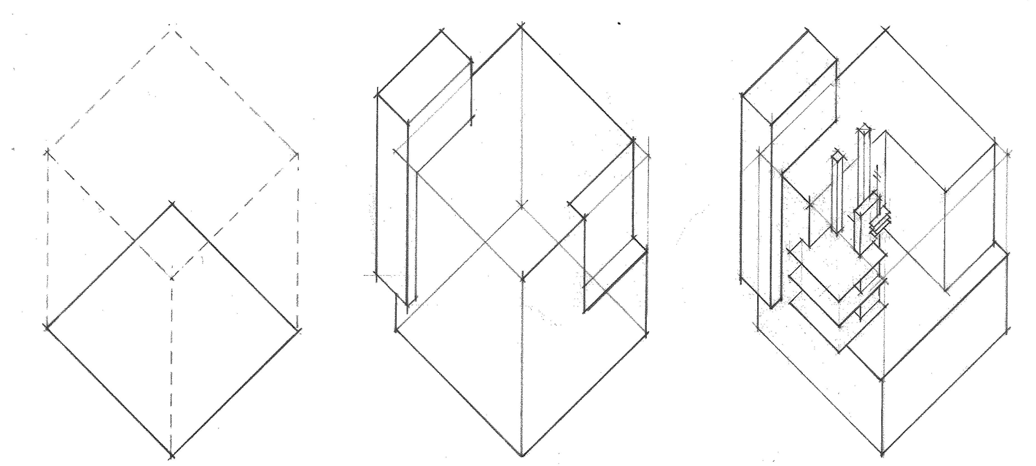


FIG 3.2.1. Hypothetical parametric model showing 3 possible generations of GA output representing varying degrees of “complexity” (image by author).

tion. The idea of using a tool associated with fractals as a fitness criteria is illustrated hypothetically in Figure 3.2.1. This figure shows a solid mass on the left with further development and variation of the mass moving to the right with regard to a self-similar and multi-scaled theme. The model on the left has very little detail; whereas, moving right we see increasing detail at 3 different scales and a higher fractal dimension (FD). These models will be generated by a genetic algorithm (GA) and iteratively manipulating with respect to some simple rules with FD used to determine fitness. FD is a coarse-grained tool used for measuring aspects of fractals and is discussed at length in section 3.2.2. GAs are discussed in section 3.2.3. A third component to the design process presented is a critical review by a panel of architects in the role of jurors. We present the case study project in section 3.3.6 and the critical review is discussed in section 3.3.7.

3.2.1 Vollendorf Method

This section describes a simple teaching exercise developed by the late professor emeritus, Dean Bryant Vollendorf (DBV), which we incorporate in our work. We term this exercise the "Vollendorf Method". We also ground this exercise in DBV's pedagogy somewhat although a comprehensive explanation of its theoretical framework is beyond the scope of this chapter. DBV was part of a tradition in American Organic Architecture and architectural education that was heavily influenced by Frank Lloyd Wright (FLLW) and the school he originated. Many of FLLW's apprentices and acolytes have continued the design philosophy he promoted and was termed, "Organic Architecture". The architect and professor Bruce Goff was a significant adherent of FLLW's organic philosophy of architecture and influenced many students during his tenure at the University of Oklahoma from 1942 until 1955. DBV was influenced by FLLW and Goff, having been born and raised in Sheboygan, Wisconsin in 1929 surrounded by the work of FLLW and later spending significant time designing and teaching in Norman, Oklahoma within Goff's still vibrant orbit. DBV also apprenticed for and later headed up the Florida firm of the prominent architect John Randal McDonald who is often compared to FLLW and worked within his dictums. DBV eventually settled in the Carolinas and became an important hub for Organic Architecture there designing and teaching many students beginning in 1971 and influencing such architects as, Jim Fox, Gary McCowan and Stan Russell. DBV is best known for his extensive body of bold renderings and meticulously detailed drawings. DBV's architectural work ranged from prefabricated homes to signature free-form concrete structures that show him moving beyond FLLW and Goff to develop his own unique and original approach to design. DBV also developed a teaching pedagogy while at Clemson University which he describes in his thesis (Vollendorf, 1975). Vollendorf taught at the University of North Carolina at Charlotte beginning in 1976. During this period this author mentored under Vollendorf and graduated with his last cohort of students upon his retirement in 1995. Vollendorf remained in Charlotte, NC and re-focused on computer-based tools for design and inspiration beginning in 1995 until his death in 2008. Vollendorf, true to his creative spirit, approached nascent computer drafting software as a *wet medium* and explored its potential for serendipity and inspiration for realizing new forms and screen presentations. Much of DBV's extensive archive has been preserved at the Oklahoma Historical Society in Oklahoma City, Oklahoma where it awaits restoration as of this writing.

The Vollendorf Method is really a series of short exercises consisting of basically 3 lines on a page with regard to certain rules as follows:

1. The picture plane is an opaque 8 1/2" X 11" piece of paper.

2. Lines must be parallel or at right angles to each other and parallel to one edge of the paper.

3. Lines must go from edge to edge or stop at another line.

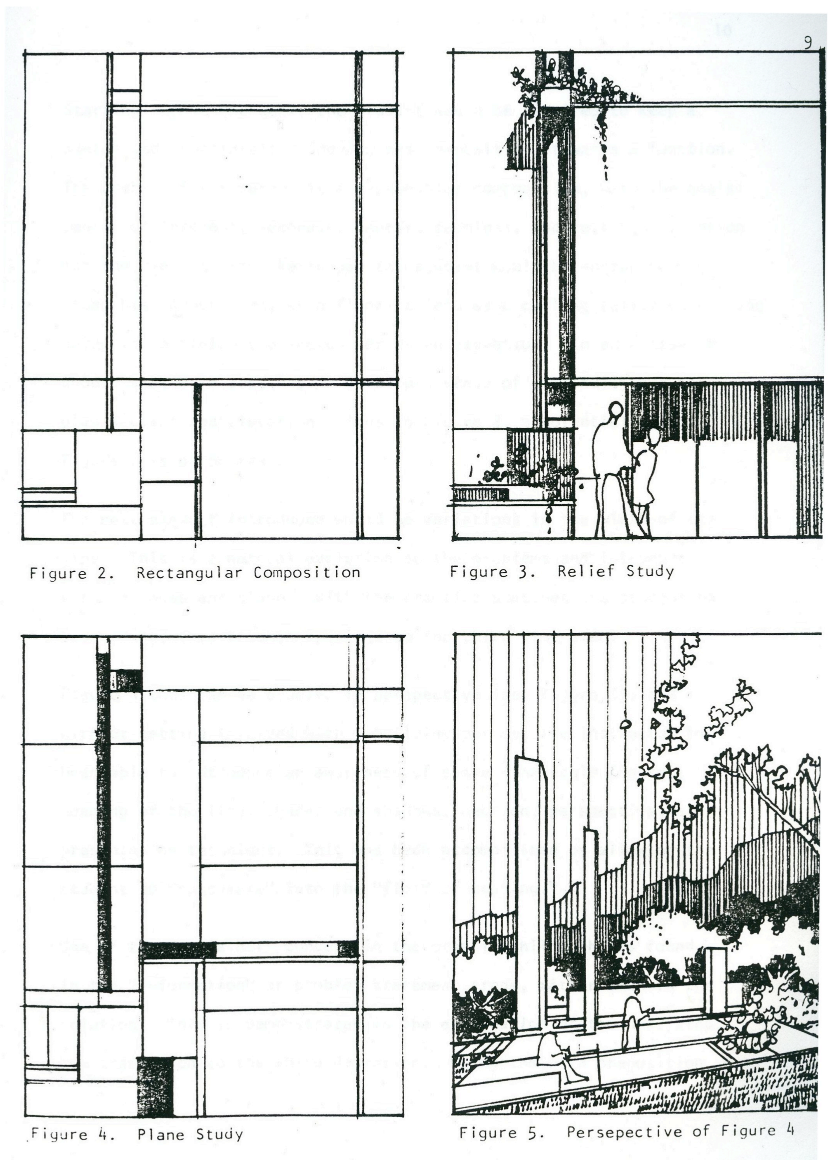


Fig. 3.2.2. Diagram from DBV's thesis representing the 3 lines on a page exercise (Vollendorf, 1975) (used by permission).

Using these simple rules, the student is asked to draw a series of lines on the page. In this manner the student is introduced to basic elements of composition. From this simple three line composition, more lines can be added which reinforce the focal point or create a secondary focal point or establish other compositional elements. DBV refers to the basic elements of composition when writing, "The problem ... is a rectangular composition, with the goals: center of interest, secondary center, terminal, and rectangular motion for the eye. In the sketch pad the student would be encouraged to study their composition, as a floor relief, as a ceiling relief responding under it to finish the sketch, or as an elevation. In each case, they would sketch in sections to develop a sense of continuity between plan section and elevation" (Vollendorf, 1975).

DBV describes the exercises, "Exercise one: With one line create a design, the line must be parallel to the edge in one direction, and go from edge to edge in the other. If the line is placed at the center, you merely have cut the plane in half. If the line is too close to the edge, it will look like an accident. If something else is needed to complete or satisfy the plane, the line is in the wrong place. Exercise two: A second line is added parallel to the opposite edge. This gets farther into the word composition, at the same time introduces center of interest. Exercise three: A third line is introduced that goes from line to edge and is to reinforce the concept of resultant space. These problems are defined as “of the plane”, the problems are dedicated to the two dimensional through bas relief thinking" (Vollendorf, 1975).

The "bas relief thinking" refers to the idea that the student is learning to see the design not simply as a 2D composition but as a plan or collection of areas which can be extruded into the 3rd dimension. Line weights may become thicker – like masses – and become 3 dimensional when seen in axonometric, section, elevation or perspective views. The student is next asked to add scale and context which at first is simply the addition of figures and plantings (see Figure 3.2.2). Vollendorf describes extending the composition into the 3rd dimension, "The next element introduced would be variations in the width of the line. This is a natural evolution to the problems and introduces vertical mass and plane. With the practice sketches the student has been doing, this becomes a bridge to the third dimension" (Vollendorf, 1975).

The theoretical framework for the 3 lines on a page exercise is touched on next. In addition to the obvious pedagogical influences of Frank Lloyd Wright and Bruce Goff, DBV links to the theoretical framework of his teaching model in connection to George Baird (Jencks, Baird, 1969) and consequently general systems theory (GST). DBV refers to a "design system" in terms of Baird's diagram of a "field of meaning" which in turn is adopted from Claude Shannon and information theory (Shannon, Weaver, 1949) (see Figure 3.2.3)

DBV offers this quote from Baird, "“The line across the top of the diagram represents increasing expectancy, and that across the bottom, increasing surprise. In terms of the capacity for registering messages ... the extent of the overlap between the line indicating the

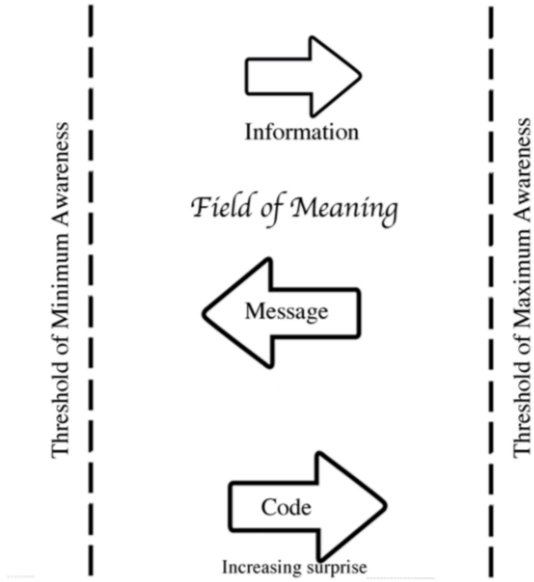


Fig. 3.2.3. Diagram referencing George Baird's, "field of meaning"(Vollendorf, 1975) (Jencks, Baird, 1969). (redrawn by author).

threshold of minimum awareness, and that indicating maximum awareness, defines the field of meaning. The length of the bottom line then, from the one threshold to the other, represents the scope of articulation of the social phenomenon in question" (Jencks, Baird, 1969). DBV then further clarifies his incorporation of information theoretic notions within a larger context of architecture, juxtaposing a verbal – explanation dependent – architectural concept with an integrated and generative one, note in the following quote the scale-free aspect of the generator concept, also related to a geometric organizational principle found throughout the plan, section and elevations of the building.

"Thus, it is easy to see how the 'explainer' equates with 'message. When this is the base consideration, there is a tendency to involve the student—or in architecture, the build-

ing—with minimum awareness, expectancy, and desire become the solution [sic]. By contrast, the generator concept is to search for the beauty in the need, reasoning from within, which relates directly to the 'code.' The generator, the expression and relation of all parts, articulated, dedicated, and found within the performance need (message), leads to an organic explanation... A good generator is self explanatory, or explainable in a design from basic conceptual thinking to the most complex urban solution. The proof of the generator concept is found in the intersection of the plan, section, and elevation aspects or qualities of a building" (Vollendorf, 1975).

A general but central notion in DBV's design system is the dynamic between order and disorder. The order/disorder dichotomy is a theme that runs through the theoretical history of GST and is often thought of in thermodynamic terms. Information theory relates entropy/negentropy with expectancy and uncertainty the latter of which is described in terms of "surprise." Baird applies a similar categorical hierarchy in his analysis "Meaning and Architecture" and suggests it as a means for framing how artifice may be thought of as a semantic system. The pragmatic aspect of a design system — or the *message* — Baird formulates as being an ordered relation on a syntax which is varied within the relation of an effective rule. Baird quotes Norbert Wiener's Cybernetics in describing the organizing principle of the syntax, "The essence of an effective rule for a game...is that it be stable in advance, and that it apply to more than one case... in the simplest sense, it is a property which is invariant to a set of transformations to which the system is subject" (Wiener, 1965). DBV equates the pragmatic with the program for the building (performance need) which represents "message". We suggest this relates to the maxim, "form follows function". The other aspect, however, approaches the pole of "maximum awareness" in Baird's terminology and can be said to have a multiplicity of potential instantiations (invariant to a set of transformations). DBV refers to this as *code* using Baird's terminology. We suggest this is related to the idea that "form and function are one" which was how FLLW described the concept. "'Form follows function' is mere dogma until you realize the higher truth that form and function are one." (Frank Lloyd Wright, The Natural House, 1954). The original quote by Louis Sullivan is, "Whether it be the sweeping eagle in his flight, or the open apple-blossom, the toiling work-horse, the blithe swan, the branching oak, the winding stream at its base, the drifting clouds, over all the coursing sun, *form ever follows function*, and this is the law. Where function does not change form does not change. The granite rocks, the ever brooding hills, remain for ages; the lightning lives, comes into shape, and dies in a twinkling" (Sullivan, 1896). Note the reference to fractals: branching oak, winding stream, drifting clouds and lighting. Fractals will be discussed next.

3.2.2 Fractals

"Clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line" (Mandelbrot, 1983).

This section describes fractals and their properties found both in nature and architecture as well as in mathematics and complexity science. Much of the following was synthesized by Benoit Mandelbrot in his seminal tome, The Fractal Geometry of Nature (Mandelbrot, 1983). It is remarkable that a wide variety of fractals in nature and in architecture also occur in the abstract realm of mathematics. Mandelbrot describes the infinite ruggedness or endless detail of fractal objects when he describes how one would measure the coast of Britain and theorizes that it is essentially infinite if you use ever finer instruments. The reason for this is that as you examine the jagged coastline at smaller and smaller increments, say with a microscope, the coastline continues to fragment and looks much the same as it did at larger scales. This deceptively simple thought problem is difficult to define formally and represents a different conception of space and dimension than what we commonly think of. Mathematicians have not reached a consensus but a generally accepted formal definition of a fractal is "...a subset of Euclidean space in which the Hausdorff dimension strictly exceeds the topological dimension" (Fractal, Wikimedia, n.d.).

Fractals in architecture are not strictly scale-free as they are in mathematics but repeat at a finite number of scales. We discuss in Chapter 4 that 2 - 4 levels are evident in the work of FLLW but there is the potential to have up to 10 levels of self-similarity in an architectural design. Fractal iteration in architecture is more loose and freeform perhaps than what we think of as the rigorous fractal geometry in mathematics. Fractal geometry in architecture often transforms or develops in different ways and as per a designer's individual approach, or as architects like to say, a designer's "hand." In architectural design as in music composition, an idea is often explored in a tripartite process represented as theme, development and variation. Fractal geometry in architecture such as the work of FLLW has this "variations on a theme" or ètude feel to it.

3.2.3 Fractal dimension

FD has been widely used as a tool for assessing the complexity of an object in far flung fields such as geology and hydrology, biology and botany. Generally, FD is considered an important quantitative tool in assessing complexity (Mitchell, 2009). Mathematicians and physicists have made significant progress in developing ideas related to fractals after Mandelbrot's pioneering work in the 1970s and 1980s. The study of cities may be couched within the rubric of complexity theory including aspects of cities that are within the purview of architects and urban planners. Scale-free power laws correlate many attributes of cities. Researchers have consequently used fractals and fractal dimension to assess them (Batty 1994, 2007; Bettencourt, 2007, 2013; Encarnacào 2012; Driscoll et al., 2013; West 2017). Similar tools are also being used increasingly in the analysis of architecture (Bovil, 1996; Eaton, 1998; Harris, 2007, 2012; Joye, 2007, 2011; Ostwald, 2001, 2016).

3.3 Results

This section describes the design process developed for this study and its application as a proof-of-concept as well as a case study problem. Final designs are organized as design presentations or "pin-ups" which attempt to mimic a traditional architectural critique although with the key distinction of being non-synchronous and non-local. The design process consists of two levels of development as well as critical review by a jury. The study problems is described and then presented to jurors in Pin-up #1 and Pin-up #2. Selected comments from the jury are provided and discussed. We include a final project presentation as Pin-up #3 provided in this dissertation alone.

3.3.1 Process

We present here a design process incorporating FD as a fitness criteria for use in a GA that is part of a traditional architectural design process. The process we describe inserts a computer-based design tool (DBVgen) into the schematic phase of a traditional design process. Design process morphologies often define an *analysis* phase and then a *synthesis* phase. Hall's morphology is different in this regard (Hall, 1969). We present a design process where the quantitative and qualitative aspects of the schematic design charette involves a relatively simultaneous synthesis and analysis of the form. The intention is that the steps repeat until it converges on an acceptable design. The process has 3 primary aspects: a design aspect, an analytic aspect and a critique aspect. This tripartite structure is not intended to be applied at a specific level but happens throughout the design process and at multiple levels (See Figure 3.3.1). The tripartite division is a superimposed structure that is assumed to be a universal organizing principal in the field and relates to many aspects of design. We introduce a computer-based algorithm which iteratively produces and measures designs which are then modified by a human designer and critiqued by a panel of experts in a number of review cycles. A successful process will converge toward a specific design solution.

design –> analysis –> critique

Fig. 3.3.1. Tripartite approach applied at all three design process levels.

The following section describes the design process we developed. We identified a leverage point within the schematic phase of a traditional design process as outlined in the Architect's Handbook of Professional Practice issued by the AIA (Demkin, 2001). We refer to the Architects Institute of America's (AIA) design process as Level 3, the 'top' level (Fig. 3.3.2).

Programming –> Schematic design –> Design Development –> Construction Docs –> Bidding/neg –> Con Admin

Fig. 3.3.2. Design process Level 3.

We zoom in on the schematic phase and insert the algorithm as a starting point or a baseline for a charette. The schematic phase then consists of two steps, a machine learning algorithm and a human designer. The first step is simply the development of the DBVgen tool we use for all subsequent experimentation in this thesis. The second step includes a human designer in the process. We refer to the cybernetic or dual aspect of the model as level 2 (see Figure 3.3.3).

Algorithm –> Designer

Fig. 3.3.3. Design process Level 2.

We further unpack the algorithmic step of the design process into a parameterized GA program using FD as the objective function to select for an exemplar composition from a given generation of individuals. The FD is determined using box-counting dimension

(BCD) as previously discussed. We refer to this aspect of the design process as level 1 (see Figure 3.3.4).

Parameters –> design variants –> FD –> exemplar

Fig. 3.3.4 Design process comprising DBVgen tool at Level 1.

3.3.2 Level 1

Level 1 of the design process used a machine learning algorithm inserted into the schematic phase of a traditional design process. The machine learning algorithm was a modified genetic algorithm that could be controlled by the designer. The genetic algorithm was initially programmed in Python and used BCD to determine FD. The GA selected for a target FD from a range of individual compositions. Encoded rules for generating compositions are based on a didactic exercise termed the Vollendorf Method as discussed in section 2.2.1.

We interpret the Vollendorf method as an algorithmically generated composition. The composition is generated by a computer program implemented in Python consisting of parameterized values for different attributes of the design. A number of horizontal and vertical lines are placed randomly on a page of custom dimension going from edge to edge or stopping at another line. All compositions that were used in the GA were in 2 dimensions and consisted of orthogonal lines. The GA performed any number of runs as defined parametrically using tournament selection to choose successful compositions from a defined number of individuals making up a population. Successful compositions are defined as those that are closest to the target FD. Initial designs are measured for FD using BCD. Designs are evolved with a GA which uses an objective function which selects designs that are closest to some target FD between 0 and 2. The target FD for the proof of concept was the maximum 2 as a starting off point for the investigation. Successful compositions from a current generation are combined with other successful compositions from the same generation using crossover and mutation to create the next generation of compositions. This cycle is repeated as defined parametrically. Lines for each composition were defined as seeds that could be swapped with other compositions through crossover. Lines could also be deleted or added to compositions based on a defined probability. Lines could also be moved along the x or y coordinates based on a defined random mutation parameter. After the select number of generations was complete, the composition that was nearest to the target FD was chosen as the exemplar composition. Initial printed outputs showed the compositions across the top advancing from left to right with the results of their respective BCD showing the linear regression of the scatter plot and the slope and sum of least squares displayed below each composition (Fig. 3.3.6).

After an exemplar was selected using its FD, a defined number of rectangles were chosen from the intersecting lines of the composition as per the Vollendorf Method at random and displayed in red. Next, the red rectangles were extruded along the z coordinate a random length forming 3D masses that were also displayed visually in red. Outputs of each exemplar for each generation are printed along a timeline beginning on the left of a sheet and adding generations to the right. The 2D exemplar compositions are shown along the top of the sheet and the random rectangles immediately below and the random masses immediately below that. Further below a graph of the

FD for all populations is shown with the exemplar FD printed and the mean displayed between generations with a green line. At the bottom of the sheet is a graph showing the sum of least squares for each generation. Sheets could be printed with any number of generations displayed and therefore could be quite long horizontally (See Plate 6.4a and 6.4b). A shorter timeline is shown here for reference (Fig. 3.3.8).

3.3.3 Level 2

This section describes level 2 in which a human designer modifies the output of the algorithm to fit a toy architectural problem. Level 1 becomes the input for the designer to modify for level 2. The designer in this study is the author. We refer to such modifications as 'fitting' or 'tuning'. The designer modifies the composition to fit the toy problem. The design problem is a project for a pavilion we discuss below. For the proof of concept, the designer's modifications were not inputed back into the algorithm, meaning a feedback loop was not instantiated. In this sense we refer to the process as linear, meaning there is no feedback between the tuned designs and the algorithm (Fig. 3.3.5). In the case study project we do allow for tuned designs to be inputed back into the algorithm for any number of iterations. When this is done we refer to the process as feedback oriented or a *closed loop*.

algorithm –> designer modification

Fig. 3.3.5. Linear process used for proof of concept.

3.3.4 Critique

In this section we present a description of the juried critique phase of the process. The critique phase attempts to follow a traditional critique by a jury of architects within the rubric of a scientific study. The reason for this was to make rigorous the often loose and "hand wavy" format of an architectural critique. A more formal review also allowed for jurors' comments to be published as part of this dissertation and for jurors' contributions to be recognized. This was considered an important aspect of the process we are presenting because, for instance, in an increasingly online and automated technical environment it is easy for authorship and credit to not be given to individuals or "content providers" doing creative and valuable work. We made rigorous the juried critique aspect of the process by formally engaging in an internal review board (IRB) protocol within the strict guidelines of a scientific study involving human subjects. The materials generated for the IRB were made available to jurors via Dropbox. The general structure of the critique is discussed next with key caveats that deviate from a traditional architectural review explained.

Jurors were shown a series of presentation materials at different milestones in the overall thesis project. Presentation materials consisted of images, written explanations and 3D prints of models. Milestone presentations were called "Pin-ups" as is standard in the field.

There were 3 pin-ups, with jurors' commenting on the first 2. The critique was asynchronous and non-local meaning that we relied on a questionnaire and e-mail interviews with the author in the form of a months-long dialogue. Social media was used to make personal connections with jurors. A website with all pin-up materials was provided at "johncdriscoll.com." An archive on Dropbox was available for jurors' to learn more about the project. This was especially important for the next chapter where a real architectural project was chosen as the case study project, and details were provided in a Dropbox folder in terms of the official Request for Proposals (RFP) and details of the project.

Jurors were required to be licensed architects. 9 jurors chose to participate from a pool of 15. The jurors were asked to make critical comments and suggestions in regard to the project presentation. Comments were answers to a questionnaire, plus interview style "back and forth" dialogue with the author. This material is referred to as "comments" and is included in Appendix. Neither a background in algorithmic design nor an understanding of the particular algorithm was

considered necessary. The intention was that the project model and drawings represent a real building and as such are provocative artifacts of the process and might speak to the method of their development. In this sense, the project as a real form in space and in an environment represents its materiality but also represents its organizing principle, i.e., its algorithmic rules and recursive self-similar fractallity.

In this thesis, the artifact is intended to quite literally represent the code. One might imagine a plant as a literal representation of its L-system. More abstractly, perhaps, one might imagine Christopher Langton's extension of Turing and von Neumann's work with self replicating CAs as a built object which encodes its own potential future development. For instance, a building could be thought of as an algorithm that creates a set of conditions that either symbolically or perhaps literally extends itself in space and time. For instance, a building could be extended by being added to over time with respect to its algorithmic organizing principle.

A building may also be extended by the means of some kinetic element or a building could incorporate artificial life in some way. These latter two conjectural examples are outside the scope of this dissertation.

3.3.5 Proof of concept

Pin-up #1 focused on the development of the design process and the development of the DBVgen tool. The toy problem was a simple park pavilion with basic architectural ideas explored such as: scale, space, form and context explored. The toy problem was intentionally oversimplified to highlight the design process as clearly as possible. Using such a simple problem ran the risk of seeming trivial but when incorporated into the larger study lends itself to understanding of how we are describing a design process and not a specific design. One of the advantages of an algorithmic design process is that there are many potential instantiations of unique designs based on the same parametric settings.

3.3.5.1 Pin-up #1

In this section we present and discuss the materials sent to the jurors for the first critique which we label Pin-up #1. Jurors are licensed professionals in architecture but do not necessarily have a background in computer science. It was considered not necessary for jurors to be familiar with computer-based tools such as FD or GA to participate in the review. The jury was asked to assess the material provided as if they were part of a traditional architectural pin-up in an academic or professional setting. This chapter represents the first of 3 pin-ups which worked toward a final design solution presented in chapter 4.

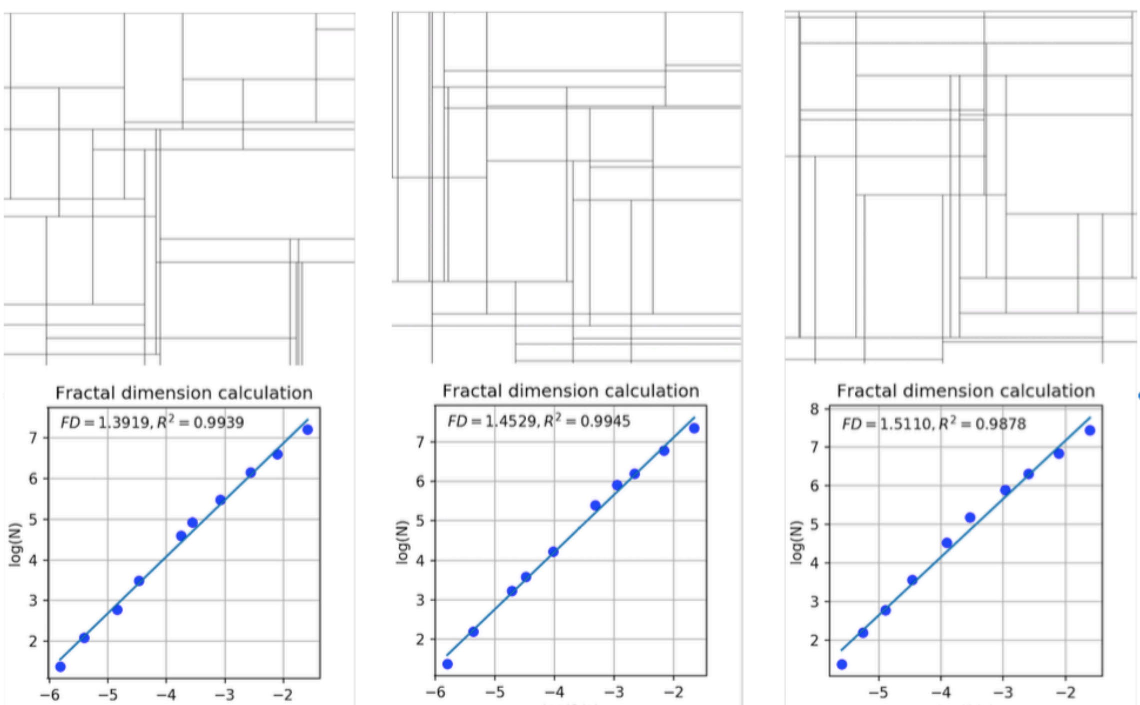


Fig. 3.3.6. 2d compositions above and box-counting dimension plots below.

The figure 3.3.6 shows basic line compositions generated randomly with respect to adjustable parameters such as the number of vertical and horizontal lines and a range for how many times they cross. These represent compositions using 30 lines with FD determined using box-counting dimension the calculation for which is shown in the graphs immediately below each composition..

Figure 3.3.6 shows the most stripped down output of what the GA we developed for this study does. The line compositions across the top represent the individual that is most fit in terms of the fitness criteria. The fitness criterion is an objective function that is being maximized or minimized. In this study, a target FD of 2 was used as a starting point for the investigation. The target FD parameter was more relevant for the case study project where a relationship between different levels of the building's scale was desired as well as a relationship top the FD of adjacent buildingsOver successive generations the FD is seen to generally increase. Exemplar designs are chosen from individuals forming a population within a given generation. The main parameters include the number of generations, the mutation rate and whether new lines are added or deleted.

Figure 3.3.8 is a vignette example of a GA run for 5 generations. Exemplar compositions for each generation are shown at top but now with a number of rectangles or masses chosen at random. Masses are allowed to overlap and any number of masses may be set in the corresponding parameter. The next set of images below show the masses extruded into the third dimension to a random height within a threshold. The graphs at the bottom

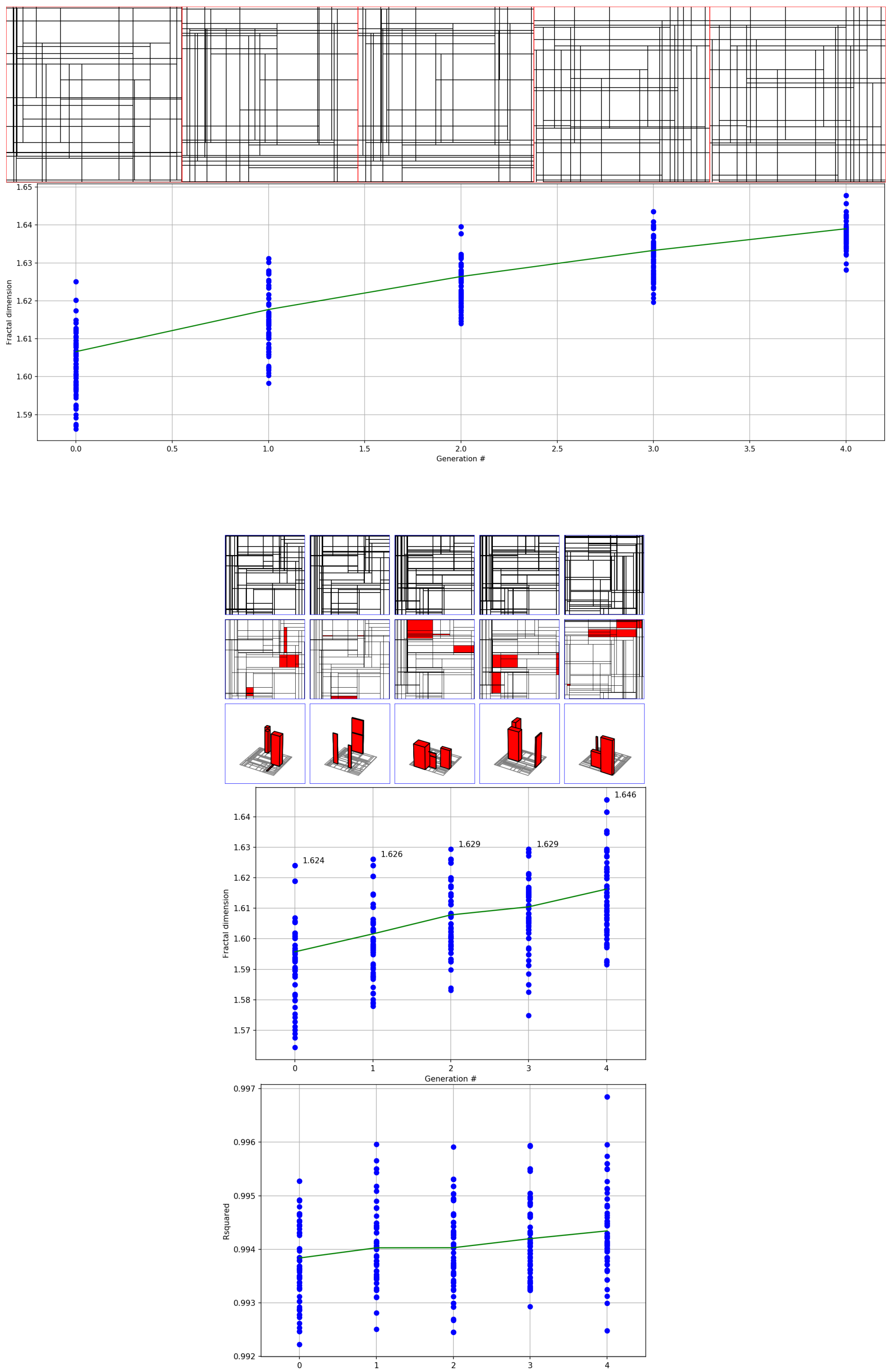


Fig. 3.3.8. Truncated timeline showing 5 models progressing in time from left to right. Exemplar compositions culled from all design variants are shown across the top with rectangles highlighted and extruded below. Graphs show the fractal dimension and r^2 for all individuals in each generation aligned vertically (image by author).

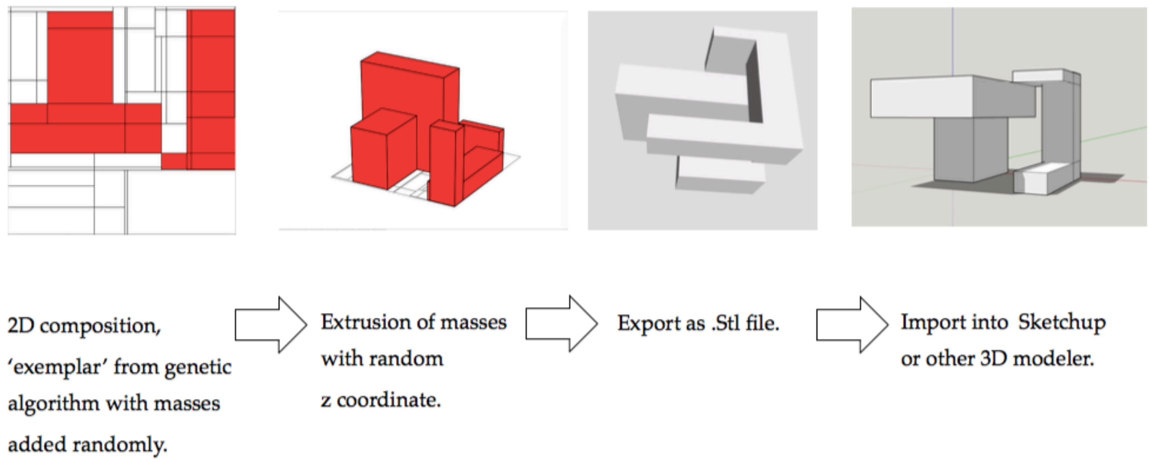


Fig. 3.3.9. Progression of outputs to BIM environment and fitting by the designer (image by author).

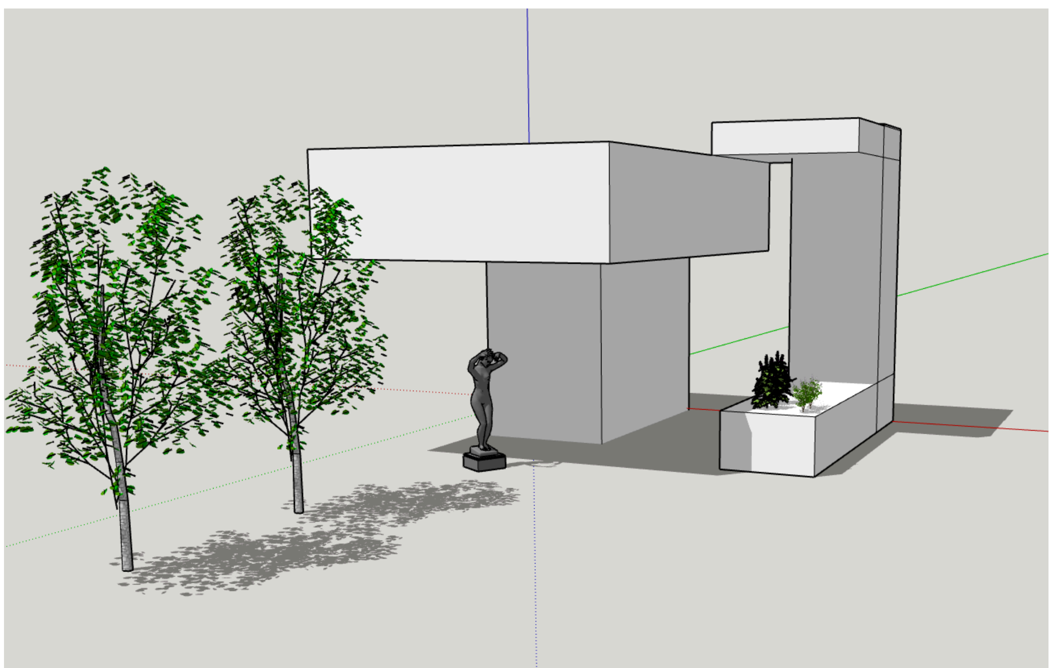


Fig. 3.3.10. Pavilion as simple proof of concept demonstration project (image by author).

display the exemplar FD for each run and the mean over successive generations. The FD measures only the 2D compositions. This example is a more or less arbitrary example culled from any number GA runs. An important leverage point offered by algorithmic design is the sheer number of potential variants a designer may peruse and be inspired by. For this example the FD for exemplars ranges from 1.624 to 1.646. Additional examples and FD results were presented to jurors not included here.

Figures 3.3.9 and 3.3.10 represent how the algorithm may be fit in a fast and loose way to a demonstration project. Here we show the design produced by the algorithm as a park pavilion. This project is a loose reference to Bernard Tschumi's Follies project for Parc de la Ville as well as Mies van der Rohe's Barcelona Pavilion. Site elements are placed in the design to create a sense of scale such as a sculptural nude, plantings and shadows. Basic components of architecture are introduced such as a sense of enclosure, elements of composition, a relationship to a site within a landscape of some kind as represented by sun angles, etc. For the proof of concept there was a minimum of fitting performed. The output of the algorithm was simply rotated and placed within a context, giving it scale and establishing the output as built architecture. In the following pin-ups there was significant fitting of the algorithm's output to a design task as will be described next.

3.3.6 Case Study: Green Street Proposal

In sections 3.3.6.1 and 3.3.6.2 we apply the proof of concept model to a real world case study project. The project we chose for the case study is more than adequate in terms of its comprehensive program. The project is a collection of new and renovated buildings that occupy almost an entire city block in the heart of downtown Ithaca, NY. This project is a response to an RFP sent out by the The City if Ithaca in the Spring of 2018. The project is developed here as a schematic design developed to the point of presentation drawings that could hypothetically be presented to the City Council and the public. For this dissertation we have not submitted the design and that phase is beyond the scope of the present work.

Program

The program for the project as issued in the RFP is briefly described here. The program is for a roughly 60 thousand square foot urban block that is presently a series of 3 parking decks that are in poor shape. The City is requesting that the decks be converted into a mixed use development of affordable housing and retail as well as additional parking and a transit hub for local and regional bussing and future transport modes. There is also a 4-theater independent cinema (Cinemapolis) on site that should be renovated and enhanced as well as an important connection to the Commons which is a three block pedestrian mall adjacent to the site. The site is also adjacent to City Hall and across the street from the public library. The City also requested a 40 thousand sq. ft. convention space but this was not considered realistic in the present proposal. Next we describe the design process and juried critique for Pin-up #2 and in section 3.3.6.2 we present Pin-up #3 which is a description of the final project and presentation renderings.

3.3.6.1 Pin-up #2

Compositions were developed in the same was as described in section 3.3.5 for the proof of concept. Significantly more fitting was done with the program for the project in mind.

In Figure 3.3.6.10 some preliminary composition studies are shown which were produced

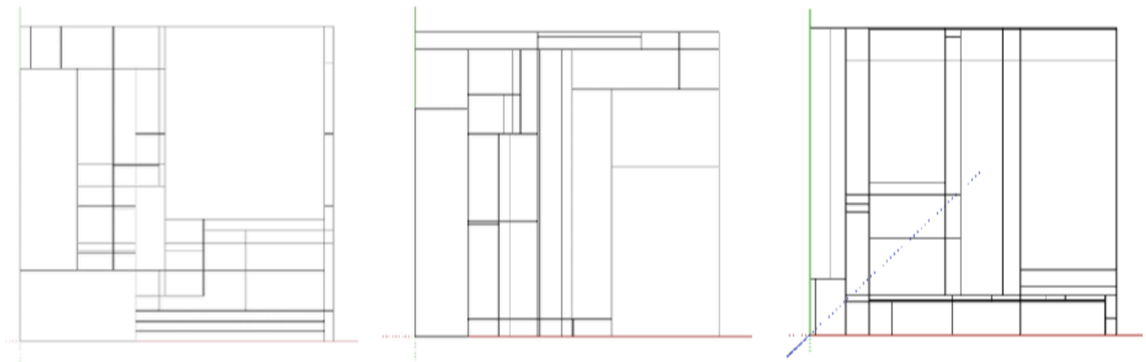


Fig. 3.3.6.10. Some examples of compositions developed by the algorithm (image by au-

by the GA using a target FD of 2 as the fitness criteria. For Pin-up #2, the DBVgen tool was implemented as a GUI in SketchUp. Models could be manipulated by hand and fed back into the algorithm for further evolution, thereby closing the loop as we discussed in section 3.3.5. The number of lines and the number of generations were modified and many runs were performed.

Outputs were assessed for FD and for composition elements such as rectangular motion of the eye, focal point, counterpoint, etc. . Compositions were selected as "seeds" for crossover with other compositions. In this sense the designer played "matchmaker" by selecting parents for reproducing offspring that were a blend of the attributes of the parents along with random mutations.

Figure 3.3.6.12. depicts how the (designer selected) initial composition was used to generate the fractal organizing principle for the project, thereby becoming the generator for

the entire complex. The composition selected (Fig. 3.3.6.11) was a compromise between a relatively high FD of 1.477 and qualities that inspired a parti for the main parti of the building complex. The FD was close to the Herald Square building which had been analyzed earlier and shown to have a FD of 1.516. The composition triggered an idea for the building in combination with many hours meditating on the programmatic requirements and the complex site conditions. The remaining images show how the idea was germinated in various ways as the generator for the project. The design explored *theme, development and variation* as expressed in the components of the building. We next discuss more in depth the three primary levels of scale where the self- similar motif is expressed – micro, mezzo and macro.

Micro

After thinking about the project in for several months and sketching massing studies for the building volumes, we began experimenting with the DBVgen tool in SketchUp to create orthogonal compositions with 30 lines perpendicular to each other. Figure 3.3.6.11 and 3.3.6.12 shows the composition and 3D model for the masonry unit block. We then fit the 3D extrusion "by eye" to be a form we assumed was easily constructible in concrete and an adequate motif for the project at this phase of the schematic design.

Although constraining the design to straight perpendicular lines was limiting, this constraint simplifies the process for now with the intention that more variety is a future goal. The rules for generating composition were explained previously so they will not be reit-

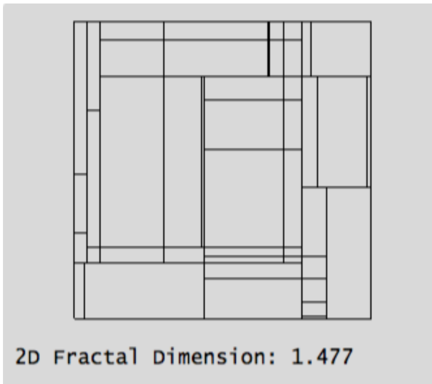


Fig. 3.3.6.11. Selected initial composition (image by author).

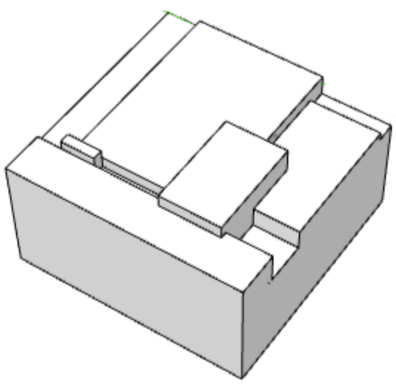


Fig. 3.3.6.12. Extruding and fitting of composition into a module used as a motif for the project (image by author).

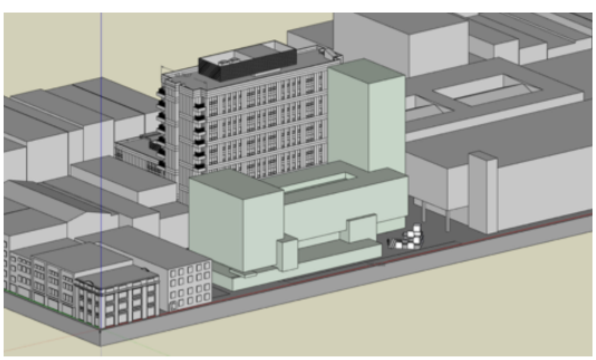
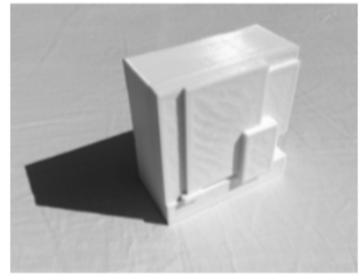
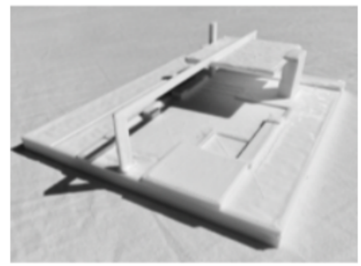


Fig. 3.3.6.13. Massing model as reflection of motif (image by author).





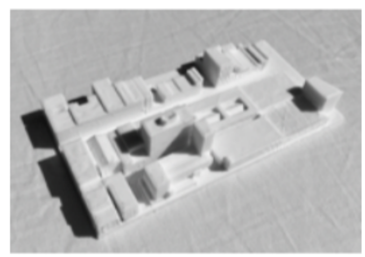


Fig. 3.3.6.14. Physical prints of micro, mezzo and macro elements of the building.

Top: micro = module.

Middle: mezzo = mid-scale (Pavilion component).

Bottom: macro = Project within larger urban context (image by author).

erated here. It is important, however, to emphasize that orthogonal compositions are focused on because of their constructibility and relative simplicity in terms of modeling and coding. It should be noted that orthogonal abstractions are still able to capture a variety of geometric form such as diagonals and curves, for instance the Barcelona Pavilion is in some is ways a composition of triangles. For this study, rectilinear motion was sought in the motif to integrate more with the Herald Square building. Importantly, following from the rules latent in the Vollendorf Method, asymmetry is expressed in the module and subsequently in the higher levels. This gives the form "never ending" quality. For instance, as one zooms in and out, there is never a resolution where motion stops but a tension built into the module that is reflected in all the parts and the building as a whole. This dynamic tension in all the parts and scales gives the building both unity while maintaining variety. A 3D formwork print was made to test the constructibility of the design (Figure 3.3.6.15). As of this writing, we have not cast test blocks. This is considered a next step.

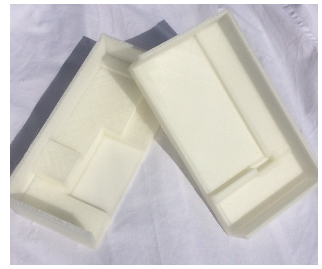


Fig. 3.3.6.15 Test formwork for masonry block (image by author).

Mezzo

Figures 3.3.6.16 , 3.3.6.17 and 3.3.6.18 show another level of applying the DBVgen tool was at the mid-level. This was considered to be more at the human scale and at the scale of architectonic systems such as structural systems (columns, beams, mid-scale massing), fenestration systems, and envelope.

Combination of elements create space, rooms. outdoor gathering loci, etc. The 2D image (Fig. 3.3.6.17) shows a composition with parametric inputs related to a specific area of the building. The composition was then overlapped on the relevant area like a mask and various masses extruded by eye and incorporated into the overall building design (Fig. 3.3.6.19). The design now starts to incorporates the three levels of detail as an ensemble

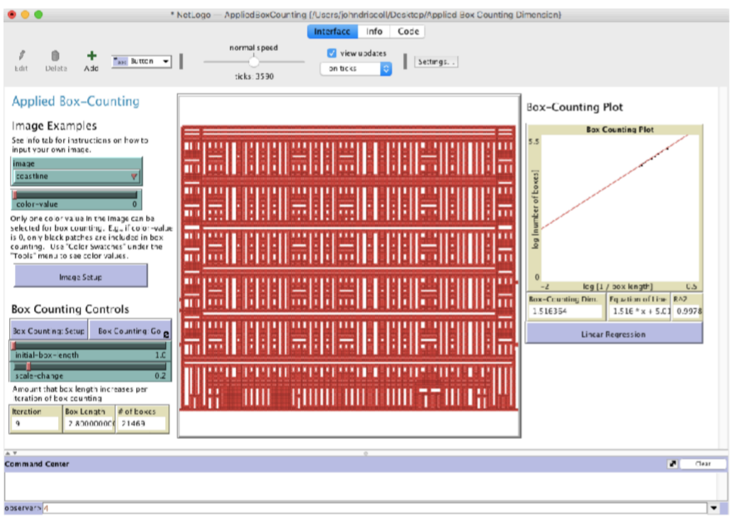


Fig. 3.3.6.16 Harold Square FD study (image by author).

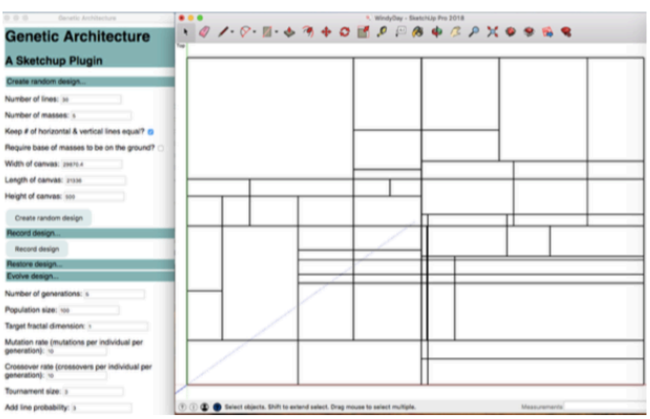


Fig. 3.3.6.17. Initial composition for mezzo scale (theme, development, variation) (image by author).

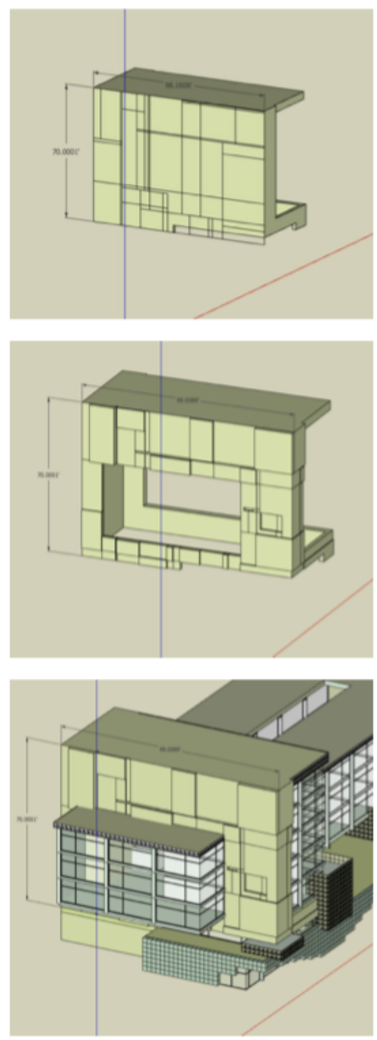


Fig. 3.3.6.18 Mezzo process (image by author).

3D composition. The idea for this building is that the complexity of the detail would increase downward so that the building would begin to pixilate as it approached the street.

Macro

The figures 3.3.6.19 - 3.3.6..22 are a few of the final presentation drawings for Pin-up #2. The macro level was considered as the level of the overall building and its connection to the larger city block plan. The intention of the design was to see the self-similar element as theme run through the building from the smallest component to the largest. The overall plan of the building began with the micro module as a motif and reflects the motif throughout the design decisions inherent in its form. It was intended that the fractal theme should be more than surface treatment and integrated into the space plan and general layout.

Keeping the center mass of the building low to five stories enabled the views to be preserved and offered a potential for deciduous trees to shade the building from the summer sun and helped to transition from the neighborhood scale to the tall Herald Square building. The site experiences high levels of traffic on the street it fronts (Green Street) as well as high levels of pedestrian traffic making it an obvious option for the new bus station that the city requires. Retail is located at ground level around the entire building with a mix of affordable and workforce housing on the floors above for a total of between 70 to 100 units depending on how the flexible space is divided into one-bedroom, two-bedroom, or three-bedroom units. The site along Green Street sits between regional vehicular

Fig. 3.3.6.19. Bird's eye perspective looking east (image by author).

Fig. 3.3.6.20 Bird's eye perspective looking west (image by author).

Fig. 3.3.6.21 Exterior perspective at Pavilion (image by author).

Fig. 3.3.6.22. Exterior perspective from street showing cinema marquee (image by author).

traffic and the pedestrian-centric historic downtown. This site is one of the six original blocks laid out as the original plan of Ithaca by Simeon Dewitt in 1806, yet has not had a strong sense of place since the Green Street "tuning fork" expansion in the 1950s. The site is an edge between the business center and traditional residential blocks, making it ideal for a community minded loci in the guise of a transit hub as well as a mixed use retail and (much needed) affordable housing. As a complicated edge between different regimes, the project lends itself to a formal solution using fractal geometry.

3.3.6.2 Pin-up #3

This section is the final presentation for the case study project (see 6.0. Plates). Pin-up #3 is a continuation of Pin-up #2 and represents a refinement of the project with no new significant algorithmic design or fitting. Photorealistic renderings were done and the scheme is described as follows from the perspective of designer as if in a traditional presentation (see Fig. 3.3.6.2.1 and 3.3.6.2.2) The original RFP issued by the City for the project outlined the main objectives in terms of "connection, context and activity." We have organized our summary of the project relative to these same terms.

Connection

In dense urban environments with smaller living conditions, having meaningful public space becomes like an extension of your home. The Commons in Ithaca is a vital component of civic life where people come to trade not only goods and services but far more valuable things – ideas and opinions, emotions and convictions, gossip and snark or just while away the afternoon. In short, the Commons is community plain and simple. Our scheme creates a strong, open air public park to the west of Cinemapolis. This park will be deeded to the city to ensure it remains a public asset in perpetuity. The park will be 50’ wide and completely open to the sky above with great southern exposure. We achieve the open air park by eliminating the deteriorated west parking deck.

Walkability is one of the most interesting opportunities the Green Street Project offers and along with transportation generally has long been associated with the site since it was a livery. The site will remain an important transportation hub; however, and we envision a conversion that is amicable to new modes of transit. Potential up-fitting at this stage includes covered bike storage including bathrooms, showers and locker rooms as well as converting Green Street to two way traffic and incorporating a local and regional bus station into our proposal. We intend the site generally to be a zone of transition from vehicular transit to pedestrian. To this end we have incorporated a comprehensive system of walking paths through the site linking to the Commons to the north through the Home Dairy Alley and Harold’s Square building as well as to Six Mile Creek to the south. The fractal character of the building allows it to open up to many idiosyncratic moves that respond to site opportunities.

Context

In our scheme we propose to limit the heights of the new buildings (at least to the west of Cinemapolis) to 5 stories which are still accessible without elevators and don't block the Harold's Square view-shed.. The 5 story scale makes more sense for downtown Ithaca as it transitions from mainly single family housing and allows for light and air and open green-space. These qualities are keeping with the walkability and density criteria offered

Fig. 3.3.6.23. Presentation perspective looking west (rendering by GoffMachline and Razin Khan).

Fig. 3.3.6.24. Presentation perspective looking east (rendering by GoffMachline and Razin Khan).

in the new Green Building Policy which the city is currently reviewing and considering making an ordinance for future development (Figure 3.3.6.2.1 and 3.3.6.1.2). Again, the fractal geometry of the building gives it a fragmented quality that allows it to respond in myriad ways. For instance, the building can respond to adjacent buildings and gradually transition between the dramatic range of typologies in the immediate area. The building can also increase or decrease volumes in flexible ways that can adapt to new conditions and opportunities, such as new modes of transit or new program.

As Ithaca continues to urbanize, our project will serve as a prototype or "seed" for growth. Namely, a project other developers can point to as a model that provides real affordable housing at an appropriate scale for the neighborhood. Buildings that are out of scale with and not integrated with the neighborhood do not foster the dense street life we see in truly vibrant cities. People way up on the 15th floor of a mid-rise can't see what's going on on the street and foster the kind of collective social atmosphere that's synonymous with bustling city streets, this is perhaps especially pronounced in low-income mid-rise housing.

Activity

We envision an outdoor park open to the sky and brimming with trees, flowers and plantings. This park will be connected to a new on-site pedestrian street filled with tables and chairs and lined with shops. We have significantly enhanced Cinemapolis by creating a park and outdoor pavilion that is open to the public. This loci is an important facet of "community," enhancing exposure to public art and culture. The pavilion will be used in the moderate seasons to show outdoor movies and in this sense is really conceived of as a theater space with acoustics and theatrical elements in mind. The park and pavilion are designed to help draw people into the the Commons from the Green Street corridor – one of the most vehicular trafficked streets in the county.

In our mind, public art is a fundamental aspect of a communities' culture and civic life and is essential to incorporate in this project especially as a gateway to the independent cinema and the concerts and fairs held on the Commons. We envision the proposed project to operate as a civic center with all that that name implies. In fact, our project generally is conceived of as a civic center both in terms of a network of venues as well as a transit and information hub directing people to a variety of event spaces scattered throughout the downtown area and at Cornell and Ithaca College. All of these moves are designed towards extending our public Commons which is already the cultural center of Ithaca.

City officials have correctly emphasized that the Green Street re-development project is especially thorny and calls for a solution that accounts for the many facets of its program. The program includes moderate to low cost co-housing, a full-scale market space, a local and regional bus station, new parking spaces, sustainable design, a convention center solution, public green space and contextual architecture. Our proposal offers a sustainable model for Ithaca's development moving forward by re-conceiving the notion of "regenerative" architecture. The complexity of this project is perhaps the strongest argument for integrating the building and site within a comprehensive system of design. We employ a fractal approach that enables the building to take a variety of formal responses to the site and programmatic conditions offering a highly varied morphology. The range of options afforded by this approach gives the building an efficient design as well as a certain aesthetic vocabulary that is contextual as well as provocative. The building seems to push or pull in multiple dimensions and is offers novel detail from many vantage points. The fractal algorithm may be extended in space either conceptually or literally. The design suggests its own continuation because it incorporates a repeating module at multiple scales and defines logical rules in terms of composition. This aspect of the design is what we interpret as the generative code of the idea, that which can be instantiated again and again in different ways. Some instantiations may relate to functional and programmatic requirements or aesthetic ones. In this sense the design is much like a body type in biology that is genetically coded for and can take on many shapes relative to niche criteria. One may envision D'Arcy Thompson's exploration of biological form applied to architecture in the sense of a geometric or fractal idea that provides for various functional conditions and yet is grounded in a formal vocabulary that repeats again and again across many taxonomies.

3.3.7. Jurors' feedback assessed

In this section we present a summary of jurors' comments with a discussion of the main points raised. The following sections explore a selection of the jurors' comments more in depth. The entire correspondence log is provided for reference in the Appendix.

Juror’s responses chunked into 10 general categoryies

	Research question	JWS	DM	SR	JF	GH	KM	KK	BH	TM	Total
1	Level 1 produced compelling designs	-1			-1	1	1	-1		-1	-2
2	Level 2 produced compelling designs	-1				-1	-1	-1			-4
3	Level 3 produced compelling designs				1	1	1	1	1		5
4	Usefulness of tool to you	-1				1			1	1	2
5	Fractals generally relate to your personal design approach	1	1						1	1	4
6	Fractals have merit generally in architecture design	1	1		1					1	4
7	Designer’s role is essential	1			1	1	1	1	1		6
8	Tool must be project specific and unique to project criteria				1	1		1	1	1	5
9	Universal quantitative tool is valuable							-1		1	0
10	AI is generally a favorable development in architecture	-1				-1		-1		1	-2

Table 3.3.7.1. Jurors' comments chunked into ten general categories. Levels 1, 2 and 3 represent levels in the design process as discussed in section 3.3.

3.3.7.1 General findings based on the critique

As we have discussed, this dissertation utilized a traditional architecture critique consisting of a panel of nine architects who engaged in a back and forth dialogue with the author/designer. Table 3.3.7.1 shows a selection of the jurors' responses chunked into ten general categories. Categories were developed as a "shorthand" for jurors' responses to the pin-ups using the questionnaire where possible as well as their self directed feedback. The feedback from the jury represents the primary evidence from which we base our findings.

Next we discuss the responses of the jury in terms of who expressed a generally favorable or unfavorable view relative to a given category based on the total number of jurors who responded to that category. The jury found the back and forth between designer and algorithm at level 2 of the design process to be the least compelling with 4 of the 4 respondents remarking that there was a significant disconnect between the output of the algorithm as a 2D composition and its use in the creative process of the author/designer. This issue overlaps with level 1 which was also considered a weak part of the process with 3 of the 5 respondents commenting that the relationship between FD and how it was informing the larger design to be inconclusive with only 2 of the 5 jurors finding it compelling. Many of the comments focused on the random 3D extrusion of the composition to be disconnected and not informed by the FD metric. For this reason as well as others, the proof of concept exercise was not convincing to jurors. The jury did find the larger design process at level 3 and the final case study project to be successful with 5 of the 5 respondents commenting that it was compelling. The majority of jurors expressed that they found the general application of fractal theory to architecture design and critique to have merit and to be relevant to their own creative process. Further, jurors' felt strongly that the role of the architect to work with the algorithm and determine the quality of the composition in relation to a specific and unique project was the most important aspect of the process with 6 of the 6 respondents expressing this. Jurors did not feel strongly or were equivocal on the value of fractals as a universal metric to assess architecture. Finally, jurors expressed their skepticism or even outright pessimism of AI within a context of design, with 3 of the respondents to this issue unconvinced regarding the value of its potential utility and only 1 of the 4 in favor.

3.3.7.2 Author/designer feedback

In terms of the subjective author/designer's evaluation of the design process, there were two main aspects that were helpful in designing the proof-of-concept exercise and the case-study project. One aspect was the novel compositions created by the DBVgen tool and the other was the back and forth dialogue with jurors over a range of issues relative to the notion of fractals in architecture. The following is from the perspective of the designer.

2D

I found that as the GA evolved compositions with higher fractal dimension they became more visually rich. Space opened up and lines began to cluster in a variety of ways lending to a dynamic movement of the eye. Some compositions were quite unique and unlike anything I would have come up with myself. The compositions seemed to improve with short runs of the GA (5-10 generations only). FD was definitely relative to the number of lines used in the composition. For 30 line compositions, which is what I primarily used, the FD generally increased from the random compositions in the range of 1.3-1.5 to a range of 1.5-1.6. When I did very long runs with the GA the compositions consisted of lines tightly packed along the edges which was not visually interesting.

3D

I agree there is a disconnect between the compositions and the random extrusions. I do not think the two are as unrelated as some of the jurors suggested. Part of this stems from the Vollendorf method itself which could be criticized as focusing on the plane as a plan or elevation over the form in the round. An obvious criticism is that the exercise does not create architecture in that there is more to designing a building than considering the form alone and then adding plantings and a scale figure etc. This is a valid criticism certainly but it misses the point. The Vollendorf method is a didactic exercise to teach 1st or 2nd year architecture students the rudiments of design. Elements such as *center-of-interest* and *counterpoint* are foundational attribute of design and are highlighted by the simplicity of the exercise. The minimal aspect (3 lines on a page) gives the student the freedom to explore and discover from the potential of first principles outward to increasing components and relationships. The student must learn to maintain the central idea within a vastly more complicated enterprise. Working from a plan view and learning to see the 3D space within the plan is fundamental as well in that it provides a shorthand means to express a more complex idea. The aspects of the plan that are extruded along the vertical axis are chosen for their compositional qualities such as emphasizing the center of interest and creating space. At this stage in the algorithm development I simply choose a number of masses to extrude randomly and this is the primary reason for the disconnect as the jury mentioned. I do not think this means the resulting 3D form is totally unrelated to the composition however. The composition remains as a plan view when I used it to design the case-study project. The 3D forms also capture aspects of the composition that I highlighted through modification basically using the push/pull tool in SketchUp to adjust the masses using my sensibilities as a designer. I did not change things to the extent that the feeling of the original composition was lost but rather highlighted what I saw in the composition. Another aspect of the DBVgen tool I found useful was to use it to generate detail across a swath of blank wall. In this application I chose many masses to randomly extrude but only slightly into the third dimension. Masses were allowed to overlap. The result was essentially the 2D composition as a bas relief. This capacity of the algorithm made adding detail to the building efficient and related to the larger idea of the building through FD. I did notice that the FD tended to go down when I modified the algorithm's outputs. Keeping the FD higher is something I feel I could work on and get better at with practice.

The simplicity of the DBVgen tool fit together nicely as a coarse grained approach. Extending the preliminary algorithm/designer back and forth into a more realistic solution to a complicated architecture problem meant that my role was critical in conveying the original idea developed at level 2 of the process within level 3 (traditional architecture process). I broke the project up into 3 levels of scale. The algorithm and designer fitting was responsible for the micro level work. At the mezzo level I used the algorithm to create detail on blank walls essentially. At the macro level I used the block unit developed at the micro level to begin the basic massing of the building. This aspect of the idea was part of my original selection of the composition I used for the block design, e.g., I saw the building in it as a response to the site conditions. I also continued to measure the building for FD and adjusted it to maintain a higher FD and one that more approximated the Herald Square building immediately adjacent to the north. This was done in 2D elevation – which allowed for FD to be used – by adding fenestration mullions and other details. Herald square was also measured for FD in 2D elevation. The next step in this work is to develop a 3D box-counting-dimension tool which will use a matrix of cubes rather than a 2D grid. The Vollendorf method could easily be implemented in a 3D space and selected for with 3D FD similarly to how the present model does. The algorithm is in a developmental stage at this point and and could potentially include such functionalities in the future but was beyond the scope here. Overall, I found the design process with the DBVgen tool to be fun and inspiring and led to a rich exploration of form as well as establishing a more deep understanding of the significance of fractals in architecture. The resulting building I think is a successful solution to the difficult program and also visually exciting from multiple angles. I like the way it seems to disintegrate or "pixellate" as it approaches the ground plane. I also enjoy the variety of spaces and forms like the tower and archways on the street and the negative/positive space the building suggests especially around the pavilion that seem to come together into a unified whole. The design is a language of form that repeats but changes as well. The main weakness I see is that there could be another element provided to contrast the orthogonality of the form, perhaps some curved soft shapes or some other geometry that would provide relief and counterpoint. The large archways delineating the entrances to the bus station and retail do this to some extent but I think a powerful contrasting element could be developed more.

Dialogue with jurors

The second part of the process that I found rewarding was the interaction with jurors over a protracted period of time. This back and forth with a range of sensitive designers gave me the chance to incubate these ideas and fully digest them before I started designing the case study project. Once I began designing I came up with the idea of breaking the building up into three distinct levels of scale with opportunities for detail at these distinct regimes. This led to a breakthrough in formulating an organizing principle around a recursive procedure that happened over and over again and could potentially integrate the project on 10 distinct levels. This was a breakthrough in part because it introduced more rigor and opened the door to quantitative assessment in terms of elaborating on the notion of "wholeness" and "integration." I feel this is a significant contribution to this concept in architecture. The idea germinated through dialogue with jurors by reacting to their comments and criticisms which led to their elaboration and so on. This is evident in the correspondence log in Appendix. Particular moments in the dialogue are highlighted and discussed in the next sections.

3.3.7.3 Design Process

The design process we developed for this project inserted a computer tool into a traditional design process that was capable of creating unique visual compositions with respect to various parametric controls. The insertion of the DBVgen tool within the schematic design phase of the process and with a designer fitting outputs within a context of architecture was considered an important leverage point within a larger design paradigm as discussed by the jury. Computer-based tools have been widely experimented with in terms of generative modeling mostly from the computer science world, but what is unique here is that we have presented an approach that incorporates such tools formally into a standardizable implementation. Our contribution is mainly in positioning the DB-Vgen tool up front in the design process where it has the most potential to help the architect. Typically computer-based tools are used for analysis or presentation but here they are integrated into the creative process. For instance, with relatively little time and effort, a simple algorithm may extend the designer's reach in terms of creating design options. These options represent "content" which can be used to inform a designer's own "hand" and "eye" in a back and forth or provide a jumping off point for an investigation or be used in client meetings, charrettes with community stakeholders, etc. Finding key leverage points is significant in providing the most benefit for the least effort. To this end, comments by the jury were positive.

According to Tomasz Mlynarski, "So to me, it is about what moments in the design process can we use these tools where they can generate non obvious answers. If the design is a process and intuition, and experience is the base of certain design decisions, what are moments in the process where a GA can create the most impact? In that, I think the most significant potential would be in GA's that provide specific solutions to some particular targeted issues. It might also help if these tools were less project specific and more generalized. That is why I think this idea of incorporating FD is so exciting. It's such a flexible method for providing feedback back into the GA." (personal communication, see Appendix, Tomasz Mlynarski, April 19, 2019, TM.2).

Gordon Hall observes, "It is sometimes easy to become enamored with my own first impressions of an idea so a tool that can continue stoking the creative engine toward better results could have immeasurable value." (personal communication, see Appendix, Gordon Hall, July 22, 2018, GH.5).

Bret Holverstott observes, "I am really awakened by the idea that fractals generate complexity on multiple scales and I will try to incorporate this into my design process. Cool way to think about it. "(personal communication, see Appendix, Bret Holverstott, April, 20, 2019, BH.6).

3.3.7.4 FD and form generation

Macro

Table 3.3.7.4.1 above shows the FD of the final schematic design at the 3 levels of scale as well as the Harold Square building immediately to the north of the building's site. The overall building was measured in south elevation and had a FD of 1.589 which was slightly above the Harold's Square's south elevation of 1.516. This was relatively close

Level / context	Level 1	Level 2	Level 3	Harold Square
BCD	1.267	1.477	1.589	1.516

Table 3.3.7.4.1. FD of different scale levels and adjacent building.

and created a relationship between the two buildings at this scale in terms of a similar level of detail.

Mezzo

The FD at the mezzo level was measured at the main window bay elevation which consisted of a composition of mullions and doors. Initial FD at the window bay was 1.437. The mullion configuration was redesigned by eye and increased the FD to 1.477 which was still lower than the macro level but more acceptable to the designer (Fig. 3.3.7.4.2).

Micro

The FD at the micro level was taken at the masonry block in front elevation. The micro level had a FD of 1.267 which was less successful at maintaining a consistent FD with the other levels of the building or its immediate context. This was a result of simplifying the block during the fitting stage.

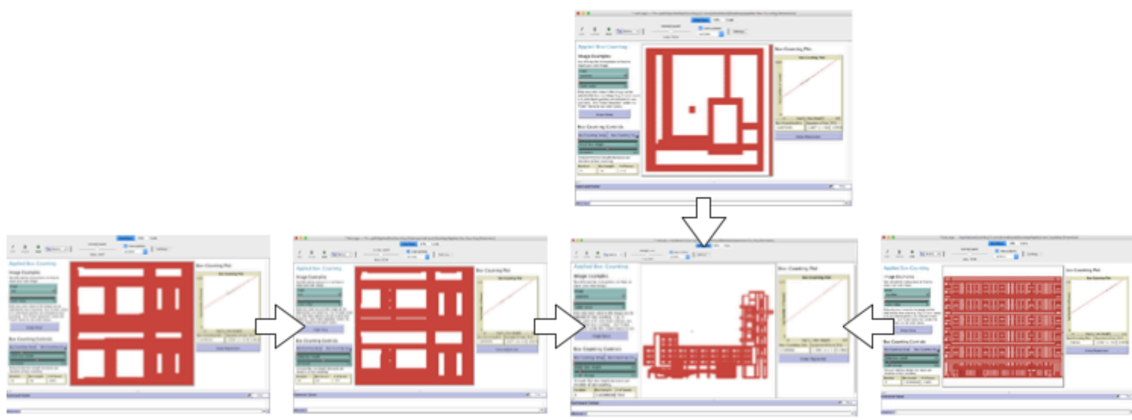


Figure 3.3.7.4.2. Design process using FD to inform the design at 3 scale levels and adjacent building.

The jury was not in agreement on whether a higher FD represented a more quality design. Jurors tended to offer more general comments in terms of the use of FD as a form generator and there was no consensus on whether a higher FD was significant in increasing the quality of the design. In a general sense but not related to any specific composition, higher FD was considered by some jurors as visually important when experiencing architecture from a distance.

Bret Holverstott describes the idea of using fractal geometry to create scale-free detail in practice. "I think I understand why our aesthetics seems to dictate that the fractal dimension increase as the scale increases. It is because the overall massing of a building should strive for a composition that is compelling if seen from a distance, not overly simple as in a homogenous skyscraper. I am reminded of how gothic cathedrals evolved to utilize alternating bays in order to keep your eye from immediately slipping to the end of the hall; good skyscrapers also break up the composition into something that allows your eye to linger on elements instead of slipping up to the top of the building. What would be extremely interesting is to find out experimentally what humans prefer, aesthetically, based on the size of the object under scrutiny (or distance away from which it is perceived)." (personal communication, see Appendix, Bret Holverstott, April, 20, 2019, BH.7).

As discussed, the general consensus of the jury indicated that the designer's role was paramount in any design process and ultimately it is up to the designer to utilize computational tools effectively.

Kevin Marion observes, "It is the choice of the designer to work with the context or to fight against it. I see this method of having great potential to work in harmony with the context of any project and at multiple scales." (personal communication, see Appendix, Kevin Marion, September 28, 2018, KM.2).

Ken Kroeger offers a different perspective on the use of FD as a means to create good design form, " To address the question about increased FD and improvement of the compositional quality – I don't think it specifically improves the composition. It simply is a variation of line work. Without having any performance/outcome values, I would bet that if you ask 50 different people which one they preferred, you would get that many answers." (personal communication, see Appendix, Ken Kroeger, October 13, 2018, KK. 23).

James Walter Schildroth, a well-known Organic architect offers, "I believe that Fractals are a part of nature and in all of the natural form of the universe. You seem to be proposing that creativity can somehow be done by computers and formulas. This is where I differ. The human mind is, I believe, connected to all this, all the time. It is this connection that informs creativity. Your idea may produce patterns but the real genius of ideas is the mind's connection to the Holographic Universe." (personal communication, see Appendix, James Walter Schildroth, March 26, 2018, JS.4).

3.3.7.5 FD as an organizing principle (the creative process)

Jurors were intrigued by the possibility of fractal geometry as an algorithm for form generation but were not satisfied that the design work presented represented a successful prototype. Again, as discussed above, the use of orthogonal line compositions that did not have obvious self-similarity may have prevented jurors from making connections between the final form and the process used in its creation. The line composition exercise was also criticized as being to overly simplistic in the context of real architecture. The comments the jurors made relative to the final building design and its FD or algorithmic process of design suggested they were not convinced.

James Walter Schildroth, someone familiar with the Vollendorf method, writes, " The 3 lines on a page exercise is a composition. Making Architecture is a far more complex process that only the human mind can do. I use mind and not brain. I believe that the human mind can gain ideas from the collective unconscious not just the limits of a single human brain. The computer can never do this." (personal communication, see Appendix, James Schildroth, September 27, 2018, JS.11).

Jurors' comments in terms of fractal form focused not on the geometric expression of fractal shapes but on the underlying organizing principle and abstract system of design, for instance, akin to a modular approach to design or the employment of a proportional system.

Kroeger references Frank Lloyd Wright in his observation, "The architect is a problem solver, whom [sic] is balancing more than just looks. Fractal geometry is more the underlying module or grid in Wright's work, from which the design develops from but not form (personal communication, see Appendix, Ken Kroeger, October 13, 2018, KK.12). Schildroth also discussed fractals generally in terms of a type of modular design and an outgrowth of designing within a unit system integrated with a deep interest and observation of nature.

"Yes, one can find Fractals in all of Wright's work and just as they are found in all of nature. The finding of fractals in the plans is not the result of his putting them in but they result from the establishment of a unit before starting the plan. Working with a unit system give a kind of natural unity of the whole because every choice made during the process of design is made in relationship to the unit. The result is fractals." (personal communication, see Appendix, James Schildroth, April 6, 2019, JS.2).

On the general question of machine learning algorithms applied to fractal geometry and the future of architecture in terms of something akin to "artificial design," jurors were mostly skeptical. Generally, a consensus around the unique and complex aspects of particular problems and what architects do and their responsibilities precluded a serious consideration of a strong notion of artificial design.

Kroeger writes, " And as an Architect, I believe that our responsibility goes beyond creating specific patterns that are only there as an opportunity for a specific image to be seen, from a specific viewpoint, on a specific day, with no people or context. That is not being responsible at all." (personal communication, see Appendix, Ken Kroeger, October 13, 2018, KK.23).

Holverstott notes, "I am a hyperrealist when it comes to design, so I have a hard time believing that I would use purely geometric mathematical generators as a design exploration. I want to know how a design decision is fabricated, transported, installed, how it feels when you move through it, where you store your waffle iron and keep your keys. (personal communication, see Appendix, Bret Holverstott, April, 20, 2019, BH.10).

According to JWS, "I am sure in the future a computer program will be able to design a building. I don't think it will be able to design Organic Architecture." (personal communication, see Appendix, James Walter Schildroth, September 27, 2018, JS.6).

3.3.7.6 Fractal dimension as a critical tool

Jurors' comments suggested that FD as a tool was useful in assessing existing architecture. FD is a simple and objective scalar metric that addresses detail in architecture and could be useful across domains. For instance, relating across projects, i.e., as a planning or zoning tool or to assess the architectural context of a place; to assess precedent; to assess different building typologies and to assess natural features and landscapes. We look at this application more in depth in Chapter 4.

Tomasz Mlynarski comments, "... FD seems interesting in how it can be used to compare buildings that are very different in style and program. It's also interesting as a tool for judging options of the same design as you demonstrated here." (personal communication, see Appendix, Tomasz Mlynarski, April 14, 2019, TM-2.6).

3.4 Challenges

This section discusses the limitations we encountered with the design and development of the algorithm and its implementation in a creative designer-centric process. We then provide a discussion on the somewhat paradoxical challenge of being both the author and designer in this study. Miscellaneous other challenges are also discussed in this section.

3.4.1 Challenges with FD as a metric

The algorithm we developed had a number of limitations. First among them was that FD as a simple scalar metric is cryptic to the layman. How FD relates to fractal geometry or to Euclidean space is not immediately clear and can obfuscate the usefulness of the DB-Vgen tool and how it is actually informing the design process and final product. For instance, West describes adding a 1 to...(West, 2017).

We did not set up the study to attempt to find a special FD such as the golden ratio or other ubiquitous relationships in nature and/or architecture. Jurors suggested that this type of study, perhaps involving a more scientific analysis would be worthwhile but did not indicate that any particular example we presented represented such. Again, it is tempting to ascribe more meaning and significance to a specific FD result such as 1.618..., etc. It is the assumption of this study, however, that FD is valuable as a general and coarse grained tool that is computationally inexpensive. FD is provocative as a trans-disciplinary metric that offers a window into the inherent complex organization of architectural design and the urban environment. FD by no means tells the whole story and is only useful when combined with other elements in a design system.

As we have discussed, FD was only measured in 2 dimensions. Algorithmically generated forms were therefore limited to 2D compositions which were then extruded along the z-axis to create 3 dimensional shapes. A box-counting algorithm could be incorporated to measure 3D outputs in a voxelized space instead of a pixelated space as a next step but for this study we focused on only the 2 dimensional and only in plan view. The Volllendorf method incorporates rotated compositions which can aid in the design of 3 dimensional forms and spaces, often for interior spaces and perspective sketches. We did not utilize this aspect of the Vollendorf method. Additionally, FD as a fitness criteria would produce uninteresting results when the GA was run for many generations, i.e., > 500. Lines tended to bunch up along the edges of the picture plane.

Another significant issue was mentioned earlier for Pin-up #2 and was that the designer fitting had a tendency to lower the FD of the original algorithm produced composition. This was noticed during the extrusion and fitting required to design the masonry block which was used as a geometric module for the entire project. The subsequent design then had a lower FD at the micro scale (1.267) than at the mezzo (1.477) and macro scale (1.589). This was not the intention of the designer and a more uniform FD may have produced a more integrated final design. The time constraints for this dissertation did not allow for additional design charettes but this issue represents an important next step in this research.

Challenges with implementing the algorithm in a designer-centric traditional architecture process were as follows. Architects often work out design problems in their head or on paper or the proverbial napkin sketch. It would be desirable if they could do this and in real time have such work assessed for FD. This may significantly improve an architect's innate ability to create self-similar form over a variety of scales. For instance, perhaps the part to whole mereological process could incorporate a larger range of scales. This process is highly individual and ethereal.

As James Schildroth notes in reference to the architects Frank Lloyd Wright's and Bruce Goff's creative process as well as his own, "I don't think that Mr. Wright started with the unit system. Mr. Wright conceived the building in his mind as real space. He put himself in the experience and worked the whole thing out in his mind before any drawing. When he could see the design in his mind and walk through and round it in his mind is when he selected the unit system to use. So both Wright and Goff discovered the unit through the process. By the way that is how I have worked since 1960." (personal communication, see Appendix, James Schildroth, September 27, 2018, JS.9, JS.10).

Bret Holverstott notes, "Is there a way to create a heuristic for designers to use if they are doing schematic design with a pencil, that allows them to quickly gauge the fractal dimension of their design and generate some simple exploratory patterns as inspiration? Sometimes we overly rely on computers to solve problems for us, and in my experience you can actually design about 10 times faster with a pencil, or at least move through about 10 iterations in the time it took you to test 1 iteration in the computer." (personal communication, see Appendix, Bret Holverstott, April, 20, 2019, BH.8).

Allowing for the algorithm we introduce to be a helpful analytic aid in this environment is understandably fraught. We introduced several workarounds in this domain, including a box-counting FD model implemented in NetLogo that is open source and available for anyone to use for free online (Complexity Explorer, https://www.complexityexplorer.org/explore/virtual-laboratory). This tool allows for an architect's freehand drawing to be inputed and analyzed for FD. Still, this is an awkward and clunky solution involving many steps and some programming literacy. For these reasons, the prototype we develop here does not scale up at this stage and transfer readily to the field.

3.4.2 Author/designer biases

The form of this study required the author to participate in the study in a creative capacity. This was a distinctly separate task from that of researcher – the proverbial right brain / left brain dichotomy. Being the author *and* designer were different roles. The author role required evaluating the design process and designs it produced objectively while participating in that process in a creative capacity. We moderated this by keeping both roles separate and clearly distinct. We also rely on the jury to provide objective analysis which offsets somewhat the subjectivity of the designer's: biases, personal preferences and stylistic choices. This was unavoidable though and there is no doubt that a degree of personal preference colors this work. Jurors' feedback reflected this issue.

Holverstott offers, "I have no doubt you could create a wide variety of compositional patterns that echo and reflect throughout the project and so show the audience that it is a generative tool rather than an imitation tool. Use it to produce originality, instead of just analyze. You've evolved a new appendage, use it to do something new and awesome." (personal communication, see Appendix, Bret Holverstott, April, 20, 2019, BH.14).

The author, serving in the dual role of author and designer, was integrated into the design process in a deep way in not only the role of architect but in the role of designing the computer algorithm in addition to the final form of the building. In the role of designer, the author was able to find significant advantage to the sheer variety of novel compositions and their corresponding FD produced by the algorithm. A composition was selected as the basis for the pavilion project that was inspiring and considered provocative by the author. The form the algorithm produced was not significantly modified but simply rotated and placed within a context giving it an architectural quality (See fig. 3.5).

3.4.3 Miscellaneous

Other challenges were the following. There were issues relating to the asynchronous and non local critique. Jurors were not receptive to the questionnaire we initially sent out as a part of Pin-up #1. For this reason. the questionnaire was not a focus of the critique and not used for Pin-up #2. Interview-style discussions were more effective in providing a platform for eliciting jurors' engagement.

Discussions were intentionally open and frank which allowed for a wide-ranging exploration of ideas associated with the thesis. Jurors were required to a sign consent agreement so their comments could be included in this work. Jurors were also referred to as "subjects" in the IRB materials. These issues may have created an atmosphere not conducive to creative engagement.

The author experimented with multiple modes of soliciting feedback from jurors. These included digital modes as previously discussed as well as in-person discussions, lectures made into a video, printed drawings and 3D printed models. 3D printed models were effective in communicating the spatial aspects of the design but could not be shared with jurors online. A possible solution in the future may be to have non-local participants print the models before a given critique.

3.5 Conclusion

This section presents the main findings and synthesis for chapter 3. We discuss the relevance to the design profession of the algorithm we introduce and key findings of the development and implementation of the design process as well as its application in terms of a case study project. We briefly reprise key limitations and strengths as well as offer some broad discussion on the topic of algorithmic design as we developed it.

The relevance of this work to the scientific and design community is primarily in applying fractal theory in a context of design. This contribution has two broad categories which are as a generative model and as a means to analyze architecture. Our findings indicate that FD as a metric is not enough to establish the merits of a design or a connection to program, site, context or natural features. We also discuss here the merits of the generative aspects of the design process we introduced. This focus was two-fold, one consisting of developing software architecture, i.e., tools incorporating fractal dimension as a fitness criterion for a genetic algorithm; the other being the implementation of the DBVgen tool in a proof-of-concept and case study architectural problem, i.e., "brick and mortar architecture." The development of the generative tool involved the exploration of a new design process. This design process was a main contribution of the chapter and is discussed in section 3.5.1. FD was explored as a generative form-making tool which together with a

GA produced novelty that was the impetus for further exploration by a designer. We found this attribute to be effective and positively received by the jury. FD itself as simply a stand-alone metric to assess the complexity of a design was not conclusive as discussed in section 3.5.2. FD as a component incorporated into a larger design system including the creative process of the designer was successful as discussed in section 3.5.3. Challenges in terms of incorporating the DBVgen tool into a creative context were primarily in the ease of use and scalability of the system. At this prototype stage, however, this limitation was considered acceptable.

3.5.1 Design Process

The design process we developed and the proof-of-concept and case study project it was applied to made progress towards integrating generative computer technology within the architect's purview. This was an important goal of the dissertation. FD as a component incorporated into a larger design system including the fitting and modifications by the author/designer was successful. The ability to modify the algorithm and to work back and forth between automated tasks and actively designing in a 3D modeling environment was compelling according to feedback from the jury. The computer allowed for a quantitative assessment of FD that was more-or-less simultaneous with the creative aspect of the process. This kind of informed investigation would not have been possible before computer technology. The DBVgen tool was flexible enough to include functionalities that were project specific such as matching FD of adjacent buildings and specific dimensions of building components. Adjacent buildings were only measured for FD in 2D which was a limitation. A 3D FD implementation of the DBVgen tool was beyond the scope of this dissertation and represents a next step. Other functionalities that were not explored and represent next steps are the ability to incorporate within the algorithm more unique details of the program and context, for instance, circulation patterns, room adjacencies, natural features such as sun angles and proximity to riparian corridors as well as certain angles or geometries relating to the site and context and so on. Some of these potentials were discussed by the jury and included in Appendix, Comments.

Systems theories look for generalized models that offer trans-disciplinary approaches. In this spirit, the design process for this study intentionally sought models that could bridge between the silos of science and design. Here we draw from fractal theory to develop an organizing principle, we refer to as a generator, that was integrated with the generating algorithm as well as the larger design process. For the proof of concept phase the final building resulting from the design process is not a traditional design by an architect but rather the output of an algorithm that was designed by the architect. A useful analogy is the following: the designer is not designing a building represented in a set of blue prints but is designing the DNA of the building that can result in many unique phenotypes relative to the unique conditions of its epigenetics. The case study project was significantly more complicated and required substantial "fitting" by the author/designer which we refer to as a "collaborative." A contribution of this work is as an experiment in a human/machine back and forth process within a schematic design phase for a real life project. This move represents a re-positioning of computational tools from the analytic realm to the creative and generative realm. This represents a paradigm shift and was shown to inspire investigations by the author/designer into novel modes of problem solving. To this end, comments by the jury were positive.

3.5.2 Fractals as organizational principle and generator for design

In terms of the proof-of-concept "toy" project presented for Pin-up #1, jurors generally did not think the outcome represented a fractal organizing principle per se or was a physical instantiation of the cybernetic process behind the outcomes. This issue was rectified in Pin-up #2. Some jurors were intrigued by the possibility of fractal geometry being a method of form generation but were not satisfied that the design work represented a successful prototype.

For the reasons outlined above, a significant conclusion of this study was that FD alone is not a sufficient metric for generating designs but must be incorporated within a larger context of design. Following this conclusion, it is further observed that FD is not sufficient alone in analyzing the fractal algorithms that may or may not be the historical basis for a design. For this reason, this chapter introduced a design process and methodology for incorporating FD as part of a larger enterprise which has the potential to include fractal organizing principles in the design. This potential of the algorithm we developed is explored more in depth in subsequent chapters.

JWS observes in relation to Frank Lloyd Wright, "Two things are important in my understanding of Mr. Wright's process. First, is his incorporation of an experiential knowledge of living with nature. The second is his development of the unit system as a way of giving a unity to the whole of his designs. Yes, one can find Fractals in all of Wright's work and just as they are found in all of nature. The finding of fractals in the plans is not the result of his putting them in but they result from the establishment of a unit before starting the plan. Working with a unit system give a kind of natural unity of the whole because every choice made during the process of design is made in relationship to the unit. The result is fractals." (personal communication, see Appendix, James Walter Schildroth, April 2, 2019, JS.1, JS.2).

3.5.3 Fractals as a critical tool

Fractal algorithms and the quantitative tools associated with fractal geometry such as FD present a new research agenda for studying architectural precedent and urban conditions such as a building's context and formal relationship with other adjacent buildings or within a cityscape. Jurors' comments suggested that FD as a means for assessing basic aspects of different designs and across typologies was significant.

Tomasz Mlynarski comments, "I think the most compelling thing about your work is this incorporation of fitness criteria rooted in FD. It seems FD can be used as a fitness criterion for all sorts of a different buildings with different styles and different programs and you can use the same criteria to rate them all. That is something fresh. You are no longer bound to rather simple fitness criteria like plan efficiency or exposure or whatever. So this is the most substantial part of your work." (personal communication, see Appendix, Tomasz Mlynarski, April 14, 2019, TM.2.2).

We posit that certain styles of architecture – having been influenced by nature – incorporate fractal geometries; such as: Gothic, Art Nouveau and American Organic Architecture. FD has the potential to assist quantitatively in assessing the structure and design thinking of such work which has largely been an intuitive endeavor up until this point. FD by itself is not sufficient to measure the fractal or algorithmic nature of such design work but we show it to be a powerful and parsimonious tool. FD as an analytic tool can aid in a better understanding of fractal organizational principles that have long lain dormant and unexplored in architecture. FD applied to analytic approaches is a powerful tool because it is relatively easy to compute and theoretically rich. This quality gives such tools flexibility and reaches across multiple domains. In this sense, our work was bridge between silos. A strong contribution of this work is embedded in the thesis that fractal tools offer an important connection between nature, the built environment and computational mechanics. The latter includes computer-based tools such as software architectures and object oriented programming which has roots in pattern languages as developed by Christopher Alexander whose work in turn grew out of the urban activist movement in the 1960s as led by Jane Jacobs. Computational mechanics also envelops the rapidly developing gaming culture – or perhaps it is the other way around? Fractals characterized as discrete, scale-free and self similar patterns have the potential to further Alexander's work – or

Simon's for that matter – in providing a cross-platform protocol linking the natural and artificial worlds. Furthermore, fractals as organizing principles in design have not been systematically assessed in historic architecture or in design processes. This represents a new research agenda. We explore the possibilities of such an agenda more in Chapter 4, however, this exploration represents just the tip of the iceberg. A thorough analysis of fractal geometry and fractal organizing principles in architecture is beyond the scope of this dissertation.

3.6 Next steps

Possible extensions of this chapter that we do not pursue are more formal experiments into FD as a meaningful metric. For instance, perhaps a double blind study with more examples of compositions and their corresponding FD would indicate if specific FD values could be correlated with desirable aesthetic outcomes.

In terms of the case study project there are many potential next steps in terms of interpreting this work as an actual real-world project. Immediate items that are ready to advance are the following.

1. Cast test blocks and build a mock up wall.
2. Redesign of the module using a higher FD

3. Presentation of drawings and project description to the public and project officials. This could be in the form of this dissertation as published as journal articles and/or a local newspaper article. It may be preferable to present directly to project officials.

Another major next step for this work will be to scale up the DBVgen tool as a downloadable plug-in tool for use in open source or commercial BIM software.

End of Chapter 3

4.0 Fractals as generator for design in Organic Architecture

"Whether it be the sweeping eagle in his flight, or the open apple-blossom, the toiling work-horse, the blithe swan, the branching oak, the winding stream at its base, the drifting clouds, over all the coursing sun, form ever follows function, and this is the law. Where function does not change form does not change. The granite rocks, the ever brooding hills, remain for ages; the lightning lives, comes into shape, and dies in a twinkling." Louis Sullivan

This chapter is written for a general audience interested in architecture and especially the architecture of Frank Lloyd Wright and the school of Organic Architecture. This chapter is intended as a stand alone paper for potential publication in a main-stream journal. Some overlap with previous material is included and unavoidable.

4.1 Introduction

Fractals were discussed in terms of scale-free self-similarity and machine learning algorithms in previous chapters. Now we will discuss fractals regarding generative organizing principles in architectural design. We focus on a number of nuanced aspects of this relationship. First is the sense that a fractal pattern represents the output of an algorithm similar conceptually to an L-system. We discuss this notion in relation to the architecture of Frank Lloyd Wright (FLLW) and Organic Architecture. Another idea explored here is the idea that the fractal patterns we see in certain architecture stem from an underlying *design* *system* similar to a vocabulary of form or a *language* of form applied to many levels and scales and as well as functions within a design. We discuss this notion in relation to the architecture of FLLW and Dean Bryant Vollendorf (DBV). Finally we explore the work of both of these architects and discuss its influence to the case study project we designed in Chapter 3..

Fractal patterns, because of their ubiquity in nature may run the risk of being considered trivial or too general. To avoid confusion we should first state clearly what a fractal is not. We assume that a fractal is not simply the repetition of a form at different scales with no relationship other than shape. We will argue that this misconception is evident in the literature regarding the analysis of FLLW's Palmer house.

The algorithmic use of fractals in design is somewhat different than a mere formal interpretation of fractals. Fractal patterns we observe are not formal constructs alone but are are the result of an underlying algorithm – pattern making machines if you will. This is sometimes termed *unfolding symmetry*. The forms themselves are not symmetric necessarily but replications of a formal idea at multiple levels within a design. We do not assume that the architects we study use this type of algorithmic scheme consciously or intentionally but rather that it is part of a deep creative process. This may have something to do with how architects think. This idea is discussed more in Chapter 5. To use a word that both DBV and Mandelbrot were fond of, fractals are *generators*. This conception of fractals is distinct from the correct but limited notion that fractals are simply scale-free self-similar patterns, period. Following is a brief background on the use of fractals in Organic Architecture.

4.2 Background on fractals in Organic Architecture

Frank Lloyd Wright called his architecture "Organic" because of his lifelong fascination and exploration of nature and architecture. This followed a long tradition in Romantic arts and architecture regarding figures such as John Ruskin, H.H. Richardson, Louis Sullivan and others.

Lewis Mumford writes, “On Richardson's solid foundations (Sullivan) laid the cornerstone of the new Organic Architecture. Sullivan was the link between two great masters, Richardson and Frank Lloyd Wright; and with the development of Wright's architecture the last stage in the transition was born: modern architecture in America was born" (Mumford, 1933). FLLW had a long career as well as a school called Taliesin where many students and apprentices learned Wright's approach and carried it forward as practitioners and teachers themselves. The Organic philosophy was grounded in the ideology of the *whole reflected in the part* and the entire design integrated according to this principle. Many in the literature have associated FLLW's design approach and his architecture with fractals following the introduction of fractal theory and mathematics in the 1970's and 1980's by Benoit Mandelbrot. Contemporary practitioners of Organic Architecture continue to adhere to FLLW's design philosophy. The fractal qualities of architecture with a focus on the work of FLLW was begun in earnest by Carl Bovill and continues as a rich research agenda (Bovil, 1996; Eaton, 1998; Joye, 2007, 2011; Harris, 2007, 2012; Ostwald, 2001, 2016). We suggest here that the literature is somewhat ambiguous concerning the analysis of fractals in the architecture of FLLW. Some discrepancies will be discussed in subsequent sections.

Fractal dimension

Fractal dimension (FD) is one technique for determining a simple scalar measure of general attributes of fractals and can be easily determined for any irregular 2D shape using box-counting dimension and computers. Fractal dimension is one of the metrics used in relation to complex systems (Mitchell, 1996) and has widely been used to analyze architecture and urban design.

Urban Analysis

Environmental and socio-technical urban planning was identified as a problem of "organized complexity" by Jane Jacobs as a response to the new urbanist craze in New York between the 1930s and 1960s, “Why have cities not, long since, been identified, understood and treated as problems of organized complexity? If the people concerned with the life sciences were able to identify their difficult problems of organized complexity, why have people professionally concerned with cities not identified the kind of problem they had?” (Jacobs, 1961). Many since have taken up the yoke of identifying what makes our built environment healthy and vibrant, notably the prescient work of Christopher Alexander. Alexander describes a mathematical model of urban dynamics in, "Notes on the synthesis of Form" (Alexander, 1964) shortly after Jacobs publishes her seminal, "Death and Life of Great American Cities" Alexander later develops his work into a set of scalable design ingredients he terms a "pattern language" (Alexander, 1977) and more recently, 15 fundamental principles of design (Alexander, 2002) he asserts are aspects of beautiful architecture and urban design including the ideas that are closely associated with fractals although he does not usr the term "fractal." Alexander also implements his ideas in a variety of architectural and urban settings using real-world urban planning projects (Alexander, Neis, 1987).

Contemporary complex systems approaches are evident in the work of researchers across multiple disciplines. A notable architect engaged in analyzing the complexity of cities and their fractal geometries is Michael Batty (Batty, 2007). Batty has been associated with the Santa Fe Institute alongside physicists Geoffrey West and Luis Bettencourt who have also applied fractal theory to allometry and urban dynamics (West, 2005; Bettencourt, 2013). Others have used FD to research the growth of cities such as Sara Encarnacao et al., ‘Fractal Cartography of Urban Areas’ (Encarnacao, 2012) who discusses five types of urban environments in Lisbon Portugal based on their fractal dimension. The author has also researched the relation between FD and various attributes of cities and infrastructure, City Population Dynamics and Urban Transport Networks (Driscoll et al., 2013).

Architecture

As we mentioned in the introduction, architecture historians and critics are increasingly applying complexity and fractal theory to architecture. The juxtaposition of FLLW and Organic Architecture and the modernists is a common thread. Yannick Joye has linked complexity in architecture to nature, suggesting that a certain range of FD relates to our evolutionary development and the natural landscapes that were favorable to our survival and well being: 'Fractal Architecture Could Be Good for You' (Joye, 2007).

Individual buildings have been analyzed using fractal theory in recent decades with a focus on the work of FLLW. Bovill published a book titled, 'Fractal Geometry in Architecture and Design' in which he analyses two significant works by FLLW and Le Corbusier respectively using box counting dimension. In Bovill's analysis he concludes that the FLLW design has a higher FD generally than Corbusier's (Bovil, 1996). FD is used by Ostwald et al. to analyze five residential designs from three architects, Eileen Gray, Le Corbusier and FLLW. The average FD of the designs is 1.378, 1.481 and 1.543 respectively. Ostwald et al. suggests these results indicate that, "Gray's architecture is much less visually complex than Wright's. This supports the standard reading of the method arising from Bovill's work and it agrees with qualitative views of these architect's works recorded in architectural histories" (Ostwald et al.. 2008).

4.3 Hypothetical fractal algorithms in the work of Frank Lloyd Wright

As we touched on in Chapter 2, Eaton, Joye and separately Harris analyze the fractal characteristics of FLLW's Palmer House (Ann Arbor Michigan) but reach different conclusions (Eaton, 1998; Harris, 2012). We suggest that these differing views highlight ambiguities in the literature. When referencing Eaton's work and the use of fractals in FLLW's use of a unit system, Joye writes, "Initially, the geometry governing his architecture created with the aid of such modules remained Euclidean. In later works, however, these elements were sometimes so organized that they gave the building a remarkable fractal organization. The Palmer House seems to be the culmination point of this evolution. Here, one geometric module – an equilateral triangle – is repeated in the ground plan on no less than 7 different scales" (Joye, 2011).

We illustrate the 7 different-sized triangles in the Palmer House (Figure 4.3.1). Separately, Harris analyses the Palmer House and reaches a different conclusion regarding the fractal character of the design (Fig. 4.3.2). Harris interprets the design as a series of iterative operations that result in a fractal pattern. The fractal Harris presents is not entirely self-similar. This is an analysis more of FLLW's fractal process than the fractal patterns that resulted from that process and provides provocative insight into how FLLW conceived of the organizing principle which generates the form and pervades its character.

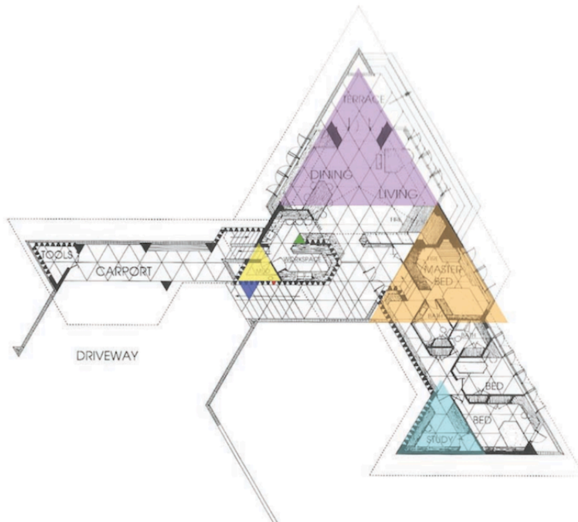


Figure 4.3.1. FLLW's Palmer House
(Wikimedia Commons, color added by author).

Figure 4.3.2. Three iterations of a self-similar pattern in FLLW's Palmer House at progressively smaller scales. (Harris, 2011).

FLLW designed on a repeating module – a unit system –on the ground plane as well as the vertical plane. We argue that the fractal qualities in FLLW's work are evident from the beginning of his career and are related to his idea of "breaking the box" which he discovered during the design of Unity Temple (Oak Park, Illinois). In the Palmer House, the unit system is an equilateral triangular grid which determines the placement of walls and other elements. This geometric underpinning by itself gives a certain unity to the overall design. The grid consists of small triangles that can be combined to be larger triangles as is true with any grid but this by itself is questionable in terms of defining the fractal character of the design. Harris' fractal process approach is more relevant to the broader literature about fractals and lends itself to more meaningful analysis. We assert that our definition of a fractal as – *patterns having multi-scale self-similarity as the result of an algorithmic process* – contributes to clarifying ambiguity surrounding the term fractal.

In terms of the discrepancy in the literature surrounding FLLW's Palmer House, James Walter Schildroth (JWS) points out that a simple re-scaling of shapes, as some have described as fractal, is not in fact the full meaning of fractals in architecture. Fractals are more significant than this and more embedded in a deep unity found in certain design strategies and throughout nature. JWS writes, "The unit is made with equilateral triangles. The plan is made by relating all parts of the plan as it is made to the unit system. The design is not made by repeating self-similar triangles. The unit system gives the whole unity. I think this unity approaches the unity in all of the natural world. What we call beauty" (personal communication, see Appendix, James Walter Schildroth, September 27, 2018, JWS.3). The deeper sense of what constitutes fractal architecture that JWS is addressing relates to the rich and multi-layered systems biological growth patterns and forms represent. Mathematical fractal signatures are found ubiquitously in nature as we have discussed. One might imagine D'Arcy Thompson's tome, "On Growth and Form" as an investigation into this idea. Organic Architecture is based on integrating with the natural order and as such, fractal geometry arises on its own accord. JWS writes, "Nature is fractal. Organic Architecture is *of* nature, not *applied*" (personal communication, see Appendix, James Walter Schildroth, September 27, 2018, JWS.13).

The challenge around a precise definition of fractals in architecture is an ongoing challenge. Thankfully, quantitative tools have been developed that allow for mathematical precision and analysis. These tools complement a qualitative assessment and, as we demonstrated in Chapter 3, can be used for producing meaningful fractal designs as well. We discuss next algorithmic techniques in architecture with regard to FLLW.

As we argue above, FLLW incorporated fractal geometry into his designs throughout his career. Much has been researched in the literature regarding the fractal aspect of FLLW's work (Bovil, 1996; Eaton, 1998; Joye, 2007, 2011; Ostwald, 2001, 2016). Other research has related FLLW's work to shape grammars. Koning and Eizenberg write, "The power of a grammar ... is that it establishes a recursive structure from which new designs can be constructed. Three new prairie houses generated by the grammar as well as a step-by-step generation of one of these designs ..." (Koning, Eizenberg, 1981). This method is an additive one where a vocabulary of shapes is used starting with a beginning form such as the hearth and building onto it with additional shapes based on some set of rules for their combinations.

Less is available in the literature, however, regarding the potential fractal algorithmic process FLLW used to establish the end result we see in the drawings and built work, although some analysis has been done in this vein (Harris, 2012). We discuss next a hypothetical algorithmic process that may underly the cascading self-similarity or *poetic unity* we see in many of FLLW's buildings and relate to his conception of parts and wholes.

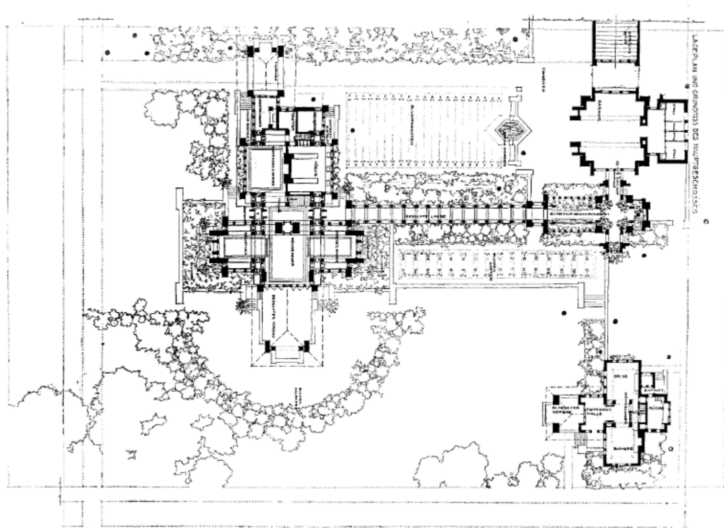


Fig. 4.3.3. Plan view of Darwin D. Martin House, FLLW Architect, Buffalo, NY, 1903 - 1905 (Public Domain).

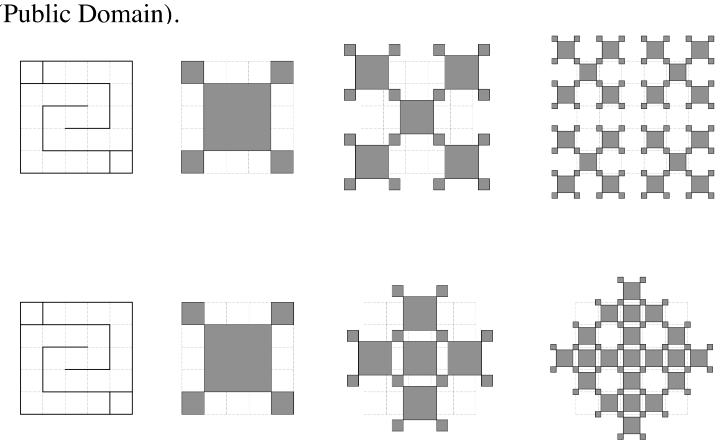


Fig. 4.3.4. FLLW's modular motif (to the left) interpreted as 2 potential iterative operations that use self-similarity and re-scaling to create geometries related conceptually to those in plan view of Martin House (image by author).

We focus specifically on FLLW's early career or Prairie Style as represented in the Martin House in Buffalo, NY (1903) (Fig. 4.3.3 and 4.3.7), although numerous examples could be chosen from throughout FLLW's work. Figure 4.3.4 shows two simple fractal algorithms that provide insight to FLLW's design for the Martin House. Indeed, much of Wright's Prairie style has a similar systematic and rule based feel. FLLW was practicing before the term "fractal" was coined but he describes a similar concepts using his own language including his use of the term 'organic' which is tied to the idea that the whole is contained in the part and vice versa. This is similar to the cosmology we discussed in terms of Vaastu temples in section 2.3.1. "We've been fighting from the beginning for Organic Architecture. That is. architecture where the whole is to the part as the part is to the whole, and where the nature of materials, the nature of the purpose, the nature of the entire performance becomes a necessity – architecture of democracy" (Frank Lloyd Wright, New York Times, 1953).

A systematic analysis of fractal algorithms in FLLW's work has yet to be done and is beyond the scope of this dissertation. This process creates a complex result yet stems from a simple process that is reflected in the organization of the finished work. The systematic feel of the finished work is evident in every detail of the building and in the overall complex – like an organizational field (Fig. 4.3.7) where the idea pervades every element within a design, from the smallest tea spoon to the organization of the main blocks of the building as represented by the roof forms.

Distinct levels are evident in the fractal organization of the plan as well as in the three dimensional conception of the building. Indeed, it is necessary to understand the vertical expression of the algorithm to see how the fractal concept unfolds and expands. The fin-

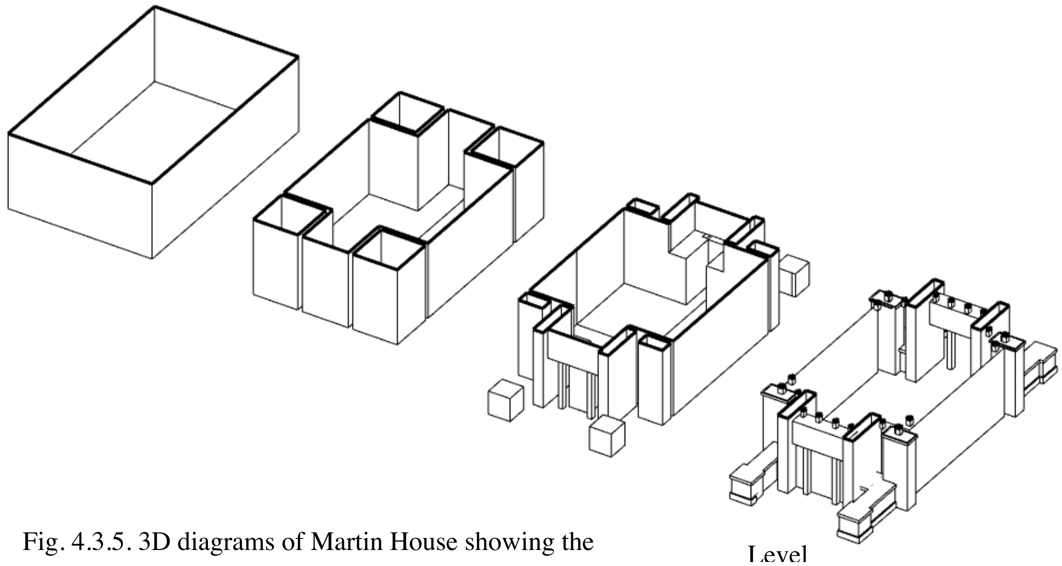


Fig. 4.3.5. 3D diagrams of Martin House showing the vertical interpretation of the fractal algorithm (by author).

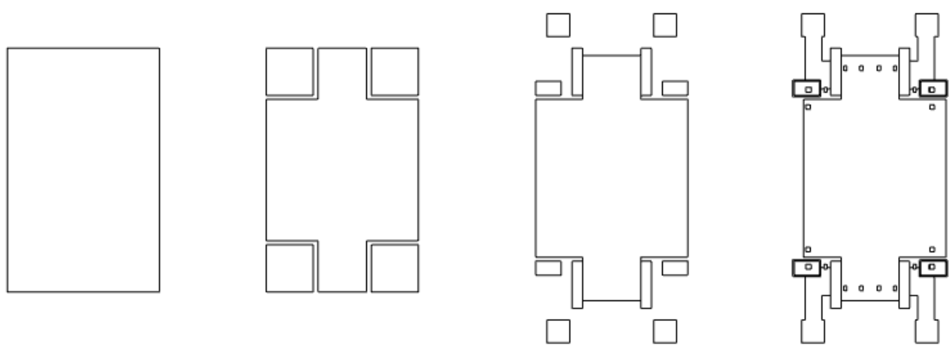


Fig. 4.3.6. 2D interpretation of Martin house as a simple iterative idea (by author).

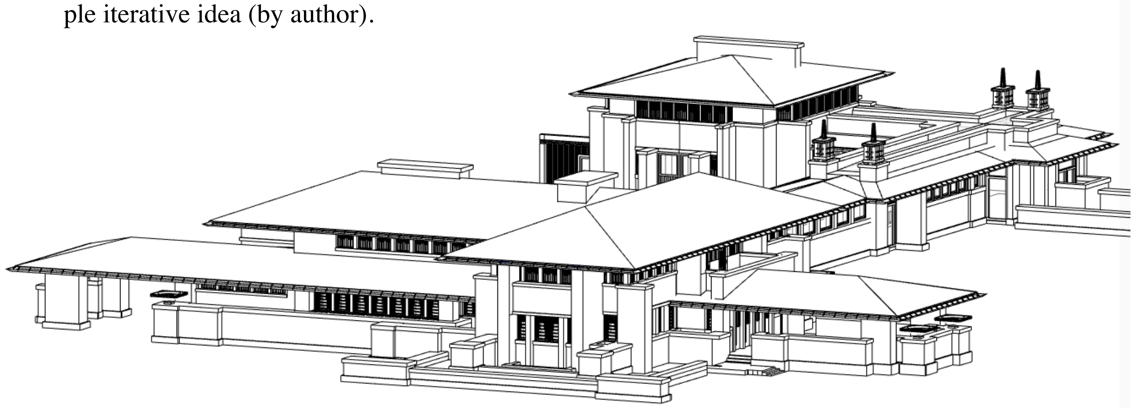


Fig. 4.3.7. Darwin D. Martin House, FLLW Architect, Buffalo, NY, 1903 - 1905 (Razin Khan SketchUp model).

ished design is the result of at least four iterations in a simple algorithm that begins with a solid block and iteratively carves it away 'breaking the box' as FLLW described it. The potential number of levels where the motif occurs within the building are illustrated in Figure 4.3.5 and 4.3.6, from left to right: at the individual building block level, as denoted by each roof form (see Fig. 4.3.7), the corners of the building at level 2, the individual masses at level 3 and down to the columns /window muntins at level 4. If we were to consider the entire architectural enterprise we could potentially have up to 10 levels of self-similarity. These are, from smallest to largest,

1. Texture
2. Brick/ masonry unit. (Usonian automatic)
3. Masses: shape of mullion/column/ mass element (hearth)
4. Collection of masses into a small ensemble
5. Rooms (larger ensemble)
6. Building: collection of rooms
7. Complex: collection of buildings
8. Site plan: building, landscaping, boundary shape.
9. Relationship of sites. Circles, hexagons, rectangles, triangles, etc.
10. Transportation plan, landscape plan, urban plan (Broadacre City).

We do not suggest the algorithm we present here was intentional or represents the design process of FLLW. But designing on a unit system where the "whole is reflected in the part" ethos and inspiration from nature may result in fractal patterns and processes similar to what we suggest. Undoubtedly, FLLW's actual process is more complex and obtuse than what we present here. James Schildroth writes, "All Mr. Wright's work was done on a unit system. The unit system is about unity and develops patterns by the relationship of thousands of choices that each relate to the unit. The result of working like this may produce fractals" (personal communication, see Appendix, James Schildroth, May 20, 2019, JS.1).

Looking at the form patterns of the Martin House it is apparent that some systematic organizing principle pervades the whole and has an algorithmic or rule based feel to it. This type of design is markedly different than just a free form exploration of an idea. We suggest the final design is the end product of a recursive *breaking apart* of the masses of the building, i.e., from generals to particulars. An actual tree in nature, such as an oak tree, offers an analogy where the entire iterative history is represented. Working backwards, the leaf canopy represents the final instance and prior residual instances remain in the sub-branches, ... , branches and trunk. In FLLW's architecture, we only see the final instance (leaf canopy), we don't see the steps along the way.

4.4 Dean Bryant Vollendorf, Search to Saguaro

Many of Frank Lloyd Wright's apprentices and acolytes have continued the design philosophy he espoused. The architect and professor Bruce Goff (1904 – 1982) was a significant adherent of FLLW's organic philosophy of architecture and influenced many students during his tenure at the University of Oklahoma from 1942 until 1955. Dean Bryant

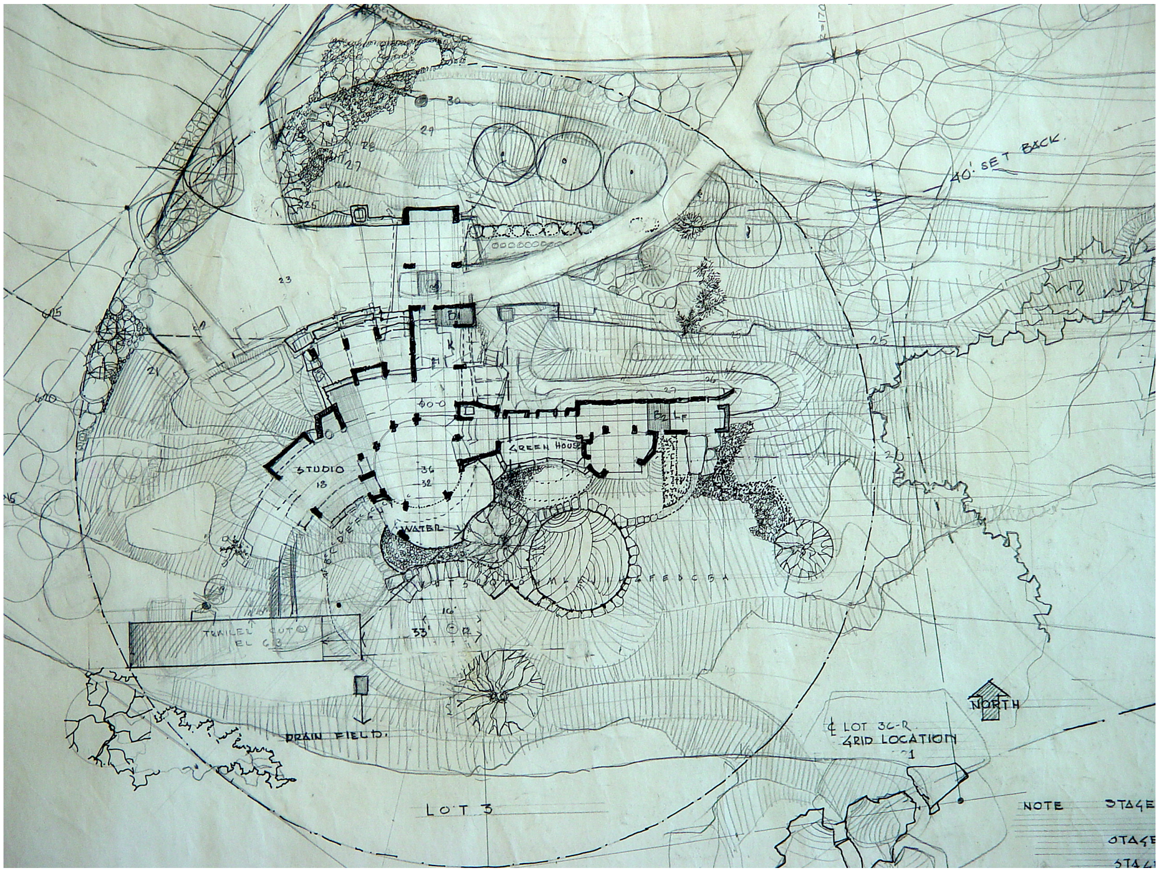


Fig. 4.4.1. Plan view of Search. Dean Bryant Vollendorf architect, 1976 (used by permission).

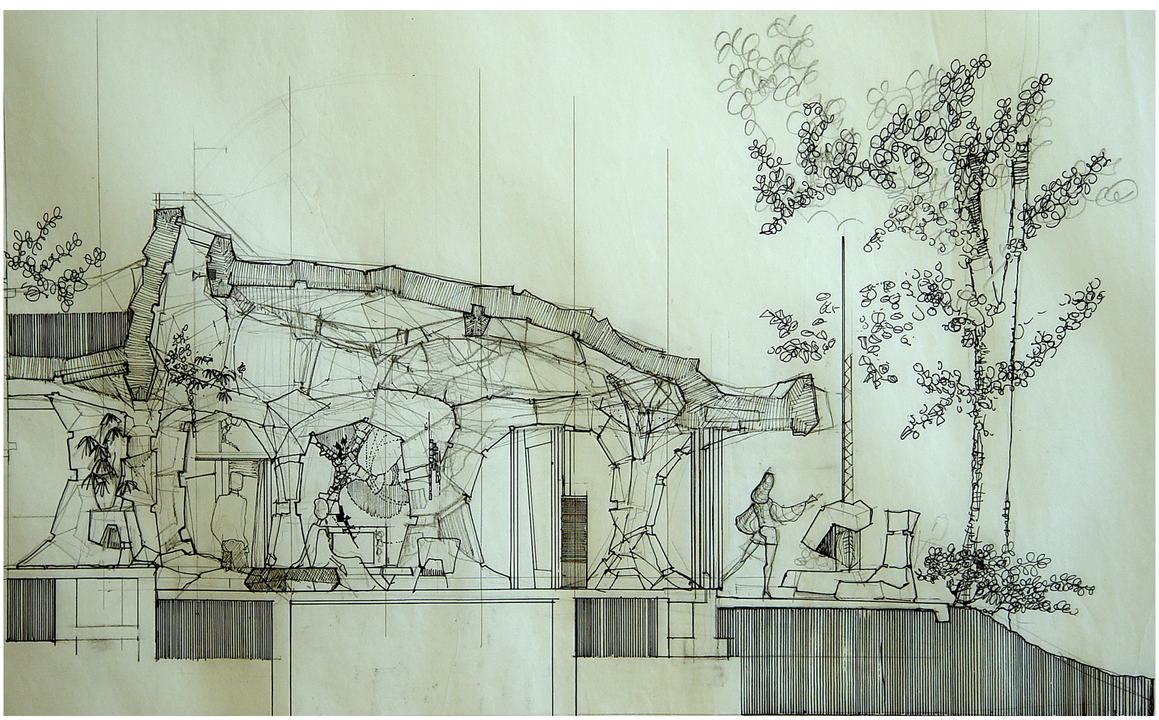


Fig. 4.4.2. Section view of Search. Dean Bryant Vollendorf architect, 1976 (used by permission).

Vollendorf (DBV) (1929 – 2008) was influenced by FLLW and Goff, having been born and raised in Sheboygan, Wisconsin in 1929 surrounded by the work of Mr. Wright and later spending significant time designing and teaching in Norman, Oklahoma within Goff's still vibrant orbit. DBV also apprenticed for and later headed up the Florida firm of the prominent architect John Randal McDonald who is often compared to FLLW and worked within his dictums. DBV eventually settled in the Carolinas and became an important hub for Organic Architecture there designing and teaching many students beginning in 1971 and influencing such architects as Jim Fox, Gary McCowan and Stan Russell and the case study project we present in Chapter 3. DBV is best known for his extensive body of bold renderings and meticulously detailed drawings. DBV's architectural work ranged from prefabricated homes to signature free-form concrete structures that show him moving beyond FLLW and Goff to develop his own unique and original approach to design we describe at length in terms of its unique example of fractals in architecture. DBV's work highlights key aspects of our thesis. Selected projects which show a progression towards a comprehensive language of form applied to different "performance needs" and at multiple scales is discussed below and presented in, 6.0 Plates of this dissertation. Selected drawings are shown and discussed in this section as well.

We explore the development of DBV's design methodology over a 20 year period with two outstanding residential projects, Search and Saguaro designed for Concord, NC and Arizona respectively. What is often described as a fractured or convoluted quality of fractals is clearly expressed in the details as well as the overall form of these two projects, so much so in fact, that the drawings themselves become a vital expression of the idea. This is evident in the extension of the idea into the landscape as well as the rendering technique itself – DBV's singular *hand*. Figure 4.4.1 shows a vignette of the main floor plan view of Search. Many aspects of Organic Architecture relating to fractals are demarcated in this drawing with a clear relationship to self-similarity over multiple scales. DBV referred to this idea in terms of *theme*, *development* and *variation* which we suggest is tied to fractal theory applied to architecture. We see at once that the design is on a unit system but one based on a radial composition of circles that seem to warp the 4'-0" X 4'-0" grid. This concept is the organizational strategy for the design or its *theme*. The circular form is repeated in the curvilinear masses of the building representing *development*. The main building material is light weight structural concrete (cellular concrete) which is composed into triangular and trapezoidal forms. From these more or less orthogonal elements the curved shapes of the overall building masses are created. The interplay between the inherent geometric concepts is similar to the creation of a cosmological system we discussed in Chapter 1, section 1.3.1 and in Chapter 3, section 3.5, i.e., creating a circle out of rectangular shapes. As we zoom in to the elements we see they are fragmented and reveal detail at ever finer levels relative to the theme. This creates a unified whole from asymmetric parts – a sense of balance within a dynamic composition. This results in many exploratory idiosyncratic decisions and unique events within a common framework– representing *variations* on the theme (Fig. 4.4.2).

The parti for the plan is a cruciform similar to many of FLLW's designs such as the Martin House discussed above but with literally a twist. The cruciform plan includes expanding radial elements based on the circular theme. As we zoom out we notice that the overall lot is circular in form and the adjacent lots are also circular. This is the theme carried into the larger environment representing an integrated self-similar formal vocabulary at a number of different scale levels. In the section drawing we see these ideas represented in the vertical dimension (Figure 4.4.2) where we can see the formal vocabulary represented in furniture and landscape elements as well.

Saguaro

DBV continued to work on the theme for Search for roughly 20 more years, developing it in different projects which culminated with his opus design for Saguaro which was a development and variation on Search but now in the Arizona desert. The drawings for Saguaro (Figures. 4.4.3 - 4.4.5) show a building form with a similar plan as the original Search but with less emphasis on the circle as a theme. The circle is still evident but has

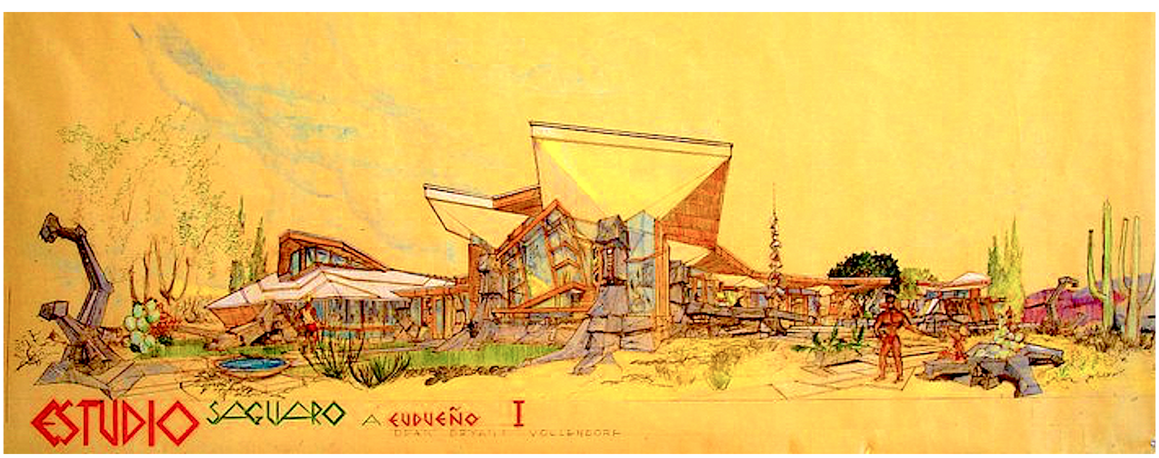


Fig. 4.4.3. Exterior perspective view of Saguaro. Dean Bryant Vollendorf architect, 1995 (used by permission).

become a counter point or relief to the main idea which could be described as a "jagged and convoluted" fractal motif that repeats in a variety of ways and at different scales and is reflected in different aspects of the building. The *theme, development* and *variation* design approach is alive in the playful shapes that define the vocabulary of forms. The theme re-occurs at two levels, 1. the level of the masses poched in plan and 2. the overall form of the building. The Search vocabulary has been significantly developed over DBV's career and can be expressed in a variety of geometric types, embracing with ease the rectangular grid as well as the radial grid and becoming a triangular piece as well – arming off to the side as a studio and car port and creating moments of symmetric balance with the opposite acute angle of the living room. Such symmetries co-exist and stabilize an otherwise incredibly dynamic plan. DBV almost inverts the old trope and has *function follow the form* in this design, representing a masterful use of his vocabulary and prepositional logic. Linguistic analogies were often used by DBV to describe his methodology such as "vocabulary," "metaphor" and "preposition." The idea of "preposition" was the many varied ways a form or space could grow or how one might move through and experience architecture, i.e., to, by, for, under, over, at, etc. The building is a "metaphor" for the design system that undergirds it. This is similar to what we have discussed in terms of FLLW and the use of a unit system and fractal algorithms but here it is more the style of the elements and the rules for how they grow and combine and transform, literally reaching out into the landscape and extending the idea of the building like a field of energy that transforms everything it touches. This is a full expression of the term, "generator."

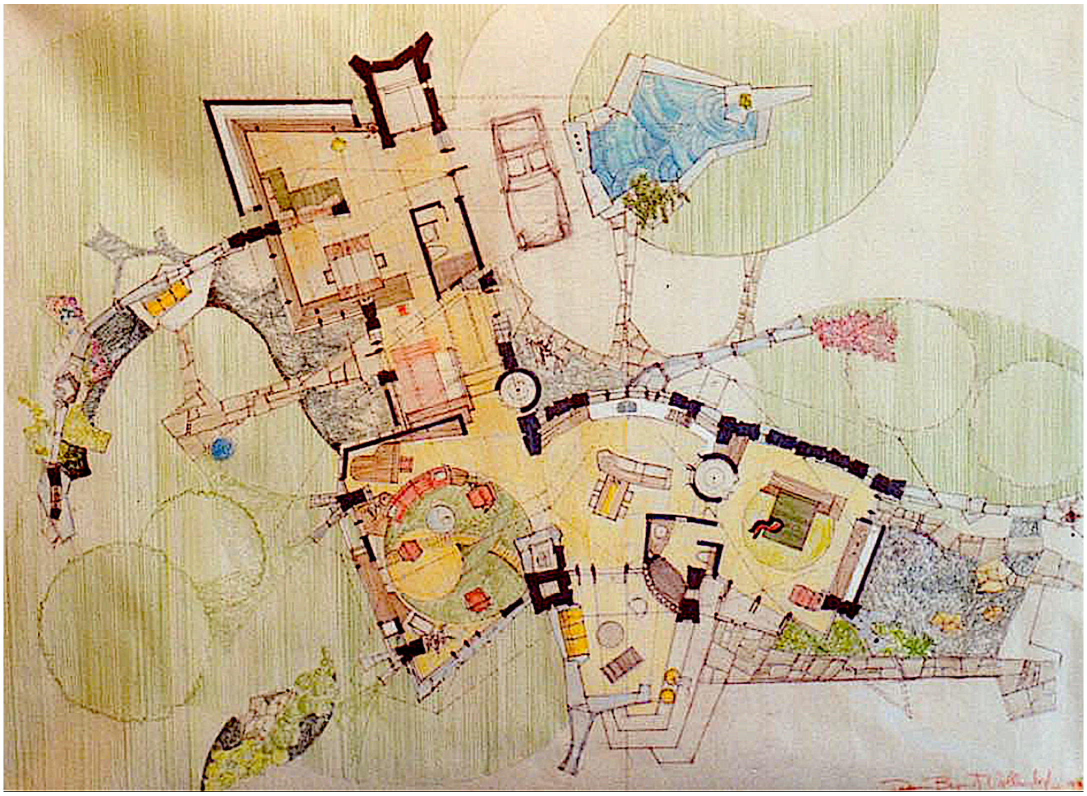


Figure 4.4.4. Saguaro plan view. Dean Bryant Vollendorf architect, 1995 (used by permission).

Fig. 4.4.5. Interior perspective view of Saguaro. Dean Bryant Vollendorf architect, 1995 (used by permission).

DBV often said that the first job of the architect was to define the problem to be solved. To continue the linguistic analogy, it is as if the problem DBV was engaged in was the invention of a meta-language or meta-morphological language, one with the ability to adapt to different grammars, i.e., formal conditions. It is as if the building is speaking different languages to describe one idea that permeates every aspect of the project. This is evident especially in the drawings and renderings DBV produced which are much more than construction documents but works of architecture in themselves. The hand of the draftsman is completely integrated with the conception of the form. For instance, looking closely at Figure 4.4.5, it is hard not to get lost in the space and form the drawing creates – almost as if it were a real space. The act of drawing in this sense becomes experiential (one may imagine).

4.5 Case study

Next we present an analysis of the fractal algorithm we developed in Chapter 3 and used in the case study project. This project we present here is an instantiation of the fractal algorithmic process we have discussed above.

The case study project was a large scale project that was designed as a response to a request for proposals by the City of Ithaca in the Spring of 2018. The program and site represent a complex design agenda, the details of which we will not discuss due to space constraints (see Chapter 3, section 3.3.6.2). The Figures 4.5.1, 4.5.2 and 4.5.3 explain the organizing principle graphically. We will describe this project in terms of the fractal algorithmic process we discussed in relation to the design process of FLLW and DBV in the previous sections.

In Chapter 3 we described DBVgen which is a computer-based algorithmic tool using the Vollendorf Method in combination with a genetic algorithm and fractal dimension we developed for this project. We use the DBVgen tool in combination with a designer in a cybernetic design process within a schematic phase of design. At later phases, the cybernetic design process is fit into the design of the building at large but no longer with the aid of a computer in a generative role. The designer at this later stage is continuing the fractal algorithmic approach into additional components of the project. We focused on three main levels in terms of the aesthetic form and space of the building. These levels were distinct scale levels. The three levels from smallest to largest are termed, *micro, mezzo* and *macro* (Fig. 4.5.1, 4.5.2, 4.5.3). After meditating on the program and site conditions for this project over several months, we began by designing the micro unit (masonry block). The module we chose was 8" x 8" which is an increment of 2' x 2' which was the secondary block type occurring at the base of the building creating a sense of "pixelation" as the building touched the ground plane. This module became the architectural motif for this project (Fig.4.5.1). An architectural motif in this sense is a visual idea that is scale-free and can apply to a range of functions and aspects of a design. We next scaled the motif up to inform the mezzo and macro scales within a – *theme –> development –> variation* – approach (Fig. 4.5.2, 4.5.3). The part is reflected in the whole and vice vera within a dynamic composition where the theme is expressed in the parts as well as in the ensem-

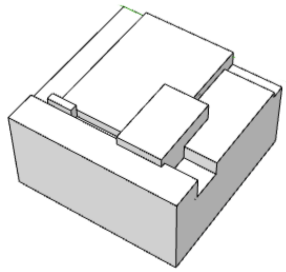


Fig. 4.5.1. Micro level: unit masonry block module used for the design (image by author).

Fig. 4.5.2. Mezzo level of detail where space and form become architectonic. This vignette shows a part of the pavilion to the right and the entrance to Herald Square to the left (image by author).

ble, from top to bottom so to speak. The last images (Fig. 4.5.4, 4.5.5) show two of the presentation renderings that were done for the final presentation, Pin-up #3, and represent the state of the project we achieved and considered appropriate as a formal response to the RFP. As such, this represents a real-world instantiation of the cybernetic design process developed in Chapter 3 and extended in the case study with regard to significant and related architectural precedent in the work of FLLW and DBV. In this way the project is a continuation of the Organic Architecture agenda using state of the art computational mechanics.

Fig. 4.5.4. Exterior perspective looking east (Rendering by Goff Machline and Razin Khan).

Fig. 4.5.5. Exterior perspective looking west (Rendering by Goff Machline and Razin Khan).

4.6 Summary

In this chapter we presented a fractal theory as an alternate critical tool for assessing the work of FLLW and DBV, and show how this relates to our own work in Chapter 3. We position fractal theory as central to the understanding of these works. The fractal theory we present touches on the algorithmic nature of *process* over a simple analysis of fractal *patterns*. We do not argue that this theory is complete or that it reflects the intention of the designer of the work yet we argue it is an important contribution to the understanding of Organic Architecture and architecture generally.

We asserted that the notion that fractal theory is potentially a way of chunking or compressing information so that a very complex object may be visualized before "pencil ever touches paper." This approach may be understood as an iteration of the idea from a general wholistic view to a particular instantiation much like music from the Baroque era. We discuss this more in section 5.3.1 in Chapter 5.

FLLW himself did not have the language we now associate around these concepts but he does tantalizingly suggest it when he writes of part to whole relations or the overarching method he espouses, "from generals to particulars." Speaking of Sullivan, FLLW writes, "“Think in Simples” as my old master used to say—meaning to reduce the whole to its parts in simplest terms, getting back to first principles. Do this in order to proceed from generals to particulars and never confuse or confound them or yourself be confounded by them." (FLLW, 1931). We offered a clear example of this idea incorporating three levels of self-similarity in a case study project and show that a a complex design may be visualized as a simple process that gradually becomes articulated through repeating operations relative to fractal theory.

We also provided significant insight into the design methodology of DBV's work over a 20 year theme-development-variation approach. We described this in terms of a formal language that is used to solve a variety of architectural problems at multiple scales and with regard to an overarching idea that is imbedded in all aspects of the design process including the act of drawing.

DBV's methodology described both in the Vollendorf Method as well as through his work and mentoring have influenced our design approach to a large degree. The project we present in the case study is an example of our interpretation of both FLLW and DBV's work as significant precedent we draw from in developing the cybernetic design process we use as well as the fractal algorithmic organizing principle we employ in the larger design process and have been discussed extensively.

Fractal algorithmic design

An important contribution of this dissertation is to help clarify the definition of the term "fractal" as it applies to architecture and design. We have unpacked the notion of "fractals" in architecture as having two main interpretations – one is as a self-similar and scale invariant *pattern* and the other is as a *process* or recursive procedure that defines the fractal pattern – the former is an instantiation of the latter. One is a physical object, the other is a set of rules applied over and over again. In architecture the rules can be somewhat ambiguous or a part of the deep creative intuition of the designer.

In Organic Architecture, a fractal is more than a scale invariant and self-similar geometric pattern. A fractal approach uses a *generator* which acts as an organizing principle that may result in many geometric expressions within an over-arching motif or vocabulary of form as appears to be the case in the work of FLLW and DBV. For instance, a fractal organizing principle may be used by a designer to explore *theme, development and variation regarding* at many scales and in many design instances.

In our case study project, we found the use of a fractal organizing principle when combined with fractal dimension to be an effective design strategy when applied to a real-world project. The method we developed was found to be a flexible strategy to respond to the complexity the problem presented. This method solved for the functional aspects of the program in the RFP as well as created a formal/spatial vocabulary that was provocative and visually rich as verified through formal critique. The critique part of the design process consisted of a panel of registered architects acting as jurors within a formal academic IRB framework.

The fractal algorithm was a generator of form, approaching what DBV describes as "code." (See Figure 3.2.3) The term "code" is loaded with a multiplicity of meanings, such as the *design code* as well as the *computer code*. These realms have significant overlap which is highlighted here and represents a contribution of this dissertation and helps bridge the gap between computer science and architectural design.

The overlap involves how an algorithmic process relates to both the fractal design process and the many design outputs (individual design solutions) as well as the repeating procedures ubiquitous in computer languages. The fractal aspect of the physical architecture speaks to its its design process which in turn is an extension of the computer architecture. The building is simultaneously a representation of its code on a symbolic level and the output of that code on a physical level. The extension may be a number of types. One class of extensions are as literal additions to the building (potentially) or the way the building influences other architects and the buildings they design. Another class of extensions may be as extending the building *conceptually* in one's mind's eye as a continuing formal idea or *virtually* in a digital space of some kind. This idea is elaborated on in the next chapter.

End of Chapter 4

5.0 Synthesis and conclusion

"Science would be ruined if it were to withdraw entirely into narrowly defined specialties. The rare scholars who are Wanderers-by-choice are essential to the intellectual welfare of the settled disciplines." Benoit Mandelbrot

5.0 Introduction

This chapter presents the main findings and synthesis for the dissertation. We discuss the relevance to the design profession of this work and key findings and contributions. In addition, we begin here to re-embed our findings into fractal theory and discuss our work in terms of a new critical methodology. We briefly reprise key limitations and strengths as well as discuss how we attempted to ameliorate areas of concern.

5.0.1 Vignette of Chapter 5

We offer here a vignette of this chapter before we begin discussing specific findings and contributions. Our general approach was intentionally trans-disciplinary and borrowed from a variety of specialties. Because of the broad nature of the topic we chose a systems theoretic framework which offered tools we could adapt to our purposes and use to bridge across silos with a common model and common language. In the most general sense, we borrowed from fractal theory to develop a design process that drew from and informed the relationships between three main regimes: nature <–> architecture <–> computer science. The architecture aspect is our focus with relevance to architecture design and urban design/planning and critical methods. The computer-based aspect of the design process we developed we refer to as the *DBVgen tool*. Our tool has relevance to architecture along two main branches – the analytic and the generative. We further explored the generative capacities of our design process in two ways. One was using the fractal dimension of a design as criteria for qualitative assessment. This is discussed in section 5.1 of this chapter. The second aspect of the generative capacities of our design process was to develop a fractal organizing principle as the basis for a unifying theme for the case study project. This is discussed in section 5.2 of this chapter. In section 5.3 we discuss the implications for our approach in terms of a critical methodology framing a research agenda and next steps in this research. With regard to the *wandering-by-choice* methodology we adopted, our findings have some relevance outside of our specific focus on architecture and design. This more general material is sprinkled throughout but discussed mainly in section 5.4 of this chapter.

5.0.2 Brief description of DBVgen tool.

Following a systems theoretic approach, we looked for a tool that could bridge across disciplines. Fractals offered such an approach and grounded our work within a broader context of systems theory and complexity science. We developed a design process which integrated a generative fractal based computer tool within a designer-centric charette. We considered the design process at three levels. Level 3 was a a traditional design process as is the industry standard. Level 2 zoomed in on the schematic phase of level 3, and inserted a generative algorithm tool to interact back-and-forth with a designer. Level 1 involved the design of the tool and programming of the plug-in and user interface.

The DBVgen tool comprised a parameterized genetic algorithm (GA) with fractal dimension (FD) as the fitness criterion. The algorithm used a unique implementation of the Vollendorf method to generate basic 2D compositions which were extruded randomly and modified by the designer for the first phase of the project – pin-up #1. Next we closed the loop so that the designer's modifications could be fed back into the GA for additional evolutions for pin-up #2. For both Pin-up #1 and Pin-up #2 a panel of 9 architects acted as jurors in a critique phase. The critiques consisted of an interview style dialogue with the author/designer both in person and through email as well as other social media tools. Final presentation renderings and a project description were produced for Pin-up #3 and presented publicly for the oral defense of this dissertation.

5.1 Design Process level 1

The following sections describe the design process at level 1, the development of the DBVgen tool and the tool's usefulness in the design process and challenges it presented and how they were ameliorated.

5.1.1 FD as a metric

The main focus of Pin-up #1 was the exploration of FD in a context of design. FD was explored as a generative tool which produced novelty that was the impetus for further exploration by the author/designer. We found this aspect of the design process to be effective and positively received by the jury as discussed below. FD itself as a stand alone metric to assess the complexity of a design was not conclusive as discussed in section 5.1.1.2.

5.1.1.1 Merit as generative tool

The design process we developed and the proof-of-concept and case study project it was applied to made progress towards integrating computer technology in a substantial way within the architect's purview. This was an important goal of the dissertation. FD as a component incorporated into a larger design system including the fitting and modifications by the author/designer was successful. The ability to modify the algorithm and to work back and forth between automated tasks and actively designing in a 3D modeling environment was compelling in terms of feedback from the jury. The computer allowed for a quantitative assessment of FD that was more-or-less simultaneous with the creative aspect of the process. This kind of informed investigation would not have been possible before computer technology. The DBVgen tool was flexible enough to include functionalities that were project specific such as matching FD of adjacent buildings and specific dimensions of building components. Adjacent buildings were only measured for FD in 2D which was a limitation. A 3D FD implementation of the tool was beyond the scope of this dissertation and represents a next step. Other functionalities that were not explored and represent next steps are the ability to incorporate within the algorithm more unique details of the program and context, for instance, circulation patterns, room adjacencies, natural features such as sun angles and proximity to riparian corridors as well as certain angles or geometries relating to the site and context and so on. Some of these potentials were discussed by the jury and included in Appendix, comments.

A general contribution of this dissertation was in developing a proof-of-concept example of the analytic and generative capacity of fractals within a schematic design phase of a traditional architectural design process. This approach was shown to inspire investigations by the author/designer into novel modes of problem solving and integration and was provocative to the jury as well. For instance, much architecture has detail at many levels but what is explored in our approach is the degree of integration of the details within an overarching organizing principle that is quantifiable as well as integrated within the software used for its generation and documentation. We establish the integration of the organizing principle by using a design process incorporating a fractal algorithmic approach as well as by using fractal dimension to establish a consistent level of detail at three different general scale levels within the deisgn. Essentially we are internalizing the design of the DBVgen tool into the overall design problem relative to a unique project and within the designer's purview. The unique aspect of architectural problems was discussed repeatedly by jurors. In response to this, we offered a standardizable design process with quantitative assessment metrics using FD that is also customizable for a given project. We also demonstrate how a computer-based-tool can be designed with a clear relationship to a unique and project specific organizational principle for a unique program and site. This was considered a contribution to the design profession.

5.1.1.2 Fractal dimension as indicator of "good" design

Our findings indicated that fractal dimension was inconclusive in terms of producing good designs or to compare and contrast the merits of different designs. We found that compositions DBVgen produced that were considered good by the designer and jury tended to have a higher FD: good –> higher FD, but higher FD did not necessarily indicate good designs: higher FD –> good/not good. Designs we and the jury found compelling tended to have a FD of 1.5 and above generally represented more desirable compositions in terms of figure ground relationships and dynamic motion of the eye. However, results were inconclusive in terms of a specific number or "sweet spot" where FD was unquestionably creating interest. At this stage, this work represents a successful prototype incorporating FD within a larger architecture and design framework. More work remains to be done to develop the DBVgen tool.

Perhaps surprisingly, different fractals may have the same FD value. We intentionally discuss FD in terms of complexity and levels of detail, although we explore the relationship between FD and fractal organizational principles in later chapters. The compositions we presented are orthogonal line compositions that do not have the appearance of standard fractal shapes. The tool we implemented did not create visually apparent self-similar geometries. FD was used in an attempt to establish more visually compelling compositions by introducing figure-ground interest through a range of objects and empty space. To use an analogy with music, FD was, in a sense, used as a rhythm or time signature in the compositions which organized the form at various scales according to a common unifying FD metric. It should be emphasized, however, that if a form is fractal, FD is a useful metric and has useful theoretical and practical applications.

In terms of the proof-of-concept "toy" project presented for Pin-up #1, jurors generally did not think the outcome represented a fractal organizing principle per se or was a physical instantiation of the cybernetic process behind the outcomes. Some jurors were intrigued by the possibility of fractal geometry being a method of form generation but were not satisfied that the design work represented a successful prototype. Pin-up #2 was a more compelling proof-of-concept application.

For the reasons outlined above, a significant conclusion of this study was that FD alone is not a sufficient metric for generating designs on its own but must be incorporated within a larger context of design. Following this conclusion, it is further observed that FD is not sufficient alone in analyzing the fractal algorithms that may or may not be the historical basis for a design. For this reason, this dissertation introduced a design process and methodology for incorporating FD as a part of a larger enterprise which has the potential to include fractal organizing principles in the design. Such an organizing principle could represent a scale-invariant geometric module or non-linear unit system of sorts. This potential of the algorithm we developed is explored more in depth in section 5.2.

5.1.1.3 Challenges with FD

This section discusses the limitations we encountered with the design and development of the algorithm and its implementation in a creative designer-centric process. We then provide a discussion on the somewhat paradoxical challenge of being both the author and designer in this study. Miscellaneous other challenges are also discussed in this section.

Another significant issue involving FD for Pin-up #2 was that the author/designer fitting had a tendency to lower the FD of the original algorithmically produced composition. This was noticed during the extrusion and fitting required to design the masonry block which was used as a geometric module for the entire project. The subsequent design then had a lower FD at the micro scale (1.267) than at the mezzo (1.477) and macro scale (1.589) (see Table 3.3.7.4). This was not the intention of the designer and a more uniform FD may have produced a more integrated final design. The time constraints for this dissertation did not allow for additional design charettes.

Challenges with implementing the algorithm in a designer-centric traditional architecture process were as follows. Architects often work out design problems in their head or on paper or the proverbial napkin sketch. It would be desirable if they could do this and in real time have such work assessed for FD. This may significantly improve an architect's ability to create self-similar form over a variety of scales. For instance, perhaps a fractal organizing principle could incorporate a larger range of scales. Developing the tool further along these lines is beyond the scope of the current work however.

5.1.1.4 Validation of model

We began this project with a NetLogo model designed to measure 2D objects for FD with box-counting dimension. Interpreting this model in Python and as a plug-in for SketchUp in Ruby required working with a colleague who had the programing skill these tasks required. The software required optimization to run the GA effectively over many generations which was beyond the skill set of the author/designer. To validate the model we tested it against the FD of the Koch curve and were within .03804 which was considered acceptable. We also shared the code within our committee. We also plan on releasing the plug-in to the public at some point in the future.

5.1.1.5 Artifacts as Serendipity

Dean Bryant Vollendorf referred to the computer as a wet medium, meaning that the tool itself represented an opportunity for "happy accidents" to inform and inspire the creative process. We found, to a degree, that the artifacts produced by the algorithm could aid in the exploration of novel spaces and forms and away from preconceived and entrenched solutions. For instance, the 3D extrusions outputted by the DBVgen tool were sometimes missing sides and had incorrect overlaps. This led to thinking about turning the design around and looking at it from another angle which is how the pavilion project in Pin-up #1 was designed.

This is a compelling reason why incorporating the computer tool within the design process and within the purview of a designer is intriguing. Errors, such as outputting the form upside down, are potential sources for novelty when incorporated into the creative process of a designer and could even become part of the organizing principle for a design. In this light, the technology explored here is more than an instrument or mere "tool" as we have been describing it. The human-machine model represents a more integrated design process or *design system* in this sense.

The cybernetic aspect of our research is not new but represents an additional step toward a human/machine design system. Its success here furthers a the development of a design process that aims to retain the human designer in a position where the skill and creativity of that role is enhanced by powerful computational tools that open doors to new forms and technical solutions. This small step has potential significance for human/machine interfaces as well as the advancement of hybrid systems as synergetic problem solvers.

5.1.2 Author as both researcher and designer

This section discusses the somewhat conflicted challenge of being both the author and subject of this experiment. In terms of the wide scope and sheer amount of work involved, it was considered appropriate at this stage to dovetail the author's experience in architecture and design into a more comprehensive agenda to simplify matters. As mentioned above, it is intended that the DBVgen tool we developed for SketchUp could be shared with the design community at some point and research could be done on how other designers might interpret our approach and use it to create novel design solutions that undoubtedly would be different than what we came up with. We hope some data gathering functionality can be built into the tool that could aid in analyzing its use in the larger design community. For now this was considered outside the scope of this research.

We expect this dissertation will be significant within computer science and AI as a milestone of sorts for how this author/designer collaborated with machine learning algorithms at this particular juncture in time. Specifically, we assert that this dissertation represents a significant exploration of fractal theory as it is currently understood and its novel application in architecture design.

This dissertation as a detailed description of process and product as well as detailed feedback from practitioners in the field may be useful in the future. We offer a suggested direction as well as raw data that may be valuable in some unpredictable way. Our hope is that the document may be considered a reflection of how socio-techno systems were understood, critiqued and applied as a nascent hybrid platform from a design perspective. In this way, valuable aspects of architecture and design may be preserved through a potentially radical paradigm shift away from human-centric control.

5.1.2.1 Challenges

As mentioned, the form of this study required the author to participate in the study in a creative capacity. This was a distinctly separate task from that of researcher – the proverbial right brain / left brain dichotomy. Being the author *and* designer were different roles. The author role required evaluating the design process and designs it produced objectively while participating in that process in a creative capacity. We moderated this by keeping both roles separate and clearly distinct. This was done by focusing on the design aspects only for the pin-ups and analyzing the process and product after the design phase was complete. We also relied on the jury to provide objective analysis which mitigated the designer biases, personal preferences and stylistic choices. This was unavoidable though and there is no doubt that a degree of personal preference colors this work. Jurors' feedback reflected this issue.

5.1.3 Juried critique

In this section we present a description of the juried critique phase of the design process we developed for this dissertation. The critique phase attempted to follow a traditional critique by a jury of architects within a formal scientific study. A formalized review phase allowed for jurors' comments to be published as part of this dissertation and for jurors' contributions to be recognized. We made rigorous the juried critique aspect of the process by formally engaging in an internal review board (IRB) protocol within the strict guidelines of a scientific study involving human subjects. The materials generated for the IRB were made available to jurors via Dropbox. The general structure of the critique is discussed next with caveats that deviate from a traditional architectural review explained.

The critique was asynchronous and non-local meaning that we relied on a questionnaire and e-mail interviews with this author in the form of a months-long dialogue. Social media was used to make personal connections with jurors. A website with all pin-up materials was provided at "johncdriscoll.com." An archive on Dropbox was available for jurors' to learn more about the project. This was especially important for the case study which entailed a real architectural project with extensive background for the project provided to jurors including the official Request for Proposals (RFP) issued by the City of Ithaca, NY.

Jurors were required to be licensed architects. Nine jurors chose to participate from a pool of fifteen. The jurors were asked to make critical comments and suggestions in regard to the project presentation. Comments were answers to a questionnaire, plus interview-style "back and forth" dialogue with the author.

Neither a background in algorithmic design nor an understanding of the particular algorithm was considered necessary. The intention was that the project model and drawings represent a real building and as such are provocative artifacts of the process and might speak to the method of their development.

5.1.3.1 Challenges

There were issues relating to the asynchronous and non local critique. Jurors were not receptive to the questionnaire we initially sent out as a part of Pin-up #1. For this reason. the questionnaire was not a focus of the critique and not used for Pin-up #2. Interview style discussions were more effective in providing a platform for eliciting jurors' engagement.

Discussions were intentionally open and frank which allowed for a wide ranging exploration of ideas associated with the thesis. Jurors were required to a sign consent agreement so their comments could be included in this work. Jurors were also referred to as "subjects" in the IRB materials. These issues may have created an atmosphere not conducive to creative engagement.

The author experimented with multiple modes of soliciting feedback from jurors. These included digital modes as previously discussed as well as in-person discussions, lectures made into a video, printed drawings and 3D printed models. 3D printed models were effective in communicating the spatial aspects of the design in-person but could not be shared with jurors online. A possible solution to this problem may be to have non-local participants print the models in-house before a given critique.

5.2 Fractal algorithms and fractals as organizing principle for design

A contribution of this work that we find beneficial to the profession of architecture as well as to the field of machine learning and artificial intelligence is the human/machine, algorithm <–> designer aspect of level 2 of our design process and the fractal organizing principle we developed as a result of this process. An important contribution of this dissertation is to help clarify the relationship between fractal theory as currently understood and the field of architecture and design. Our research resulted in an important distinction between our two main interpretations of how fractals are understood and used in design

– one is as a self-similar and scale invariant *pattern* and the other is as an iterative *process* that defines the pattern – the former is an instantiation of the latter.

Our experimentation with a case study project using fractals as an organizing principle in a design process as well as our research into Organic Architecture in the work of FLLW and DBV suggests that a fractal in architecture is more than a scale invariant and self-similar geometric pattern. A fractal approach can define a *generator,* as we have discussed, which may result in many geometric expressions within an over-arching motif or vocabulary of form. For instance, a fractal organizing principle may be used by a designer to explore *theme, development and variation* at many scales and in many design instances.

In the case study project, we found the use of a fractal organizing principle in conjunction with the FD metric to be an effective design strategy when applied to a real-world project. This method solved for the functional aspects of the program as called for in the RFP and created a formal/spatial vocabulary that was provocative and visually rich as verified through formal critique. The case study project represents a proof-of-concept that the design process we developed is a step towards the goal of solving for the complexity represented by the socio/techno and environmental context today's designers face.

5.2.1 Integrated fractal organizing principle

Although more work needs to be done, the potential for the fractal organizing principle we developed to integrate the physical architecture and computer architecture is provocative. The DBVgen tool represents a bridge between these fields that highlights their inherent similarities through GST and fractal theory. In a theoretical sense, an organizing principle's integration can be understood as both a reflection of its code and the output of that code.

The fractal organizing principle was a generator of form, approaching what DBV describes as "code" (See Figure 3.2.3). The term "code" is loaded with a multiplicity of meanings, such as the *design code* as well as the *computer code*. These realms have significant overlap, which is highlighted here and represents one of the contributions of this dissertation.

The overlap in the meanings of "code" regards how an algorithmic process relates to both the design outputs (individual design solutions) as well as the computer program itself. Although more work needs to be done, the potential for the fractal organizing principle we developed to integrate between physical architecture and computer architecture is significant. This tool is a bridge between these regimes that highlights their inherent similarities through a general fractal theory which we have contributed to in this work. In a theoretical sense, a building might be understood as both a reflection of its code and the output of that code. One might imagine a plant as a representation of its L-system.

We by no means argue that we have achieved this level of integration in the project we present in Chapter 3 but we have made substantial progress in developing an organizing principle we call a fractal algorithm (fractalgorithm) that is at once the instantiation of physical form as well as a encoding of rules which may result in many variations. This is interesting because it is relatively simple algorithmically but may result in countless unique solutions to a project's program, site and context. For instance, the organizing principle is analogous to a *genotype* that creates a set of conditions that either symbolically or perhaps literally extends itself in space and time relative to unique conditions, e.g., a *phenotype*. The extension may happen in a number of ways. One class of extensions are as literal additions to the building or influence over other architects and the buildings they design or for the larger urban plan. Another class of extensions may be as extending the building literally in one's mind's eye as a continuing formal idea or extending the building *virtually* in a digital space of some kind. Still another class of extensions would be as wetware of some kind, i.e., a building as a living organism with the ability to grow and reproduce etc. The full potential of the fractal organizing principle we have described here is pregnant with possibilities and highly speculative at this point. Continuing to develop fractal theory towards such possibilities represents an exciting next step in this research.

5.3 Fractals as a critical tool

In this chapter we have mostly focused on fractals used in a generative sense and integrated with computer technology. Now we turn backward toward architecture history. We look with fresh eyes on the past and discuss the implications of a fractal theory as a new critical approach and mode of inquiry into architecture and the design process as well as its implications relative to the creativity and thinking of the designer.

5.3.1 Research agenda offered

In this section we discuss a new research agenda we offer using fractal theory to analyze architecture precedent. Fractal algorithms as well as the quantitative tools associated with fractal geometry such as FD present a new research agenda for studying architectural precedent and urban conditions such as a building's context and formal relationship with other adjacent buildings or within a cityscape. Jurors' comments suggested that FD as a means for assessing basic aspects of different designs and across typologies was significant.

5.3.2 Fractal theory applied retroactively to FLLW and DBV.

In this section we discuss a fractal theory we developed in Chapter 4 as an alternate critical tool for assessing the work of FLLW and DBV, and show how this relates to our own work in Chapter 3. We position fractal theory as central to the understanding of these works. The fractal theory we present touches on the algorithmic nature of *process* over a simple analysis of fractal *patterns*. We do not argue that this theory is complete or that it reflects the intention of the designer of the work yet we argue it is an important contribution to the understanding of Organic Architecture and has significance when applied to architecture generally.

FLLW himself did not have the language we now associate around fractal theory but he does tantalizingly suggest it when he uses a proto-language and writes of "part to whole relations" or, "from generals to particulars." For instance, speaking of Sullivan, FLLW writes, "“Think in Simples” as my old master used to say—meaning to reduce the whole to its parts in simplest terms, getting back to first principles. Do this in order to proceed from generals to particulars and never confuse or confound them or yourself be confounded by them." (FLLW, 1931). We offered a clear example of this idea in a case study project and show that a a complex design may be visualized as a simple process that gradually becomes articulated through repeating operations relative to fractal theory.

We also provided significant insight into the design methodology of DBV's work over a 20 year theme-development-variation investigation of an idea. We described this in terms of a formal language that is used to solve a variety of architectural problems at multiple scales and with regard to an overarching idea that is imbedded in all aspects of the design process including the act of drawing.

DBV's methodology described both in the Vollendorf Method as well as through his work and mentoring have influenced the author/designer's approach to a large degree. The project we present in the case study is an example of our interpretation of both FLLW and DBV's work as significant precedent from which we draw from in developing the cybernetic design process we use, as well as the fractal algorithmic organizing principle we employ in the larger design process and have discussed extensively.

5.3.3 Other architecture

We posit that certain styles of architecture – having been influenced by nature – incorporate fractal geometries; such as: Gothic, Art Nouveau and American Organic Architecture but what of de Stijl, international style, post modernism, deconstructivism, etc.? FD has the potential to assist quantitatively in assessing the structure and design thinking of such work which has largely been an intuitive endeavor up until this point. FD by itself is not sufficient to measure the fractal or algorithmic nature of such design work but we show it to be a powerful and parsimonious tool when combined with a fractal algorithm interpretation as demonstrated in the case study project presented in Pin-up #2. Fractal algorithmic analysis can aid in a better understanding of fractal organizational principles that have long lain dormant and unexplored in architecture.

A strong aspect of this work is embedded in the thesis that fractal tools offer an important connection between nature, the built environment and computational mechanics. Some computer-based tools such as object-oriented-programming have roots in pattern languages as developed by Christopher Alexander. Alexander's work in turn grew in part out of the urban activist movement in the 1960s as led by Jane Jacobs. Computational mechanics also envelops the rapidly developing gaming culture – or perhaps it is the other way around? Fractals characterized as discrete, scale-free and self-similar patterns have the potential to further Alexander's work – or Simon's for that matter – in providing a cross-platform protocol linking the natural and artificial worlds. Furthermore, fractals as organizing principles in design have not been systematically assessed in historic architecture or in design processes. This represents a new research agenda. We explored the possibilities of such an agenda some in Chapter 4, however, that exploration represents just the tip of the iceberg. A thorough analysis of fractal geometry and fractal organizing principles in architecture is beyond our scope at present.

This dissertation in one sentence represents an elaborate argument for detail in architecture. Fractal patterns have detail at many levels of scale and this is evident in various styles of architecture as discussed in Chapter 2. We assert that the work of FLLW and DBV presents an excellent example of detail at many levels. The examples we explore here are simply a first step to systematically analyzing the works of FLLW and the Organic school and other architect's work and styles of architecture in terms of a standardized notion of fractals in architecture. This approach offers a rich research agenda to anyone who is interested in exploring fractals as a basis for design and critique in architecture at large.

5.4 Towards a theory of fractals in architecture

Here we discuss some abstract ideas and conjectures relating our work to broader theoretical contexts and a more nuanced description of our findings with regard to fractal algorithmic design used in architecture. As discussed previously, we found that fractals in the architecture we analyzed are not necessarily as simple as repeating shapes at different scales such as the Koch curve or Serpinsky triangle, etc. Fractals in architecture are more akin to repeating *thematic-organizing-principles* applied at different scales. This idea includes other compositional and design ideas within some overarching theme which creates a sense of unity to the entire project. For instance, the Martin house we studied in Chapter 4 revealed a repeating thematic-organizing-principle using center-of-interest as a compositional device employed at at least four distinct scales. Employing a thematic-organizing-principle as opposed to a particular geometric shape means an entire range of compositional elements and ideas may be at play and opens the door to a much broader idea. A more nuanced definition of fractals used in architecture we suggested in Chapter 2 is, *designs having multi-scale and multi-functional representations of some unifying organizing principle as the result of an iterative process*.

5.4.1 Efficiency

This section discusses aspects of fractal theory applied to architecture that might be used to design more efficient buildings and cities as well as other notions of "efficiency" that our research suggests.

Self-similarity at multiple scales

The "crinkliness" (West, 2017) or convoluted quality of fractals allow rectilinear forms to approximate more complex shapes which makes them more efficient space fillers in certain contexts (imagine integration in calculus). The endless detail and ever-folding quality of a fractal allows it to approximate other shapes such as the coastlines explored by Richardson and Mandelbrot (West, 2017). In architecture, as we have discussed in Chapter 2, the Hindu temple plan or *mandala* begins with a square but through gradual fractal iterations approximates a curved shape. In the vertical dimension this process continues, producing a perception of endless geometry unfolding into space.

Masonry blocks are usually rectilinear and, therefore, employing a geometric strategy that can approximate other shapes has a certain pragmatic efficiency that fractals afford in an architectural context. For instance, approximating a circle or dome shape with rectilinear elements by employing a simple repeating algorithm is efficient because the masonry units can all be the same and a circle has more interior area per exterior edge than a square which makes a circle more efficient for a building because it defines space with less material. A dome likewise contains more interior volume per exterior surface then a cube. Other more complex geometries such as the macro form of cities are theorized to result in part from the space filling property of fractals (Batty, 1994). The space-filling properties of certain fractal geometry is also related to biological uptake and distribution systems characterized by 3D space filling trees composed of one dimensional elements essentially (West, 2017).

Trees and networks

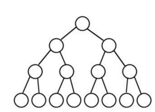
Forms found in nature and in architecture often include a hierarchical structure as well as a non-hierarchical structure which may be a more reticulated network or what has been called a *rhizome* or *meshwork* (Deleuze, Guattari 1988). This dichotomy has many overlaps with general notions of order and disorder. We won't delve too deeply into this rabbit hole but will make a few remarks regarding how information theory has been discussed in architecture theory and how this might relate to our work with fractals.

Drawing from Herbert Simon's idea of "partial decomposability" (Simon, 1996) we conjecture that there is potentially a balance between a hierarchical and non-hierarchical model that lends both efficiency and flexibility to a system, i.e., a balance between optimization and robustness. This relates to the utilitarian function of a form as well as its symbolic meaning. Meaning as suggested by Baird in reference to information theory is related to "surprise" within some organizing system. To put it more bluntly, meaning relates to some proportion of repetition and variety. Investigations regarding fractal theory along this thread are potentially rich especially when considering the general model Rényi has introduced which defines an equivalence between a variety of information theoretic measures including fractal dimension (Takayasu, 1990; Schroeder, 1991). At the present stage, further exploration of this idea is well beyond the scope of this dissertation but mentioned here relative to its potential implications regarding the theoretical aspect of this work.

5.4.2 Fractal thinking

Another type of *efficiency* that fractals may afford is what we call "fractal thinking" which we speculate is part of the creative process designers engage in. Fractal thinking is the notion that a fractal-like organization system is a way of chunking or compressing information so that a very complex object may be visualized before "pencil ever touches paper." This approach may be understood as an iteration of the idea from a general wholistic view to a particular instantiation much like music from the Baroque era or the architecture of FLLW and Organic Architecture generally. The word "organic" implies a hierarchical organizational structure from the whole unified organism to sub-systems such as the circulatory system to cells to organelles within the cells such as chromosomes and mitochondrion and on down to molecules and atoms and sub-atomic particles at the quantum level. Fractal ideation may involve a similar hierarchical chunking of ideas like Russian dolls or a "tree" configuration that allows a designer to mentally visualize incredibly complex designs in his/her head without getting mired in the details.

Imagine you are tasked with memorizing 8 numbers. This can be 'chunked' into a set of four tuples and further this new set of 4 subsets may be chunked into 2 subsets having 2 tuples each. So the "general" idea is a set of 2 which cascades into 8 when unpacked.



$\{[(y_i), (y_i)], [(y_i), (y_i)]\} \rightarrow [(x_i,x_i),(x_i,x_i),(x_i,x_i),(x_i,x_i),] \rightarrow [(x_i),(x_i),(x_i),(x_i),(x_i),(x_i),(x_i),(x_i)]$,

where x_i is some single digit natural number and y_i is a corresponding 2 digit number.

A mental model may be applied to help as a narrative thread. For instance, now imagine each tuple represents the age of a person and then each person is dining with another, now we have two people with two digits each. Finally, imagine they are on a double date with another couple. Now we have our 8 numbers in a simplified form that is "easy" to remember.

Discussing abstract notions such as 'thinking' in any context is fraught but here we focus on the process of designing 'in one's head' which is a very real aspect of creative work and something jurors have described as important in our critique. How a very large project might be conceptualized down to minute details before 'pencil touches paper' is a valid question/agenda. Applying fractal theory to this is appropriate as it provides quantitative tools which are an appropriate coarse grained measure of 'complexity' in a variety of contexts including architecture and biology. Branching structures as universal solver

Fractal branching structures can also be more efficient distribution systems than other strategies such as a reticulated network or a homogenous non-hierarchical structure of some kind – a *rhizome* in Deleuze and Guattari's terminology (Deleuze, Guattari 1988). The efficiency of branching structures may account for their ubiquity in inorganic nature such as streams and rivers, lightning, geologic formations (fault-lines) as well as organic distribution and uptake systems such as neurons, vasculature, plant forms, etc. The efficiency of branching structures might also account for their use in building infrastructure such as plumbing and wiring and ductwork as well as vehicular transport networks, e.g., highways, byways, tri-ways etc.

The seeming universalism associated with fractal structures is fascinating and has been used to build models to help explain biological and urban scaling (West, 2017; Bettencourt, 2013). We have discussed at length how a fractal organizing strategy might be applied to the plan of a building or a city at large but here we discuss a more nuanced and theoretical idea that fractal structures might represent a universal solution in nature and artifice that is used again and again to solve a variety of problems.

Could a fractal be an adaptable strategy to future and unpredictable conditions similar to a *body type* in biological evolution? This idea posits that a fractal organizing principle represents some universal (Platonic ideal) form that can be tweaked to solve a variety of architectural and urban design problems such as packing problems, space filling problems, distribution problems etc. In this vein of reasoning, once this fractal structure was evolved/designed it could be applied to solve many problems more quickly than starting over from scratch to find a unique solution and was therefore "encoded" in nature and artifice in various ways we will not elaborate on here. This idea has interesting overlaps with the idea of robustness in genetic networks (Wagner, 2012, 2014) where genotype spaces can be quickly searched and speciation occur given some necessity such as a rapid change in an organism's or eco-system's fitness landscape. This idea could help explain the punctuated equilibria seen in a variety of organism's phylogeny. Fractal branching structures as universal solvers in biology and architecture have much promise and represent some interesting potential theoretical applications for ourselves and/or others.

5.5 Conclusion

The potential for synergies between the silos of computer science and architecture design within a cybernetic design process as presented in this dissertation offers a proof of concept model to rise to Jacob's challenge of defining a city as a problem of organized complexity. This "wicked problem" is a vital issue architects and planners must better engage with moving forward in our increasingly fragile and resource depleted times.

We have advanced toward this goal in this dissertation by sketching out an agenda that has the potential to combine the best aspects of what designers do with powerful new technology. We shift the standard data crunching model and run it backwards to *produce* data and generate raw material for the architect to sculpt – an element of design like a material in addition to brick and mortar. We have argued for algorithmic design and, more broadly, artificial intelligence, to be an engineering problem as well as an aesthetic problem and, as such, within the architect's purview.

Given this situation, we have defined a path forward to inspire the profession of architecture to regain control of the design process by including the design of architectural computer systems within its envelope. Our path forward incorporates fractal theory as a connective tissue between science and design. This idea has much potential for future research. However, because of space and time constraints, there are many facets of this work yet to be explored. There are undoubtedly many other ideas that we have not explored that could also serve to connect the architect in a more substantial way to the enormous power of computational mechanics and help address the social and ecological devastation we are witnessing in our lifetime. A world where architecture and nature are integrated, symbiotic and generative is a vision we have tried to provide in this dissertation. Algorithmic design is in its infancy and we have the opportunity to orient it towards a regenerative arcology – to use Paulo Soleri's term for architecture in harmony with nature – otherwise we may have to use Mary Shelley's term. It is ironic but perhaps prescient that computer code and data structures are being called "architectures." It is natural that the architect/doula help conceive these new and increasingly strange *monsters*.

End of Chapter 5

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Appendix: Correspondence Log

This appendix includes the jurors' comments during the duration of the project from 7.19.18 to 4.21.19. Comments were made via email or in face to face conversations. Questionnaire responses are also included. Comments are organized by jurors' initials, date, and comment number. The authors own questions and answers are indicated by "JD."

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COMMENTS

Jonathon Ferrari
JF. October 2, 2018
Pinup #1 sent on 7/19/18
.1 Speaking of Goff ever heard of Daniel Liebermann ? Very interesting architect I apprenticed with one summer in grad school also trained with Wright. He has a great little body of work around Frisco... Just found out he passed away . . . https://www.ptreyeslight.com/article/danielliebermannarchitectdies84
JD. October 2, 2018
.1: Thanks a lot for taking a look at his. We are pretty close to having a genetic algorithm plugin for SketchUp implemented which I don't think exists yet (from my limited search) so things are progressing. **.2:** With your background in biology and architecture your thoughts on evolution and selection as a process for solving design problems will be really interesting to hear.

.3: It’s fun to explore the potential of algorithms and architecture with you in relation to some of the Organic Architecture tradition. How do you think an architect like Frank Lloyd Wright or Bruce Goff would be using the latest computer technology if they were alive today?

JF/JD. April 8, 2019

.1: JF. The overall building form is stylistically modern, e.g., international style. I don't see that it is derived from a fundamentally different geometric idea such as fractal algorithms etc.

JD. I could see that being a valid criticism of the process. I am looking at 3 discrete levels of scale and relating the fractal dimension across these scales.

.2: JF. Every project is unique. What this type of tool really calls for is a way to input all the forces and criteria of the site and program into the algorithm so it will grow into a unique solution that reflects the conditions of the program.

.3: JD. Right. That is the ultimate objective. I think about the algorithm for a flower. How does it know when to stop growing a stem and to bud a flower? One possibility would be that the flower is the terminal of the plant and when the energy of the resource runs out the stem stops growing and a flower is the expression of this cessation. So, it's as if the flower is always trying to bud. Similar to the standard ending of a rock and roll song. When the music stops, the band does an ending bit that may go on for a while and is fundamentally different than the body of the song.

JD. There is a biological... (this is what I am trying to remember. Ring any bells?) **JF/JD. April 9, 2019**

.1: JF. Wow, I can't remember...
Was it about the branching trees coming together in the canopy to fill the space, but not quite touching ??? ...

.2: JD. Hmm, right we did talk about that. But no, I think it was something about how cells or molecules have evolved to behave. Something from biology and evolution....
End of correspondence.

Gordon Hall JD/GH. July 22, 2018

Sent pinup 1: 7/22/18

.1: JD. Please assess the images in terms of composition, ie., focal point, secondary focal point, counter point, rhythm, etc.?

.2: GH. Fig 5/plan 2, Fig 6/plan 4, Fig 7/plan 1, Fig 8/plan 2 to me are the most compelling grounded w/ visual interest and a high order of visual synergy. 3D extrusions less compelling on their own merits before design intervention as shown in Fig. 9 10.

.3: JD. Is there anything akin to: theme, development variation happening here?

GH. Yes

.4: JD. The algorithm being used to create these images selects exemplars based on their fractal dimension [FD]. On the timeline images, FD increases from left to right. Does a higher FD appear to improve the compositional quality of the designs?

GH. Yes. Much of my impression has to do with an increase in visual density of lines, ergo, higher contrast with regard to positive/negative space

.5: JD. How do you think this design process could be effective, interesting, or useful for an architect?
GH. It is sometimes easy to become enamored with my own first impressions of an idea - so a tool that can continue stoking the creative engine toward better results could have immeasurable value.
.6: JD. How do you think this process relatesif at allto other architectural design processes with which you are familiar?
GH. Seems generally consistent w/ what we do in a traditional design process. **.7: JD.** Please briefly describe your internal creative process.
GH. In architecture . . . first balance/evaluate pragmatic realities for each design challenge ... and they are all different. Triage aesthetic priorities as form evolves. Manage daylight integration with form. Compose skin. Site –> Plan –> mass/volume –> light –> skin. Internal process when making music: Serendipity with reckless abandon.
.8: JD. Are there any aspects of the algorithmic design tool presented here that you resonate with in terms of your own creative design process?
GH. Always aspiring to maximize part to whole relationships and high order fractal' evolution as a cognitive goal.
.9: JD. *On a scale of 1 to 5, with 1 being least useful and 5 being most useful, check a box stating how useful you believe this design algorithm could be to an architect.*
GH. 5
.10: JD. How do you think you could integrate the design algorithm as a tool in your design process?
GH. Depending on the level of input control, in my practice it it is more common to generate form based on programmatic constraints as opposed to finding purpose / utility in the form post facto. As a practical example I could see this being employed to help correlate an exterior composite with an interior volume.
.11: JD. Are there changes to the algorithm as you understand it that might make it more useful for you or other architects you know?
GH. It seems to me that the algorithm would necessarily need to be project specific and highly scalableespecially with respect to complex geometric constraints.
.12: JD. On a scale of 1 to 5, with 1 being least useful and 5 being most useful, check a box stating how useful you think applications of artificial intelligence might be to the practice of architecture in the future.
GH. 3
.13: JD. On a scale of 1 to 5, with 1 being least useful and 5 being most useful, check a box stating how useful you think the design algorithm demonstrated here might be to the practice of architecture in the future.
GH. *5*

.14: JD. What are your general thoughts on the implications of artificial intelligence [AI] to the practice of architecture in the future?
GH. With respect to residential design which is my primary design focus at this juncture (subject to change) . . . Design AI as a consumer tool could diminish the traditional role

of the architect in much the same way as other DIY resources such as Pinterest. In that regard, I'm being somewhat cynical based on personal experience. **15:** So much of the professional relationship is rooted in expectations the desire for expediency and low cost could have huge implications on the professional side such a resource could be very useful in driving efficiency in the iteration process with regard to fractal continuity / synergy as a measure of quality I think it is equally important to consider the necessary disruptions in any fractal system. **.16:** Any system, no matter how perfect in structure, will always be subject to external forces such that "genetic" anomalies might infect a fractal system only to improve the overall composition or create a useful tangentsorry, off the reservation again.

.17: I think that what I'm getting at is that a.i. (intentionally lower case) could be very useful professionally as an analytical tool but not to replace the visionary / visual activity and judgment of a human practitioner. AI (upper case) may definitely have a role in automating production.

.18: Generally speaking, one consideration of importance is the relationship of professional time. During my time using Archicad professionally for 7 years, I was constantly confounded by the amount of time spent managing the application vs. design productivity.

.19: As these systems become more pervasive I think we design professionals may face an existential question. But with regard to specific process under consideration fig. 9/10 sums it up nicely. I get it.

GH. October 1, 2018

.1: Wow! I have been pouring through the background of your research for the last few hours... extremely impressive and ambitious. There is a lot to unpack here. In mainstream culture, I sort of feel like we are accustomed to thinking of the ultimate goal of machine algorithms (with respect to AI) as the cornerstone of autonomous (nonhuman) decision making. **.2:** If I am understanding your underlying thesis correctly, it seems that the relationship between human and machine you are promoting is one of dominion (over) as opposed to subordination (to). I may be way off the reservation here but I can't help but think of parametric data streams in terms of forced limitations. **.3:** I hated using Archicad because, among other things, so much of the power in the parametric platform was not terribly useful in the context of one-off custom design a reality reinforced by the difficulty in manipulating Archicad solids. To me, BIM apps have more value in prototyping and repetitive functions where architects and designers run the risk of being reduced to the role of copy editors.

.4: As I read the narrative and review the images, the algorithm seems geared to promote and explore many possible outcomes from which one can cull promising leads. There is an underlying analogue process at work in sorting and prioritizing criteria that I find very human and comforting. **.5:** Conversely, I wonder... if (for example) in the interest of project expediency, FD could itself be coded as a driving parameter in the algorithm as opposed to a post facto method of measurement? I am guessing that might start approaching something resembling an autonomous AI, effectively bypassing many of the what-if's that constitute the artistic joy in serendipity.

I have the questionnaire printed and ready to begin formal comments... should have it in your inbox before noon tomorrow.

JD. October 3, 2018

.1: Thanks for your thoughtful and thought provoking comments. I think you are definitely ON the reservation in terms of the motivation and intention of my thesis, i.e., to put the architect back in control of the technology, tools and materials of the trade which in our day is getting pretty tricky with the advent of computer-based tools and the approaching ramifications of AI whatever they may be. **.2:** I think architects doing mainstream work by and large have been reduced to copy editors to a large extent. Maybe this is why so many *design* focused architects work in custom residential? I wonder (from my more pessimistic side) if the development of AI will mirror the development of the internet 20 years prior. **.3:** I remember when we graduated (mid 90's) the internet was perceived as a free and open. 'information highway' where everyone would have equal access and connectivity to knowledge and to each other. Now it is quite a different story. Probably more like Orwell's 2 way T.V.s or at the least a top down market controlled by a handful of tech companies. **.4:** If AI follows this same path then this nascent state is like the mid 90's perhaps, i.e., still forward thinking and assuming the best possible future. **.5:** In terms of my thesis work the full ambition I think is to somehow document this spirit of the age. In retrospect it may be considered a very creative period in terms of exploring the potential of AI (before it is commodified).

Do you use Archicad primarily as your drafting tool? Do you use SketchUp at all?

.6: For pinup #2 I have a simple FD plugin that allows a back and forth between algorithm and human. The FD is used to measure post facto but in an iterative way for many generations of the genetic algorithm which gradually converges on a pre selected FD (I have been using a max FD of 2 for now). It would be interesting to program a fractal generator into the algorithm as well. I haven't thought of a good way to do this although I have seen some interesting tools that do. http://cgchan.com/suicidator/

GH/JD. February 16, 2019

A brief overview of the FD algorithm in operation and the Green Street SketchUp model for

Pinup #2.

.1: GH. Not having detail everywhere is good. Areas of blank space is important not to overwhelm.

.2: JD. The scale of the individual is interesting as the point of reference with smaller scale (CMU) below and larger scale of the building above.

.3: GH. But every occupant is a different size so for instance a child will have a different perspective of scale than an adult. Every design problem is different and each solution must be a response to the criteria of the problem– such as the site, budget and expectations of the client.

.4: GH. In terms of the computational aspect of the design process it would be nice to be able to have it output vector files for use with other software and feed this back into the algorithm. The color of the SU model is kind of stark, grey scale might be better.

(Personal note: The fractal motif occurring throughout scales is perhaps related to DBV's comment about a building allowing you to see the space behind you)
.5: JD. The building pixelates as it reaches the ground, becoming more complex and organic. As you zoom in to the building more and more detail is revealed at ever smaller scales. There is a repeating self similar detail or motif at different scales throughout the building. I think Wright and other architects did this naturally as a kind of geometric way of thinking.
.6: GH. I like to come at a problem kind of the other way around and think volumetrically first and let that guide the smaller structure such as developing an amorphous grid. **.7:** One of the interesting things about DBV's teachings that I keep coming back to is the idea of 'Serendipity'. This is related to finding the constraints in a design problem. **.8:** Some projects begin with constraints such as the size of a bathroom and the size of a bedroom which become modules from which the larger design grows from. The plan of these modules might be literally a pre-made object that is cut and pasted into a design.
.9: JD. I wanted the composition that is automatically created by the algorithm to be more than simply wallpaper but to also become the plan of the building and related to function. A criticism of this might be that the architect is trying to force fit a predefined layout into a program it doesn't fit but in terms of the bathroom and bedroom issue you mentioned it seems this is something architects have to do all the time.
.10: GH. Like dealing with preexisting conditions.
JD. Or the module of a city block or the constraints of a landscape...
.11: GH. Understanding the constraints in a particular design problem is an important part of the process. I like to define 3 or so important criteria early on and they are always different from project to project. For instance, one such project resulted an Excel tool which helped to communicate and educate the client on the difference between net and gross square footage which was an important constraint given the size of the site.
.12: JD. I wonder if it's possible to start from the constraints given in a project such as the code criteria or ADA which in some ways establish a limited number of design possibilities .
End of correspondence.

Bret Holverstott
Sent pinup 7/19/18
BH. April, 20, 2019
.1: Modularity. I am hyper focused on modularity and I noticed that you skip a level of scale. Between the "micro" scale and the "mezzo" scale there exists a level of scale that is more directly related to the structural span of the floor & ceiling system. **.2:** In modular construction, this standard span of around 15 feet becomes a box module, although even in non modular architecture it is still a sweet spot that avoids going deeper than 117/8" TJI's in the floor system. **.3:** Of course, in modular architecture the determining factor is not, in fact, the structural span but the ability to convey the box over the road. There are other modules related to fabrication, most of which arrive at 8/9 feet (sheathing & drywall sheets), or 10 feet (CLT sheets) and area also related to transportation. In length,

modular architecture prefers a 4060 foot span determined by a combination of transportation, crane, and floor deflection factors. In panels, the length factor is about 14 feet due to expansion and contraction of the panel. **.4:** My point is that there is a level of analysis that could be extremely interesting between these two scales and closely relates to room sizes. **.5:** In plan, floor/ceiling modules matter; in section, sheathing and panel modules matter; and there is also a module related to window sizes: ratio of length to width determines tempering. area of glass determines thickness and tempering; egress and fall hazard dimension determine operational modules; glazing to wall area, or glazing to floor area relationships further bound the system. Anyway, it seems to me that this level of modularity could be generated by fractal geometries.

.6: Complexity. I am really awakened by the idea that fractals generate complexity on multiple scales and I will try to incorporate this into my design process. Cool way to think about it. **.7:** I think I understand why our aesthetics seems to dictate that the fractal dimension increase as the scale increases it is because the overall massing of a building should strive for a composition that is compelling if seen from a distance, not overly simple as in a homogenous skyscraper. I am reminded of how gothic cathedrals evolved to utilize alternating bays in order to keep your eye from immediately slipping to the end of the hall; good skyscrapers also break up the composition into something that allows your eye to linger on elements instead of slipping up to the top of the building. What would be extremely interesting is to find out experimentally what humans prefer, aesthetically, based on the size of the object under scrutiny (or distance away from which it is perceived).

.8: Methods of design. Is there a way to create a heuristic for designers to use if they are doing schematic design with a pencil, that allows them to quickly gage the fractal dimension of their design and generate some simple exploratory patterns as inspiration? Sometimes we overly rely on computers to solve problems for us, and in my experience you can actually design about 10 times faster with a pencil, or at least move through about 10 iterations in the time it took you to test 1 iteration in the computer. **.9:** When designing we need to feel that we are in a state of flow that is not limited by technology. **.10:** I am a hyperrealist when it comes to design, so I have a hard time believing that I would use purely geometric mathematical generators as a design exploration. I want to know how a design decision is fabricated, transported, installed, how it feels when you move through it, where you store your waffle iron and keep your keys. **.11:** I could imagine revising a design, for instance in augmenting the window configuration on an elevation to provide additional scale complexity. **.12:** With regard to the Rainier Tower, have you talked to Robert Baxter? I believe he configured the windows using a Grasshopper plugin.

.13: Your examples. I found your macro scale design example compelling, compositionally, although it does end up being a little bit of a throwback to Frank Lloyd Wright. It would be interesting to show some examples that don't so closely remind us of one particular designer. **.14:** I have no doubt you could create a wide variety of compositional patterns that echo and reflect throughout the project and so show the audience that it is a generative tool rather than an imitation tool. Use it to produce originality, instead of just analyze. You've evolved a new appendage, use it to do something new and awesome.

End of correspondence.

Ken Kroeger

KK/JD. October 13, 2018

.1: KK. Taking your introduction and then reflecting on your quote of Senge and Fuller – the ship at sea, and using a systems perspective/leverage point. If I think about applying your notions of AI (GA and FD), then we could come up with an overall layout that would make a provocative composition of what the ship would "look like."

.2: However, I have a slight opposition in your utilization of the "thought problem" identified of whom has the most control of a ship – as a new process, AI should help us with more than composition (the "design" of the ship) and allow us to be more responsible for understanding the needs of a ship – the captain, crew, navigator, or even trim tab on the rudder would be pointless without WATER. Water has the most control and is the reason for having a ship at all.

.3: JD. Right but I think we run the risk of losing the sense of the metaphor here. The idea is simply that the design phase of a construction project is incredibly important.

.4: KK. In my opinion, the water is the "leverage point" and what design should respond to – without water, there is no need for a ship is the basis for the need. There is no "control" over any one specific item how the air impacts the sails; how much space is needed for food, water, or fuel; how the sun and temperature causes the materials of the ship to flex, move, and proceed on its journey; address the stars in which the navigator uses to reach their destination; or even point out the need for such a vessel in the first place. The designer should not be as worried about "what it looks like," but how it functions.

.5: JD. Dean would say as Wright did 'form and function are one' not 'form follows function'. The actual quote is something like 'form is forever following function' and makes it feel more like a yin yang dance or something, like not quite catching it as they both change relative to each other. Biological analogies come to mind...

.6: KK. In Senge's terms, the designer should be creating a common vision with shared values and purpose, translate those values into decisions, and create process for continuous improvement. An architect should not superimpose their wants on a site, but rather learn (translate those values) from a site. **.7:** My attempt at comprehending the examples and information provided (along with reading your posted dissertation proposal) are more about applying (or even suggesting developing a new process) for design and less about outcome. However, you are asking for feedback as if we are to critique as a design pin up discussion, which I feel are two different things.

.8: It seems that your work is more about method than outcome, and therefore to me, lies the crux of my inability to completely provide a valid critique in the format you prescribed. A part of design reviews (at least academically) is an understanding of the thought process and development. Not really understanding the FD and GA only leads me to say –how are those apparent numbers meaningful? **.9:** Do you think with your AI method, historical architects (Wright, Goff, DBV, et. all) would have designed completely different structures?

.8: JD. Not completely different but yes, more informed certainly.

But at the end of the day isn't it the physical form of the building that we have to go on? Regardless of the process the Egyptians had for building the pyramids but we can still react and assess them. The outcome is necessary as an artifact that represents something ephemeral. **.9:** I am hoping that the outcome will speak to the algorithm that was involved in it's creation and in this sense be a more true expression of the tools of construction. Like structural rationalism that reveals the structure, this could be 'computational rationalism. **.10:** I think of it almost as if the building itself could be the tape in a Turing machine that could be read. Similar perhaps to how a running bond coursing represents the method / logic of brick and mortar construction.

.11: KK. First, Architecture should be more than coming up with a series of constructs that create patterns or compositions without context or meaning. It would be extremely capricious (and naive) to suggest that there is an overlying composition that can fit any situation (which I don't think you are doing, but is a concern with AI, or at least AI in its infancy). **.12:** The architect is a problem solver, whom is balancing more than just looks. Fractal geometry is more the underlying module or grid in Wright's from which the design develops from but not form **.13:** So utilizing AI should be more than a simple tool for creating abstract patterns. DVB's teachings were not just about creating patterns and compositions, but how to take the 2D form and think of it in multiple plans and to create space. And to use those compositions with different scales and needs.

.14: JD. I decided to really zoom in on fractal dimension as a simple mathematical formulation that has relevance to spatial data but hadn't been employed as a design or 'generative' tool before. So this is really how I am investigating the larger ideas we may associate with A.I. **.15:** Having said that, there are two more higher level aspects to my thesis which I think are important. One is incorporating the jury/critique paradigm we are so used to as architects in a more formal way, i.e. doing an IRB and publishing white papers on my results. **.16:** The other is developing a design process model where the role of the designer is paramount but also includes the swiftly changing landscape of design in terms of big data and computation. **.17:** As a designer myself, I am interested in how human creativity may be both saved going forward and perhaps enhanced with A.I. Both of these more abstract aspects of the thesis are about bridging the silos of science and design which has been an important agenda of systems science since the 50's.

.18: The algorithm uses an approach based on biological evolution and natural selection or a genetic algorithm (GA). The GA is pretty much out of the box and not something I am focused on so much. **.19:** All it is doing is adjusting the fractal dimension towards a target FD. The 'learning' involved is the iterations of designs that are approaching this goal or 'solution' so the algorithm is learning to solve this problem and getting better and better at it. The extension of this work could be much more complicated in terms of adding criteria to the fitness function which is how designs are 'selected'.

.20: KK. Why go through all the generations to randomly apply masses/extrusions?

JD. The random extrusions are just a placeholder for nowuntil the algorithm can be developed more. At the end of the day I only have so much time and I can't investigate everything I would like to. I'm only a humble grad student, man!

.21: KK. How is the evolution of the pattern generator doing anything more than providing an arbitrary construct that provides no framework for form, function, or interaction?

Design is not a linear approach, but is a complex network on intertwining needs, materials, environments, and users.
JD. Preaching to the choir here. This is exactly why I got involved with systems science in the first place and why I think t is so important to bridge between silos in a more transdisciplinary way then how we currently operate. I get what your saying but at the same time would reflect back to you that the the design process I am proposing and developing here is an attempt to approach complex multivariate problems from a design perspective that is both qualitative and rigorous mathematically. I totally accept that you feel it is not doing what I am purporting it to do but there is more to come keep in mind.
.22: KK. If you wanted to use AI as a design process, then there would need to be more factors integrated. Perhaps this is where you want to take it, but from what you showed, it is lacking any real depth or ability to do anything greater than what a person could easily do.
.23: I could understand if each generation provided information on what is being altered and for what reason or factor used besides a series of lines and ‘red extrusions’ (and those being random extrusions not based on any of the generation pattering).
And as an Architect, I believe that our responsibility goes beyond creating specific patterns that are only there as an opportunity for a specific image to be seen, from a specific viewpoint, on a specific day, with no people or context. That is not being responsible at all.
Looking at your examples, the process is not been clearly defined or described. I feel that there needs to be something more than “randomly mutated for a number of generations” or “now with a number of rectangles or masses chosen at random.” This would be akin to saying that context or materials don’t matter.
.24: JD. I would offer a clarifying caveat here that might be important to make more clear in my background materials leading into this work – namely that I am trying to develop a design process that has the potential for dealing with the inherent difficulty of multivariate non linear problems (read architecture problems!). The design process I propose does not deal with specific variables (context, material) but offers an *approach* to dealing with them. Systems science is ‘stuff free’ in this sense, more about the relationships between things rather than the things themselves. Systems science as you may know is also often criticized for this and I agree there is a lot of validity in this criticism as you demonstrate.
.25: KK. You obviously selected 5 example generations, but then on the subsequent figures, never continued with the same context generations. This is what a portion that missing for me – the process and analysis. In this initial pin up questionnaire, it may have been simplified too much. Your examples could be anywhere or anything and have no connection to anything besides lines that have been generated.
.26: This is a worry for me simply applying AI into the design world and that people would just plug some numbers into the computer and expect what is generated is what Architecture is about. Very similar to somebody going into a local hardware store or downloading some “plug and play, Anyone CAN BE the architect” software and thinking

that because they moved some clip art images around on a page, they are creating informative and responsible design.

.27: As similar comparison is everyone running around with their phones taking pictures at random, without any thought to composition or elements or even suggesting that a person sets up a camera and a computer randomly takes imageseventually a person/computer (AI) might take an image that rivals someone like Ansel Adams, but does that make them a great photographer? I know this is one of the great debates about AI, and you have not placed the “human balance” into the pin up yet, so please bear with me.

.28: An easy answer to your first question yes, the figures you show all provide imagery with composition. Applying this question to the case study project, I would suggest that hierarchy of the form is not present the primary and secondary focal points are blurred. Similar, it is difficult to understand the rhythm of the changes in the canvas.

Moreover, the document text / graphics does not give any notion to why then is this “method” of design critical and how it is new.

.29: Specific “Architectural” critique To address the question about increased FD and improvement of the compositional quality – I don’t think it specifically improves the composition. It simply is a variation of line work. Without having any performance/outcome values, I would bet that if you ask 50 different people which one they preferred, you would get that many answers.

.30: JD. This was the main question for this first phase (pinup #1), namely is there any substantial qualitative difference between compositions along some FD gradient. The larger question posed would be if analytic tools incorporated into some design process could help the human practitioner do what he/she does. Not to say that architecture could be distilled down to scalar representation or that a basis in geometry and composition are foundational in any design process per se but that given a design process could these types of tools be an aid.

.31: KK. Further, I have initial misgivings with the random massing (red “boxes”) with no reference to the “fractal” generation and “fractal lines” of the generations developed that seem to have no reference to site or scale.

.32: JD. The way that the program is set up at this stage chooses masses at random but this is developing. The next iteration of the algorithm will test the entire 3D space for FD not only the 2D composition.

.33: The design process we are incorporating has the potential to include the site, context, program for a real architectural problem. The idea is that by incorporating the human designer in the process the output as well as the algorithm can be manipulated over and over again countless times working towards a final outcome that could be Architecture with a capital ‘A’. **.34:** The problem presented here is a toy problem to highlight the issues we face as designers in an increasingly tech dominant world. Including a jury critique style phase in the process with professional architects such as yourself fosters an environment where these issues you raise can be aired and potentially Balanced with the potential for automation, iteration and mathematical processing.

.35: KK. And thinking of fractal – how are you applying various levels of scale and detail to this? For example, from the larger urban context to the building detail. Will that be coming in the next pin up?
.36: JD. Yes. Fractal dimension is interesting to me because it is basically a tool which measures scale or the scales at which detail exists. This seems pretty primary in a designers toolbox and hasn't been available until the birth of computer technology and the capitalization of that in the 80's.
.37: KK. An interesting process/task (for me to want to engage this AI method more) would be if you could generate various patterns for various disciplines, for example take the typical MEP, structural, and fire suppression work and overlay (maybe in different colors) those to architectural and urban planning/civil generations. Could this process be applied to a greater composition that could potentially eliminate some of the typically issues with design discrepancies/layout conflicts between trades?
.38: JD. Right, this is a potential that I have been interested in and in some ways led me to using FD as an architectural design tool. The primary characteristic of fractal geometry applied to real world contexts in nature and urban conditions is as efficient space fillers. This is where the work by West and Bettencourt really comes into play. There is a potential here to improve the efficiency of designs relative to various gauges such as duct or cable length say in terms of MEP or city roads and green space on the urban level.
.39: KK. Figure 9 and 10: By graphically adding some simple modeled trees and a sculpture – how is that adding scale or context? Are those 4050' maple trees or 34' ficus trees? Is that a 1' garden sculpture or 60' figure? In my opinion, scale is an important component for design. However, if this is utilizing AI as a development tool, then there needs to be more explanation of generating forms. I feel that DBV was trying to teach people how to see space and represent that in a 2D media. This perhaps is lost a little in your discussion.
.40: JD. Good points. When does a sense of space and scale manifest and how can this be more than the designers 'eye' or innate ability – so it can be communicated and incorporated at large?
.41: KK. Furthermore, your text says it gives function – but that is unclear – is it a covered garden pavilion or multi story museum? It does not appear that function is a critical component in the process. Should it be (ie. Form follow function)? Would you apply your AI strategy differently for a museum vs house? Gas station vs hospital?
.42: JD. The way I'm thinking about this I feel solves this problem. Ultimately the algorithm is a tool for the designer just as a pencil or tape measure is. The designer can use this tool in whatever way to create complex solutions to architectural problems of high dimension.
.43: KK. What about materiality? How does that impact your AI generation study?
JD. Can I say you're asking real questions that are important in a charette/critique but I'm
presenting more of a toy problem that ignores most of what architecture is. Perhaps the sequence of elements is at issue. **.44:** It sounds like you're saying the conditions of the specific problem are not something that can be simply left out of the model if the model

is to have any real value. I agree. **.45:** The irony perhaps is that computational mechanics allow for many more variables to be considered than what a traditional architect thinks about. I wonder if the profession can allow for this or stay ahead of it. I muse to myself sometimes that the great architects of our times are working for NASA designing new rovers for Mars...

.46: KK. If materials are not a concern, I would say think about the EIFS "issue" as concern problems started developing due to water leakage in EIFS clad buildings. This created numerous lawsuits and issues with buildings and dealing with the penetration of water. While the EIFS industry states that the EIFS itself is not responsible for the water infiltration issues and is the result of poor craftsmanship and bad architectural detailing, it created a major problem in the building profession(s) and demonstrated flaws with certain design processes or lack of knowledge of site conditions and material use.

.47: JD. Good point. This reminds me of a waterproofing conference I went to hosted by Kemper. All the details seemed to be creating a double vapor barrier on the inside and outside of the building which will trap water in the envelope and seems a recipe for disaster. Now with blown in insulation we are not providing venting at all just assuming the building envelope to be basically hermetically sealed. The problem is is that we haven't had time to judge whether this will work over the lifespan of the building but it is the trend. **.48:** I question the whole passive building paradigm sometimes for this reason and interior air quality but I also understand its value and efficiency so it's confusing to me. EIFS in a similar way creates a vapor barrier on the exterior of the building? EXP same issue I would think.

.49: KK. Fig 12 – why did you modify the canvas size and height? How is an "architect" supposed to understand what to manipulate in an AI world? This is the linchpin of my concern that goes back to people not understanding what they are doing and just "plug and play" objects.

JD. Just quickly with more elaboration required, the architect is able to create parameters rather than just set values for them. This is a sea change really in how the architect/computer interface is designed currently.

KK. How and why did you select that specific generation for the canvas?

JD. For now the number of generations and all the parameters were just basic first attempts

based on processing time. I ran some runs for much longer in an attempt to maximize the fractal dimension of the composition (results are posted in the Dropbox folder) but the results were not impressive. The designs that I chose for the pin up were ones that I felt were interesting.

.50: KK. Fig 13 – The FD is "focused on here stemming from studies that have shown a relationship between multiscale complexity as measured with FD and natural forms such as landscapes and urban environments".... Please explain what you used as a relationship? What natural forms and urban environments did you utilize? How is that applied to the AI process you are proposing?

.51: JD. There is a lot to unpack here and I have had this feedback from others, I think the background section of the proposal could be more detailed with regard to how FD has been used to measure buildings and landscapes. Here are a few quick references:
This is a paper I did that measured the FD for a variety of cities worldwide. https://pdf-s.semanticscholar.org/3972/551af1d28a9f8a001820d0d0f4c05be6a051.pdf Other relevant studies: https://pdfs.semanticscholar.org/7720/41aad09440ef32486103f52bbcf0184dfa91.pdf https://journals.sagepub.com/doi/pdf/10.1068/a211447 https://aperturesinthewall.org/AWcontent/uploads/2015/07/Yan-nickJoye=FractalArchitecture CouldBe GoodforYou=001.pdf
.52: .11: KK. Fig 14 – It appears that this "canvas" has nothing to do with the context of your example project, except for the size and general shape of the building façade. The graphic focal points are the exterior stair and what appears to be roll up doors (which could just be a graphic tool). The applied canvas does not engage the building use/program, existing surroundings, or environment, and it is unclear what is the order or rhythm?
.53: JD. There will be much more detail and relation to context, materiality, program etc. in the subsequent pin ups. However, the garage as a typology was chosen deliberately because of its simplicity in terms of these aspects.
.54: KK. What is that important in the building? How does the design tell me what the building is used for? How does it tell me that this is a Cinemapolis? And simply by applying text (in this case a sign) does not reflect use or form. How am I supposed to know it is a parking garage? Is this important to know? Does it give me any clue to use on the street? How does it engage the street – pedestrian and vehicular interaction?
.55: How does it respond to being in Downtown Ithaca?* This could be "applied" anywhere – could be LA, Seattle, Atlanta, or even Schleswig, IA? Is this important How is this a "holistic approach" or even "retain the spirit of architecture?" How is one to use this at multiple scales (applying the idea of fractals) from the largest urban scale to building detail? **.56:** I think you could have come up with this "canvas" without the help of AI, so how is applying AI to a design process relevant? *This is one of the major problems I have with many current architectural practices – no context, NO Genius Loci. **.57:** I believe that this is one of the overlying reasons why we are faced with issues that you described in your introduction (motivation) of your dissertation proposal. This appears that composition is more important than use or inhabitation. And I dare say that as an Architect we are more responsible to the built form than what it looks like – **.58:** how is a blind person going to address the "space" of this building? How is the use of space defined going to have a positive effect on behavior, communication, or social interaction? **.59:** Using the method of increased FD through "AI" allows for a greater range of exploration that a person would not necessarily be able to physically perform drawing the lines for composition over and over again, in turn, creating endless "crystal isometrics" **.60:** but at what point does the human interaction and need take over? If as designers/architects we only look at composition, then this process would be highly effective. But there is more than just one sense (visual) this tends to eliminate the other senses.

.61: As you are using the AI to form genetic algorithms for architectural design, each evolution should be working towards "better" or different solutions. Otherwise, why use it at all besides being able to generate large numbers of compositions?
.62: What I want to know or understand (especially if you ask me how useful this would be for an architect), I would need to understand for each of the generations what properties are being altered/"mutated" and how and why is it evaluated. Architecture and design should be more than just "what looks good."
.63: As a specific example, it is difficult to understand how to quantify the association between the FD and masses. Using Fig 5 as an example it is stated that the masses are chosen at random and can overlap in the corresponding parameter. Going from one large mass to a series of smaller masses (increased FD) is going to seem to improve the compositional quality, as there is more to engage the eye and mind.
.64: JD. An example that I talk about a lot to try to give some intuition into FD is Jackson Pollock. There is a physicist at the University of Oregon (Richard Taylor) who has been using FD to authenticate Pollocks from fakes.
https://plus.maths.org/issue11/features/physics_world/2pdf/index.html/op.pdf
The intuition is that artists naturally create highly fractal patterns which have self similar detail operating at many scales (scale-free). A rip off Pollock would not have this same quality. The point is that Pollock was doing this naturally without a formal understanding of fractal geometry which only came to light through the work of Mandelbrot in the 80's. **.65:** What if he had a way to measure this innate ability? I think it would perhaps provide opportunities to develop a stronger sense of scale-free self similar geometry. The example I give in the Background of Wright's Palmer house is another instance of an architect having this innate ability yet not having the mathematics or language to discuss/communicate other than its graphic representation which now we can analyze. **.66:** The next step for me is to *realize* such complex visual patterns using modern tools (AI). I would argue that the richness of fractal geometry is more than mere aesthetics or visual interest but has a direct relationship to function in terms of its efficient space filling characteristics. **.67:** This property of fractal geometry has inspired Geoffrey West to develop a theory of biological scaling based on the fractal structurer of uptake and distribution networks. **.68:** Michael Batty who I referenced above has been in close contact with West at SFI and is interested in similar ideas applied to urban form. In terms of Batty's work, one could say a diffusion limited aggregation model is aesthetically pleasing but it is also an efficient structure in many ways. **.69:** But as you indicate, I am unsuccessful in establishing the connection between these properties and the specific elements of design inherent in any architectural project other than the basic elements of composition. **.70:** Of all places to start however, I think the simple elements of point, line and plane have a wonderful universality that can be approached from many perspectives. Dean's 3 lines on a page exercise is so fast and simple that it lends itself to being an algorithm and starting a conversation about the principles of architecture. **.71:** As Dean was often criticized, the concern is that it is only formalistic and does not address the real problem, i.e., how would a blind person experience this space? This is the reason I chose to include experienced Architects only in the review process and not present this tool as a didactic exercise

to teach the principles of design. .**72:** My approach is that this is a tool that can facilitate the experienced designer but does not prescribe the solution in any way. It is more like a tape measure then a generator of form. .**73:** FD is also not a great measure of fractal geometry either so in that sense its being offered here really as a placeholder for what is possible. .**74:** The main drive of the research being really how does design process change when the computer-based tools can also be internalized in the process. The architect or design committee is able to get under the hood and design the algorithm as well as the physical form of the building. .**75:** I have
intentionally narrowed the scope of this (to practically complete a dissertation) to only look at FD and only within the schematic phase of a project. The project solution generated from this study is a quick sketch or charette. Addressing environmental and site conditions or structure, materiality or at a fine grain, waterproofing details I think are the purview of the seasoned hand at the wheel here. Maybe this is not true and the scope needs to broaden within the schematic phase. Maybe with a nod to scale-free self similarity, these other elements of architecture could be included as kind of a macro/mezzo/micro charette which looks at the scale of landscape or urban condition as well as the building scale and human scale and detail scale. Great feedback for sure, my new challenge is to convince you that this tool could be useful to an architect :)

KK/JD. March 28, 2019

.1: KK. First off – Dean told me to look at the works of Dominque Zimbacca, as he thought there was some similarities to what I was doing. If you haven't added him to your catalogue, take a look at his work.

JD. Never heard of him before, thanks for sharing, French Organic school...I never knew... Dean is still introducing new architects to his students!

.2: KK. Next, my thoughts are less about form but how to apply context, human interaction, and hierarchy of needs/uses. Is there some way to utilize your generation protocol to assign the modeling to address such things as needs.

.3: JD. The area where my thesis work comes closest to addressing these essential elements of architecture is in the space filling attributes of fractal geometry. There is quite a bit of research, (mostly coming out of the Santa Fe Institute where I studied for a summer) but also related to D'Arcy Thompson's *On Growth and Form* about efficient space filling geometries in organic and inorganic nature. This relates to your question very loosely. I have not tried to investigate this attribute of fractal geometry. **.4:** I'm focusing on the tool not as a means to design a building or solve an architectural problem but as a tool in a toolbox of many others to be used by designers to assess the level of detail at different scales in the building and to have some metric to talk about 'levels of detail'. Detail could be a graphic pattern at a small scale or the floor plan or master plan at a large scale. **.5:** One could say there is no relationship graphically between these things but I think it is interesting and related to how some architects and schools of architecture have considered organizing a building, such as a repeating motif which occurs again and again in different parts of the building and at different sizes and have different functions and uses. **.6:** So, for instance, the massive, blocky style of Dominique ZimbacCAs furniture reflects the elemental quality of the big overhangs and bold geometry of the building. I would like this tool to develop to the point where an architect's hand or personal style could be identified across different types of objects. Not for this thesis though.

.7: KK. On your architectural construct, the two elements that jump out at me are the pavilion and the tower component; while making the retail and floor plate residential seem less engaging.

.8: JD. That's a good point. Another comment I heard was that I'm not getting inside the building at all. I could explore developing the interior of the floor levels and see how that is expressed on the exterior. I would like to to have the building become more interesting as it approaches the street so this is an important criticism I think.

.9: KK. Why do these elements take such prominence? both physical size and the apparent application of the micro level building block detail?

JD. They have been developed more. I think I could spend more time with the body of the building and especially the floor level facing the street.

.10: KK. how would a custom masonry block relate to the existing adjacent context?

JD. I'm using fractal dimension here to say that there is a similar level of complexity between

the block and the 'block', the smallest building unit and the city fabric at large.

.11: KK. on the smaller tower (above the bus area), might be issues with the amount of glass looking right into the other smaller unit (at intersection).

JD. Right. I noticed that too and decided to not be concerned with it at the schematic level. I guess there would have to be some opaque wall here. I think there is far too much glass generally so adding wall within the fenestration elements might solve this corner problem as well.

.12: KK. are you going to apply this to the extent of furniture and fixtures?

JD. Yes. That is a good idea. The pavilion is kind of going there. I 3D printed a bunch of models of different parts of the building and I would be interested in printing a fixture or a chair prototype.

KK. Otherwise, I very much like the architectural generation(s) and studies that you have shown. It is more clear, once the architectural model has more to it.

JD. Thank you. It is more developed now. PinUp #3 will go further.

End of correspondence.

Kevin Marion

JD/KM. September, 28, 2018

.1: JD. To bring you up to speed and jump right in, here is my latest correspondence based on recommendations David Milstead had made.

.2: In terms of Kandinsky's "Point and Line to Plane" (which I picked up and have been enjoying) I hadn't realized how much music was featured in that book. The relationship between music and architecture has long been a fascination of mine and one of the reasons I was first attracted to Goff's work, his piano roll compositions specifically. I saw them at the Goff exhibit at the Art Institute of Chicago in the late 90's, with Dean Vollendorf incidentally. It is really interesting as a combination of graphic design and musical composition. May beg the question, 'what would architecture sound like?' I recently toured Taliesin East and was made more aware of how important music was to Wright both in terms of the number of pianos and performance spaces as well as the water and wind sounds of Taliesin.

.3: KM. Music and sound in relation to architecture and other spatial environment is indeed fascinating. I am not educated in or talented with reading or performing music, but I love to listen. One of my favorite songs I believe lends itself to some of your design concepts. "Lateralus" by Tool, 2001

.4: JD. Back to 'Point and Line to Plane'...There are some really great examples in that book of basic elements of geometry represented in painting, art and architecture as well as music and dance. He references the tips of Chinese pagodas as examples of 'point' which is so obvious and simple I completely missed it. I was expecting a reference to dentils too which I think Wright likened to the desert horizon line at Taliesin West. **.5:** I also really liked Kandinsky's graphic representations of music which reminded me again of Goff's paintings which seem sometimes like linear musical scores or fancy piano rolls. Again, these ideas are interesting in relation to my thesis because they seem so much like algorithms that create designs (or music in this case).

.6: The 3 lines on a page exercise I am using in the computer algorithm for this project creates random compositions with crossing lines. This is the main idea in Dean's 3 lines on a page exercise, i.e., to use 3 (or more) orthogonal lines to create focal point (center of interest), secondary focal point, counter point etc. Similar to the pagoda example, this is basically creating the element of point (in Kandinsky's terms) which is inherently non existent. A kind of quick way to get at the metaphysical aspect of architecture in a simple exercise. I think this is what Dean was after too.

.7: I my case, I'm using this idea as a generator and then feeding the composition into a computer algorithm that changes the composition based on its fractal dimension. Fractal dimension is a mathematical way to measure how much a 2D object fills the plane. A fractal dimension of 2 would mean that every point on the plane is filled therefore becoming 2 dimensional. Most complex design or natural forms have a fractal dimension which approaches 1.7 or so. This means that it is somewhere between 1 and 2 dimensional. **.8:** Anyway, I use this technique to adjust the designs slightly but any mathematical operation could be used really or combinations of them. **.9:** The basic idea is that in this case the designer is also *under the hood* so to speak in terms of designing the algorithm. **.10:** Dean liked say that the computer was a 'wet medium' and he was inspired by the happy accidents that the computer would make (especially in the early days of 3D modeling) which could have been anything from the way the computer created the image or what it looked like just before it crashed. Things like that.

.10: KM. I do this very thing for my 3d sculptures from which I derive some of my 2d art (and my most recent video art). I am not dictating fractal dimensions or personally developing algorithms, but I'm certain there are elements of both going on within the software operations and they way I manipulate the virtual models. **.11:** Also interesting that 1.7 is close to phi/golden ratio, 1.618. The Fibonacci Sequence was a big player in the composition of "Lateralus".

.12: JD. I'm trying to think in a similar way in terms of how the computer code could be integrated into a holistic design approach instead a simply fancy way to draw. The latest algorithm that I have for pin up two will explore this more and is now an extension for SketchUp that you will be able to download and test drive if you want. **.13:** My friend who is helping me code has implemented a *closed loop* tool in SketchUp that will allow a design to be outputted by the computer algorithm and then manipulated by hand (human designer) and then re-inputed into the computer and on and on. **.14:** This is exciting because now there is a potential for a design that pre exists (precedent) may be fed into the algorithm and adjusted based on its fractal dimension. We haven't gotten quite to this step yet and I don't know if we will for this dissertation but its a future possibility that could be really interesting.
.15: KM. This sounds awesome, as a lot of my digital art is created using SketchUp. I am looking forward to the test drive!!
JD. All of the above is generally an attempt to understand and perhaps influence how artificial intelligence is progressing and how it might relate to the creativity of the designer and the design process. **.16:** Kandinsky writes, "The need of balance in the creative powers which can be grouped under two schematic heads– intuition and calculation . . . " I think this is the nut I'm trying to crack really, how the creative intuition of design may be balanced with new computer tools and potentially an artificial intelligence. **.17:** I don't think this question has been adequately addressed in our modern age and I wonder how Wright or Goff if they were alive today would be using the power of computation to further Organic Architecture.
.18: KM. It would be something to see those guys get a hold of the technology we have today. We saw a little of what Dean was able to do with it in the short time he had and it was pretty incredible. This is definitely a valid endeavor and I look forward to pinup #2!!
.19: JD. I hope this makes some sense, I'm sorry if its not totally clear. I think it will become more clear as this thesis gets going.
I'd appreciate any comments you may have and how your design process may relate or not and how you are thinking about A.I. and the future of architecture. Big topic for sure but increasingly relevant and ominous.
KM. As I mention in my answers to the survey at least once or maybe twice, I feel my academic brain has been dulled by 20 plus years of professional practice. I have had a few shining moments with the rare client that gives some room to flex your design muscles, but more often than not it has been a struggle to output good thoughtful design and then actually have it built as designed. Thanks again for inviting me into this exercise. It has been a welcome and invigorating change of pace!!
JD/KM. September, 28, 2018
.1: JD. Please assess the images in terms of composition, ie., focal point, secondary focal point, counter point, rhythm, etc.?
KM. The nature of DBV's 3 lines on a page inherently creates visual dynamics within the two dimensional realm. The crossing of the first two lines becomes the focal point with the third line defining the secondary and potentially a counter point. Specific rhythm is

already apparently with these first three lines. As more lines are added, more visual movement is introduced and complexity naturally increases.

.2: JD. Is there anything akin to: theme, development and/or variation happening here?

KM. Certainly, the possibilities seem endless on development variation. In practical application, lines can be oriented based on real world conditions. Without context, placement is random, but with true context the placement and orientation of the lines gain meaning and more parameters can be established such as weight, color and material. **.3:** It is the choice of the designer to work with the context or to fight against it. I see this method of having great potential to work in harmony with the context of any project and at multiple scales.

.4: JD. The algorithm being used to create these images selects exemplars based on their fractal dimension [FD]. On the timeline images, FD increases from left to right. Does a higher FD appear to improve the compositional quality of the designs?

KM. I would say that greater complexity is achieved with the higher FD, but not necessarily compositional improvement. I would be my assumption that carrying the exercise further would eventually result in what would seem like a filled page without contrast or definition and eradication of any compositional quality. Knowing that fractals can persist infinitely at scales beyond the perceptive abilities of humans I believe there is a fine line to be discovered by the designer on when to decide to finalize the process.

.5: JD. How do you think this design process could be effective, interesting, or useful for an architect?

KM. As I alluded to above, when combined with real world context, I see this method to hold great potential as a tool to develop designs that respond to contextual elements harmoniously. **.6:** Also, it presents potent opportunity to create design families within the whole, an evolution of elements that relate to one another throughout the project, creating a final result that is ultimately cohesive and meaningful.

.7: JD. How do you think this process relates – if at all – to other architectural design processes with which you are familiar?

KM. I think it is somewhat unique, although I should admit, after years of professional practice with very little recent experience with the academic side of architecture, I am not an expert in current or historical design methodology. I have found a personal approach that combines several different thought processes, DBV 3 line method being one of the primary ones.

.8: JD. Please briefly describe your internal creative process.

KM. I coined a term a while back in grad school, "contextual expressionism.” To me it means expressing one's personal design aspirations while respecting the context. One doesn't surrender to context nor destroys it, but studies it, becomes intimately familiar with its properties, and then applies his or her design within, around and amongst it. The context is not erased, but combined with the efforts of the designer, harmoniously becomes something new that expresses qualities of each party.

.9: JD. Are there any aspects of the algorithmic design tool presented here that you resonate with in terms of your own creative design process?

KM. I find the idea of infinite scale within the concept of fractal dimensions to be an essential part of my creative process. I have a strong desire to create things that relate to their surrounding environments and that have parts and pieces that relate back to the whole. **.10:** Within a completed design these instances may be so subtle that most experience them only on a subconscious level, and only a select few may literally discover the connecting elements.

.11: JD. On a scale of 1 to 5, with 1 being least useful and 5 being most useful, check a box stating how useful you believe this design algorithm could be to an architect.

KM. 4

.12: JD. How do you think you could integrate the design algorithm as a tool in your design process?

KM. In my opinion, mostly on a conceptual level and not as a purely automated process. I think some automation could be introduced, but only with opportunities for the human designer to intervene and massage and adjust results.

.13: JD. Are there changes to the algorithm as you understand it that might make it more useful for you or other architects you know?

KM. Another admission... complex math has become a distant discipline for me, so I may not be fully understanding how the algorithm is being applied. I use various softwares everyday that likely work via algorithmic applications, but I have limited understanding on how that actually works.

.14: JD. On a scale of 1 to 5, with 1 being least useful and 5 being most useful, check a box stating how useful you think applications of artificial intelligence might be to the practice of architecture in the future.

KM. 3.5

.15: JD. On a scale of 1 to 5, with 1 being least useful and 5 being most useful, check a box stating how useful you think the design algorithm demonstrated here might be to the practice of architecture in the future.

KM. 4

.16: JD. What are your general thoughts on the implications of artificial intelligence [AI] to the practice of architecture in the future?

AI holds great potential in being a partner to the human designer, but no more than that.

JD. September 28, 2018

.1: JD. Just read through your comments and they are very interesting. I especially like this, “I would say that greater complexity is achieved with the higher FD, but not necessarily compositional improvement. I would be my assumption that carrying the exercise further would eventually result in what would seem like a filled page without contrast or definition and eradication of any compositional quality. Knowing that fractals can persist infinitely at scales beyond the perceptive abilities of humans I believe there is a fine line to be discovered by the designer on when to decide to finalize the process.” **.2:** This is in line with what I saw when I ran the algorithm for many many runs (2 days worth). I think stopping the process at some point and allowing for the 'hand' of the designer to manipulate the output and then run again perhaps is more the direction I am going with the next iteration of the project (pin up #2).

.3: Your graphic work (paintings) are very much about scale and self similarity, I'm curious to see how you might incorporate this tool in a design, could be interesting. You have stayed in a creative vein with your graphic work, pushing the envelope for sure. I noticed the lyrics in 'Lateralus' speak to this somewhat. Wow, that is a powerful tune. I was not expecting it to hit that hard...ha!
.4: Thanks for participating in this project, your contributions are excellent and well suited to the intent of the project. I'm sensing so far that those who maintain a creative and talent focused design discipline seem to relate to fractal geometry. I wonder of there is something geometric in the mind/brain that is fractal?
Thanks again for your help with this. Maybe I can return the favor when you get your PhD :)
End of correspondence.

David Milstead
DM. July 7, 2018
Sent pinup #1 on 7/19/18. Milstead returned consent on 7/21/18.
.1: Yes it has been a while. Good to hear from you. I did not get to attend the memorial for Jim. It is to sad we have lost him. He left a huge footprint.
I have briefly looked over your project. Are you "writing" a program?
.2: I assume you use a built project and add a bit of info for a new design and the "program" allows for interaction where the interaction comes to a conclusion of a possible new design???
Let me know if I am on the right track . . .
JD. September 25, 2018
.1: Did you see this article in the Times on Goff? It's one perspective but nice to see mainstream press on Goff. I wish some investigative journalist would look into the Bavinger House destruction, such a shame.

Our last conversation covered some the issues I was attempting to raise for my first 'pin-up'. I think the questionnaire I attached to the previous emails was not effective. I have not received any back from a dozen or so architects I sent them to. So for pin-up # 2, I will just ask for feedback in personal email threads. I'm about ready to send pin-up #2 so please stay tuned–

.2 You mentioned Kandinsky's "Point and Line to Plane" which I picked up and have been enjoying. I hadn't realized how much music was featured in that book. The relationship between music and architecture has long been a fascination of mine and one of the reasons I was first attracted to Goff's work, his piano roll compositions specifically. Have you seen videos of those accompanied with the music they make? I saw them at the Goff exhibit at Art Institute of Chicago in the late 90's, with Dean incidentally. It is really interesting as a combination of graphic design and musical composition. May beg the question, 'what would architecture sound like?' I recently toured Taliesin East and was made more aware of how important music was to Wright both in terms of the number of pianos and performance spaces as well as the water and wind sounds of Taliesin.

.3 Back to 'Point and Line to Plane'...There are some really great examples in that book of basic elements of geometry represented in painting, art and architecture as well as music and dance. He references the tips of Chinese pagodas as examples of 'point' which is so obvious and simple I completely missed it. Ha! I was expecting a reference to dentils too which I think Wright likened to the desert horizon line at Taliesin West. I also really liked Kandinsky's graphic representations of music which reminded me again of Goff's paintings which seem sometimes like linear musical scores or fancy piano rolls. Again, these ideas are interesting to me in relation to my thesis because they seem so much like algorithms that create designs (or music in this case).

.4 You mentioned that you like to begin a design or composition with two crossing lines to create a focal point. Is this accurate to say? This is the main idea in Dean's 3 lines on a page exercise, i.e., to use 3 orthogonal lines to create focal point (center of interest), secondary focal point, counter point etc. Similar to the pagoda example, this is basically creating the element of point (in Kandinsky's terms) which is inherently non existent. A kind of quick way to get at the metaphysical aspect of architecture in a simple exercise. I think this is what Dean was after too.

.5 Im my case, I'm using this idea as a generator and then feeding the composition into a computer algorithm that changes the composition based on its fractal dimension. Fractal dimension is a mathematical way to measure how much a 2D object fills the plane. A fractal dimension of 2 would mean that every point on the plane is filled therefore becoming 2 dimensional. Most complex design or natural forms have a fractal dimension which approaches 1.7 or so. This means that it is somewhere between 1 and 2 dimensional. Anyway, I use this technique to adjust the designs slightly but any mathematical operation could be used really or combinations of them. The basic idea is that in this case the designer is also *under the hood* so to speak in terms of designing the algorithm. Dean liked say that the computer was a 'wet medium' and he was inspired by the happy accidents that the computer would make (especially in the early days of 3D modeling) which could have been anything from the way the computer created the image or what it looked like just before it crashed. Things like that.

.6 I'm trying to think in a similar way in terms of how the computer code could be integrated into a wholistic design approach instead a simply fancy way to draw. The latest algorithm that I have for pin up two will explore this more and is now an extension for SketchUp that you will be able to download and test drive if you want. My friend who is helping me code has implemented a *closed loop* tool in SketchUp that will allow a design to be outputted by the computer algorithm and then manipulated by hand (human designer) and then re-inputed into the computer and on and on. This is exciting because now there is a potential for a design that pre exists (precedent) may be fed into the algorithm and adjusted based on its fractal dimension. We haven't gotten quite to this step yet and I don't know if we will for this dissertation but its a future possibility that could be really interesting.

.7 All of the above is generally an attempt to understand and perhaps influence how artificial intelligence is progressing and how it might relate to the creativity of the designer and the design process. Kandinsky writes, 'the need of balance in the creative powers which can be grouped under two schematic heads– intuition and calculation...' I think this is the nut I'm trying to crack really, how the creative intuition of design may be balanced with new computer tools and potentially an artificial intelligence. I don't think this question has been adequately addressed in our modern age and I wonder how Wright or Goff if they were alive today would be using the power of computation to further Organic Architecture.

.8 I hope this makes some sense, I'm sorry if its not totally clear. I think it will become more clear as this thesis gets going. I'd appreciate any comments you may have and how your design process may relate or not and how you are thinking about A.I. and the future of architecture. Big topic for sure but increasingly relevant and ominous.

DM. January 26, 2019

.1 The last email between us was July 22, 2018. Just went back and read a couple of the emails. One mentioned that there would be three interviews.....I guess that is over? Let me know if you are still working on this. Have a lot of work still. I have always taken up the task of getting the Rosenbaum shed rebuilt. Attached is a photo I took of it in 1993 along with my first draft of the floor plan and elevation.

End of correspondence.

Tomasz Mlynarski

TM. April 14, 2019

.1: It is difficult to see the GA having a substantial effect on the design output in the timelines. **.2:** I think the theme would be in how the FD fitness function drives the design to a certain conclusion.

.3: I would say it is difficult to see in these examples how the generations change, refine, or converge to a better solution.

.4: The incorporation of objective fitness criteria such as FD is interesting in that it can compare different programs and styles and asses their fitness equally.

.5: On a scale of 1 to 5, with 1 being least useful and 5 being most useful, check a box stating how useful you believe this design algorithm could be to an architect: 4

.6: Yes, FD seems interesting in how it can be used to compare buildings that are very different in style and program. It's also interesting as a tool for judging options of the same design as you demonstrated here.

.7: On a scale of 1 to 5, with 1 being least useful and 5 being most useful, check a box stating how useful you think applications of artificial intelligence might be to the practice of architecture in the future: 4

.8: On a scale of 1 to 5, with 1 being least useful and 5 being most useful, check a box stating how useful you think the design algorithm demonstrated here might be to the practice of architecture in the future: 4

.9: It's a great tool that is still being worked out. Your research here is one step to making these types of algorithms more relevant to design.

TM. April 14, 20192

2.1: I reviewed your dissertation, and my comments follow below. I also answered the questionnaire. I would first say that in general, you have the right approach to much of the work in that you understand the importance of the input of the designer in the process. Much of this work, in the beginning, would want to have the machine create everything and designer intervention was seen as somehow contaminating the result.

2.2: I think the most compelling thing about your work is this incorporation of fitness criteria rooted in FD. It seems FD can be used as a fitness criterion for all sorts of a different building with different styles and different programs and you can use the same criteria to rate them all. That is something fresh. You are no longer bound to rather simple fitness criteria like plan efficiency or exposure or whatever. So this is the most substantial part of your work.

2.3: If I had to be critical, I would say it is not clear how the GA refines its solution over time. It seems like each generation is rather different from the previous and there are no different lineages or families of solutions. However, maybe I'm misunderstanding something in the Pin up.

JD. April 16, 2019

.1: Thanks for your thoughtful responses and for filling out the questionnaire. I have one follow up I would like to ask. In terms of the role of the human designer. Do you think computer-based algorithmic tools can make what humans do as distinct from what a computer can be programed to do more clear to us and help us improve that whatever it is? I guess I'm asking what that human aspect is to you as an architect?

I know this is a little open-ended but if you have any insight I think it would be useful.

TM. April 19, 2019

.1: If the question is whether I think it would be possible to design an algorithm that can create a building with the same detail and articulation that a human can, then I guess the answer would be yes. Although I think the effort that it would take to create such a tool would be greater than if a human was to do it in the first place. Much like already and for probably a decade at this point we have had robots that can be programmed to lay brick. Even though the robot can perform the task quicker the logistics of preparing such an operation in programming and set up make it easier and quicker to have a person do it.

.2: So to me, it is about what moments in the design process can we use these tools where they can generate nonobvious answers. If the design is a process and intuition, and experience is the base of certain design decisions, what are moments in the process where a GA can create the most impact? In that, I think the most significant potential would be in GA's that provide specific solutions to some particular targeted issues. It might also help if these tools were less project specific and more generalized. That is why I think this idea

of incorporating FD is so exciting. It's such a flexible method for providing feedback back into the GA.
End of correspondence.

Stan Russell

Sent pinup #1 on 7/19/18

SR. July 19, 2019

.1: I think this is a wonderful tribute to Dean. As much as we tried, it's too bad we couldn't convince him to further document his teaching methods. Gary had even sent him a recorder, to get started, but the only times he recorded anything, he would get started on his background, etc., then wander off into some of his stories. It was pure Dean! **.2:** When Jim passed away, I could imagine him getting to the pearly gates, only to find a Dean waiting on him saying, "Finally, you're here! I've been waiting on younobody here understands me!"

.3: One of my Clemson classmates, who went on to get a PhD in Architectural History, presented a paper a few years ago to the Southeast Society of Architectural Historians, entitled "Organic Expressionism in the Carolinas." I thought he did a good of documenting, briefly, Dean's methods in the studio. He was certainly one of a kind.

JD. July 19, 2019

.1: I wish I could have been at Jim's memorial, it would have been nice to be up in Highlands again– glad Jim had such a good run there.

.2: Here is what I have come up with for a thesis for my dissertation and how I incorporated Dean's teaching methodology. I'm using the 3 lines on a page exercise as a point of departure for exploring architecture in the computer age. I tried to make everything as self-explanatory as I could and to use images as much as possible to communicate and not words. I think Dean would appreciate that.

.3: Computers are having a huge effect on architecture, obviously, and Dean appreciated this future reality, I think, and jumped right in. I am inspired by his comment that the computer is a 'wet medium' and how much Dean loved to find serendipity everywhere, including on the screen. I have tried to push this further (standing on the shoulders of those that have come before) with this thesis. I'm curious to hear what you think.

SR. July 20, 2019

I contacted my friend Al Willis and he said he would be happy for me to share his paper (attached) with you. Also, he said he would be happy to communicate with you regarding Dean's teaching methods. Al is a very bright guy, kept in touch with Dean and was interested in Dean's teaching methods, over the years.

JD. July 20, 2019

Ha! That's a great image of Dean and Jim at the pearly gates. Love it...
Thank you for taking the time to look over this stuff. I am going to look for the paper you mention and see if I can find it online. Organic Expressionism in the Carolinas. I should reference this for my final dissertation for sure.
End of correspondence.

James Walter Schildroth
Sent pinup #1 on 9/26/18

JWS. September 27, 2018

.1: Your thesis is most interesting. I have tried to understand Dean Vollendorf's approach that you are putting forward. I really never could. I always enjoyed the architecture he made but could not see how this graphic exercise was enough to make real architecture. **.**
2: I think that Wright and Goff had a more comprehensive intuitive mental process. I have also worked my design from within my mind and not as a formula or graphic exercise.
.3: I see the new technology as tools that help me present and do construction documents. My design work is mostly done in my mind before any lines are drawn.
.4: I know this is not supporting what you are putting forward but it is my way.
I am going to attach an essay on Fractals and the unit system that I wrote a few years ago. I am willing to continue a discussion with you if you can stand it.

JD. September 27, 2018

.1: Thank you for looking through my work so far. I am planning to send pinup #2 shortly, and it will be more integrated with accessible software. Do you use SketchUp at all for presentations? Some folks are using SketchUp for basic working drawings now.
.2: I think the relationship to fractals and using a unit system such as an orthogonal, triangular or hexagonal grid and radial grids is powerful. In my proposal (attached), I talk at length about fractals in nature and in architecture. An example I like a lot in terms of multi scale self similarity is Wright's Palmer House (below).
.3: I agree there is a more fundamental intuitive or subconscious thing involved in what designers do that can not be captured in a simple line exercise. I'm packing this into the word 'creativity' and sometimes "human creativity." **.3:** Do you think there is a way that the computer or advanced AI in the future may play a role in this deep intuitive/creative process somehow? **.4:** I think the mathematical and complex geometrical ideas we create as designers may be understood and assessed with the analytic power of the computer. **.5:** I wonder how the computer may or may not augment our innate creative ability. For instance, perhaps teaching us to 'see' more deeply into multi scale self similarity of complex geometry. Kind of like training wheels for the mind...
.6: Focusing on the organizing principle early on as grammar and a geometric unit system could also include establishing the algorithm in some way. For instance, the 3 lines on a page exercise establishes an orthogonal grid in some way (or could easily be thought to incorporate a grid). **.7:** I remember Dean saying Goff differed from Wright in the sense that Goff said the grid was 'discovered' through the process, whereas, Wright definitely began with the grid and worked from it. Do you agree?
.8: I love the idea you write about that the unit system and fractal geometry is the basis of all natural form and architecture that grows from this idea is in relation to nature. Fractal geometry is like being outdoors.

JWS/JD. September 27, 2018

.1: JWS: I have tried to learn Sketch Up. I have the program but not very good at it. My friend Goff Machline and others have done all my renderings in Sketch Up.

.2: JD. I think the relationship to fractals and using a unit system such as an orthogonal, triangular or hexagonal grid and radial grids is powerful. In my proposal (attached) I talk at length about fractals in nature and in architecture. An example I like a lot in terms of multi scale self similarity is Wright's Palmer House (below).
.3: JWS: I really don't see fractals in the Palmer House. Of course there are equilateral triangles. The unit is made with equilateral triangles. The plan is made by relating all parts of the plan as it is made to the unit system. The design is not made by repeating self similar triangles. The unit system give the whole unity. I think this unity approaches the unity in all of the natural world. What we call beauty.
.4: JD. I agree there is a more fundamental intuitive or subconscious thing involved in what designers do that can not be captured in a simple line exercise. I'm packing this into the word "creativity" and sometimes "human creativity." **.5:** Do you think there is a way that the computer or advanced AI in the future may play a role in this deep intuitive/creative process somehow? I think the mathematical and complex geometrical ideas we create as designers may be understood and assessed with the analytic power of the computer. I wonder how the computer may or may not augment our innate creative ability. For instance, perhaps teaching us to "see" more deeply into multiscale self-similarity of complex geometry. Kind of like training wheels for the mind!
.6: JWS. I am sure in the future a computer program will be able to design a building. I don't think it will be able to design Organic Architecture.
.7: JD. Focusing on the organizing principle early on as grammar and a geometric unit system could also include establishing the algorithm in some way. For instance, the 3 lines on a page exercise establishes an orthogonal grid in some way (or could easily be thought to incorporate a grid). **.8:** I remember Dean saying Goff differed from Wright in the sense that Goff said the grid was "discovered" through the process, whereas, Wright definitely began with the grid and worked from it. Do you agree?
.9: JWS. I don't think that Mr. Wright started with the unit system. Mr. Wright conceived the building in his mind as real space. He put himself in the experience and worked the whole thing out in his mind before any drawing. .10: When he could see the design in his mind and walk through and round it in his mind is when he selected the unit system to use. So both Wright and Goff discovered the unit through the process. By the way that is how I have worked since 1960.
.11: The 3 lines on a page exercise is a composition. Making Architecture is a far more complex process that only the human mind can do. I use mind and not brain. I believe that the human mind can gain ideas from the collective unconscious not just the limits of a single human brain. The computer can never do this.
.12: JD. I love the idea you write about that the unit system and fractal geometry is the basis of all natural form and architecture that grows from this idea is in relation to nature. Fractal geometry is like being outdoors.
.13: JWS. Nature is fractal. Organic Architecture is of Nature not applied.
JS. March 26, 2019
Pinup #2

.1: Just watched you presentation. *The Holographic Universe* was an important book for me. I read it in the mid 1980's. Less about making form for me. It was more about the interrelationship of everything. The human mind as the creator. I was trying to sort out my old belief in religion and find an understanding that aligned more with Nature. Along with reading many other books in my search I did if a new way of understanding how life works.
.2: I like your mind. I may not agree with all that you putting forward in your thesis but I can see what you are doing. I will follow you work with great interest.
.3: We both have a relationship with Dean Vollendorf. He is a strong force. I must say that I could never totally understand his process of design. What bonded us together was the results of our individual design work.
.4: I believe that Fractals are a part of nature and in all of the natural form of the universe. You seem to be proposing that creativity can somehow be done by computers and formulas. This is where I differ. The human mind is, I believe, connected to all this, all the time. It is this connection that informs creativity. Your idea may produce patterns but the real genius of ideas is the mind's connection to the Holographic Universe.
JD. March 29, 2019
.1: The more I study fractals the more convinced I am that they are a new and meaningful way to understand Organic Architecture and Mr. Wright's work. **.2:** The paper linked to above is a fascinating look at the algorithm evident in the Palmer House and Price Tower. The author's invention of a quasi repeating motif explains the fractal organizational structure of the plan and explainslike you mentionedthat it's not simply about a repeating triangle at different scales.
.3: I feel more and more that Mr. Wright was specifically exploring fractal algorithms but not calling them that but referring to 'wholes and parts' and nature and life. **.4:** It would be very good to explore all of Wright's work for the use of fractal algorithms in his organizational strategies. This is exciting to me because it is relatively a new approach to assessing Organic Architecture and has not been written about much or systematically incorporated into the profession. **.5:** This may be exactly what we as designers are doing in our heads when we put forms together. Does this relate to your design process?
.6: I think a problem in how I have been presenting my thesis work is that it is in some way about using a computer to create forms independently of a designer. This is mirrored in the Computer Science field when they use terms like "artificial intelligence" to represent computational tools or "machine learning" as if the computer is a living organism. **.7:** This is even more hyperbolized in contemporary theories of consciousness by the like of Daniel Dennett and others who suggest that our folk theory of "consciousness" is an illusion. But this is tangential.
.8: I am not thinking that design can be replaced by computers but that computational tools can allow us to explore and understand better what we automatically have been doing as geometricians and architects all along from time immemorial. **.9:** The linked paper is worth a quick scan, I think you will enjoy it. I would like to apply the computer tools I have been working on more in this direction – to explore the design of algorithms that can iterate and produce complexity of form. Designing the seed that can grow into form.

.10: Thank you for being interested in this work and your brilliant insight expressed in your work. I may be a little over the top with all this, and I apologize if I am coming across too strong, but I can't help but think this is a major turning point in understanding Organic Architecture and having new tools to communicate it to the masses and juxtapose it with what it is not.

JWS. April 6, 2019

.1: Two things are important in my understanding of Mr. Wright's process. First, is his incorporation of an experiential knowledge of living with nature. The second is his development of the unit system as a way of giving a unity to the whole of his designs. **.2:** Yes, one can find Fractals in all of Wright's work and just as they are found in all of nature. The finding of fractals in the plans is not the result of his putting them in but they result from the establishment of a unit before starting the plan. Working with a unit system give a kind of natural unity of the whole because every choice made during the process of design is made in relationship to the unit. The result is fractals.

.3: I have used unit systems in my work since about 1950 when I was first introduced to it by Will Willsey, Architect. I have used the unit system on every design since, even additions and remodeling jobs.

JWS. April 6, 20192

Forwarded e-mail between JS and students at Taliesin West.

.1: Unit System. I use a unit system for every building I design. I pick it based on the materials I select before designing and many other reasons. It provides unity in the design. As you work out a design you will make 10,000 choices. With a unit system as an organizing guide, the choice of say where to locate a wall can be made on the unit or half unit or quarter unit. Or if there is a specific location that is not on any of these, then that is OK. The unit will just give you organization without really thinking about it. **.2:** I believe the unity results in architecture that is more satisfying to humans. It approaches the order and unity we experience in the natural world. It is implicit and as human beings we have come to see this as satisfying. Nature is the great teacher. **.3:**
Frank Lloyd Wright used both a plan unit and a vertical unit. **.4:** The good old square four feet on a side is a good unit with which to start if this is your first time.

.5: I pick the unit system after I choose the materials and structural system. The budget also is a factor. The general feeling of how the building may function and the functional relationship to the site is also a consideration.

.6: But the unit system is always selected before any design plans are started. First, the site plan is drawn with the features and topography shown. The next on top of site plan is the unit system.

.7: The building material abode or stucco is really only a plaster on the surface of a base material. What is the base material? There are other materials to take into consideration such as the floor, the roof structure, the windows, and the doors. Each of these may suggest the unit system selected.

.8: Materials: I choose the materials for a house before I design the house. I pick a material because each material selected has properties and a nature that will direct and inspire the design that will develop. Some materials make square form very well but cannot make angular or circular forms easily and must be forced.

.9: I pick materials for many reasons before design. It you have a feeling that your project needs the fluid feeling that is curvilinear then look at using materials that can accommodate this kind of design. The material will have properties that will affect the way the design is detailed and shaped. Concrete sprayed, concrete block, concrete placed in forms all concrete but very different properties and construction methods. If you choose one material it will help suggest ways to work with your design.

.10: Lumber is mostly square and rectangular as it comes from the lumberyard. It is what is used here in Maine for most residential construction. **.11:** I often start with a material and look at the detail I will need at the changes, at the doors, windows, corners, and also at the ground and the roof or sky. I ask how would I make these details with this material? This is first before any plan or design. How does the material detailing help me make form and light filled space?

JD. April 8, 2019

.1: I agree with you that the fractal geometry or fractal-like qualities we see in Mr. Wright's work and other organic architects such as yourself are outgrowths of using a repeating module and being influenced by forms and growth patterns in nature. **.2:** But it should be said that just because a design uses a module it doesn't necessarily mean the geometry is fractal. For instance, I don't think Corbu's or Mies' work is fractal. Just my opinion.

.3: Thinking about the organizing principles in Organic Architecture as fractal algorithms is only one approach to better understanding and appreciating this work. Mr. Wright himself, of course, didn't use the term *fracta*l because it didn't exist at the time but he does talk about similar ideas in terms of parts to whole, designing from the inside out and being inspired by NATURE. **.4:** The use of the term “automatic” is especially interesting when applied to the Usonia block houses which could be built “automatically” by their occupants but also in a sense could generate “automatically” as a pattern based on a module and simple rules that define a process.

.5: I think a key difference between fractal geometry and other geometries is that fractals require a couple of iterations to establish the repeating pattern. In mathematical fractals these are precise rules defining subsequent iterations, but in architecture it may be more relaxed and intuitive. A fractal geometry has the sense that it can be extended indefinitely.

.6: Much of Mr. Wright’s work has this feel that both in site plan and in scale the design could continue beyond its current form and still feel “of a whole.” Again, I don't think this is true of classical architecture.

.7: The attached drawings are from my sketchbook and attempt to illustrate the idea of a simple pattern that repeats at different scales like a simple algorithm. **.8:** This idea is also closely related to the idea of a motif which is repeated at many scales and in many different functional solutions, say from furniture to a site plan. This is what I think Dean was after in his code <–> message idea. The code is like the scale invariant motif that repeats in an open ended way and has many functions (message). **.9:** Anyway, just one way to look at it but I think there is a lot more unpacking to do with applying the mathematics of fractals to the analysis of Organic Architecture as well as using it for inspiration in creating new things.

JS. May 5, 2019

1. All Mr. Wright's work was done on a unit system. The unit system is about unity and develops patterns by the relationship of thousands of choices that each relate to the unit. The result of working like this may produce fractals.

End of Appendix