Fractal dimension as objective function in genetic algorithms, towards a new paradigm in architecture

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"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).

1.0 Introduction (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 only 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 (Fall, 2017) we have seen some of the worst wildfires ever 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.

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, we 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 Jacob's quote above. We must identify the problem we face as one of *organized complexity.*

Solutions to the global challenges we face undoubtedly require a wholistic approach that looks at the problem from multiple perspectives. One important and powerful perspective is that of the designer. Design is not only an aspect of how we make sense of the world around us but also how we alter or change the world around us. 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). 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 innocuous part. From a systems perspective this is a leverage point. A leverage point represents a part in a large and interconnected system where a small change in a part may have a synergistic effect on the whole. Design represents such a leverage point which has the potential to alter the direction we are headed in terms of how we steward our environment.

1.1 Approach

Another way of thinking about design is in how we manage data. 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 produce new data. Managing the incredible amount of data available in our modern world has paralleled the development of computer technology and we have come to rely to a large extent on computational approaches in analyzing 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 towards strong artificial intelligence. Another milestone in this progress happened recently in May of 2017 when Google's program AlphaGo beat a master player at the game of Go. Artificial intelligence (AI) as a generative tool has the potential to profoundly affect our physical environment. Architects must incorporate this technology if we are to remain relevant and address the complexity inherent in designing our built environments.

The following section discusses how the design profession is responding to the complex challenges we face by incorporating computer technology and artificial intelligence into the design process. This shift represents a paradigm shift and in some important ways designers must rise to the challenge of incorporating modern technologies while at the same time remaining valid within an increasingly automated process.

Researchers and designers are beginning to rise to Jacobs' challenge by utilizing computer based tools to address the problems facing us today. The real-world problems architects must face are multifaceted. They represent a gradient from coarse to fine grained issues such as: ecology, civilization, culture, economics, typology, precedent, life-cycle, energy/resource use, ergonomics, materials and tectonics etc. 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.

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 built and consequently on our built and natural environments.

Recently, however, we have seen in architecture the influence of computer aided design (weak AI) gaining momentum as architects borrow data mining techniques and analytic computational approaches to help solve the "wicked" problems our built environments represent, although a comprehensive theoretical and pragmatic approach is still lacking (Buchanan, 1992). 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 that applies rigor and analysis to the creation of form. The field of design science anticipated by Fuller and others is still in its infancy and much remains to be done to bridge the gap between science and design.

We may now have the tools necessary for assessing the scope of the problem but AI by itself remains largely a black box in the architect's world. It is important to integrate AI as a toolset within a context and culture of architecture to more adequately address the problems we face while retaining the essential aspects of architecture such as precedent and creativity that make architecture what it is. The question then becomes not simply how can we apply science to architecture, for instance using the power laws we observe in cities to improve the way we design buildings but rather – how can we do this and retain the spirit of architecture?

1.2 Computer-based design

This section provides an overview of computer based design tools available today and how the notion of design and the design process are changing. I describe how these tools might integrate within a new design process to help address the complexity inherent in the problems faced by contemporary architects. I offer an introduction to two computer based tools that have been filtering into the design professions from computer science, genetic algorithms (GA) and fractal dimension (FD). Finally an introductory outline is provided of the case study project proposed as a proof of concept for the design process we will develop.

In the field of architecture today, rigorous analytic tools have filtered into computer aided design (CAD) platforms. These tools are collectively referred to as *parametric design* and include building information modeling (BIM) and smart city modeling (CIM). This development has begun to change the notion of design itself as the use of computational tools in the design field has moved the architect away from traditional design – architect as the originator of form – to something we might call *algorithmic design* or *generative design*. Here the architect is the co-developer of computer-based processes that result in physical form (this parallels the appropriation of the term 'architect' to refer to a software developer). Computer based tools are changing the traditional ways that designers design. The shift away from the design of an object to the design of an algorithm could be thought of as a shift from product to process. This shift is also a shift toward automation and potentially a form of strong artificial design.

It is important for the human element to remain a substantial part of the design process. This proposed research stresses that the role of the human designer and human creativity is necessary in producing quality designs and quality environments and must remain or, in some sense, be re-introduced into the design process. It is important to maintain the traditional time-tested vocabulary of architecture and the human-centric elements of the design process such as how the architect processes and interprets precedent and influence and develops his/her style or *hand* (Zarzar, 2003). It remains to be seen if the advances in computer technology and science will be wedded with the traditional practice of architecture yet it is vital that this occur.

There is a gap between traditional architecture and emerging technologies that calls for a new science of design (Buchanan, 1992). To help close this gap the proposed research will develop a design process that draws from AI and the science of cities as well as other scientific disciplines including cybernetics, systems science and complexity science.

Cybernetics, systems science and complexity science offer important lessons and a helpful toolkit to help to understand and manage the paradigm shift in architecture described above. Ideas from these fields that have filtered into the architects domain include: emergence, self-organization, cellular automata, genetic algorithms / programing and fractal geometry to name a few. Two of these tools which will be used in the proposed research are genetic algorithms (GA) and fractal dimension (FD). GAs are computation-based analogs of evolutionary processes in nature. GAs are programmed computer models based on theories taken from evolutionary biology such as *mutation*, *sexual reproduction* and *selection*. Selection is based on survival within a fitness landscape. "Survival" in this sense is simply some objective function that determines which variants within a generation are allowed to reproduce. GAs solve complex problems from the bottom up in much the same way as nature does (Mitchell, 1998). This research focuses on fractal geometry, specifically the box-counting dimension (BCD) as an objective function for developing a GA as a sub-system within a generative design process. FD will be used as a coarse grained measure of spatial complexity both for its equivalence to other information theoretic models and for its deep relationship to principles in architecture and nature. The next section describes why FD is an adequate measure of complexity and how it has been incorporated in biology and architecture.

A key aspect that may explain why larger cities are more efficient than smaller ones is the same reason that larger animals live longer than smaller animals, namely the geometry of their uptake and distribution mechanisms. West and others have argued that these mechanisms are fractal in their geometry and this helps explain economies of scale or why larger systems are more efficient than a simply scaled up version of a smaller system. Fractal geometry is self-similar at many scales and can fill space more densely with less overall network 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 conduits in a building. This idea is over simplified in some ways but it does hint at a parsimonious approach to gauging the organized complexity of a system in terms of its multi scale self-similarity.

Fractal geometry and its corresponding measure, 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 to 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 70s. Today, conformal field theory (CFT) in physics applies the notion of scale invariant self-similarity and conformal bootstrapping to notions of universality in high energy physics, quantum gravity and in mathematics, ergodic theory investigates conformal iteration in the study of dynamical systems (Przytycki, 2010). As mentioned above, the physicists West and Bettencourt have developed mathematical models which apply notions of scale invariance and self similarity to the life sciences including cities and architecture (West, Bettencourt, 2007).

A developing body of research exists for applying FD to urban planning, architecture and art as an analytic tool and to a more limited extent as a design aid. Fractal geometry has been cited by various sources as being an organizing principle in architecture and cities both historically and as a design principle in practice (Bovil, 1996) (Batty, 2007) (Ostwald, 2013). Often, however, fractal geometry has been interpreted as patterns applied as a 2-D surface treatment to buildings rather than as an integrated organizing principle at the heart of a building's parti or deep structure. Some research has shown that for two dimensional spatial data representing large systems, FD approaches its maximum value of 2 without quite reaching it. For instance, cities tend to reach a maximum FD between 1.7 and 1.8 (Abundo et al., 2013) (Encarnacao et al., 2012). Individual buildings that have been analyzed with FD are slightly lower than those of cities. For instance, a selection of designs by Frank Lloyd Wright range in FD from 1.5 to 1.6 and those of Le Corbusier are between 1.4 and 1.5 (Ostwald, et al., 2015).

In the art world, 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 Taylor and his team use have been shown to be a signature of the "hand" of Pollack 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). FD has been shown in these examples to be coarse grained approach to assessing the multi scale self-similarity in cities, architecture and art and a computationally inexpensive indication of complexity. However, the quality of a design is not indicated by its FD alone (Lorenz, 2004). I make the assumption that quality design requires human creativity which is not so easily analyzed. To our knowledge, a systematic study of the rigorous use of fractal geometry as a component of a creative design process has not been undertaken.

The research agenda for this dissertation will look comprehensively at the use of fractal geometry as an organizing principle for design. Fractal geometry is one approach to understanding and designing for the "organized complexity" Jacob's believes that nature and cities represent. The integration of fractal geometry as an analytic and generative tool within the design process promises to provide the architect with greater means and flexibility when designing solutions to complex problems. I explore from the architect's perspective the potential for genetic algorithms and fractal geometry to enrich the architectural design process towards a more comprehensive and ecologically sensitive approach – one which reflects the complexity of our modern world. I will apply this design process to a real life charrette with a team of architects and other experts in the field of AI.

The proposed research will develop and test a design process integrating fractal geometry as a means to produce higher quality designs. This problem will be approached as a multi-variate search problem. In terms of the complexity inherent in architectural and urban planning issues it is assumed this problem cannot be optimized for but that optimization can be approximated through search heuristics. The proposed research will develop a genetic algorithm (GA) for this purpose that is programmed to select for geometries that have higher FD in successive generations of design variants. After a number of converging generations, the highest FD geometries will be selected and used as schematic design impetuses in a human-centric design charrette and then re-introduced as baselines for additional GA runs.

The human-centric phase of the design process will incorporate the precedent of historic styles as well as a formal design methodology and critical review by a jury of experts. The jury will serve ultimately in assessing the quality of the designs achieved in the form of high FD outputs of the GA as well as in the form of designs for a real world case study project in an urban context. Additional analytic metrics will be applied to exemplar variants and human-centric designs to assess efficiency. These will include volume to surface area relationships and circulation space to occupiable space relationships as well as other basic performance measures which will be relative to software used and develop as the project progresses. The design process this research will develop will be tested in a case study.

The case study proposed is a "real world" design project that incorporates the design process introduced above. The design project will be a schematic design for an exhibition pavilion for a site in a historically significant context. The design project will be reviewed by a panel of experts constituting a jury who will review the design process over a number of critiques.

The next chapter provides a detailed background into the history of architecture and how it relates to cybernetics and systems theories as well as contemporary state of the art computer science and machine learning. The background and literature review for this research focuses primarily on the the use of fractal geometry as a design principle and analytic measure in architecture through the lens of general systems theory and complexity science with a focus on genetic algorithms. The overlap between architecture and recent advances in computer science is emphasized with particular focus on the fractal component of architecture as well as fractal dimension as an analytic tool and scalar measure of "complexity" as discussed in the literature (Mitchell, 2009). The background section is focused on the use of genetic algorithms in computation and design and then move on to a detailed review of fractal geometry in architecture historically and how it is used as an analytic and design tool today. Chapter 3 outlines the methods to be developed including the design process proposed, the objectives set forth, and the real-world case study project offered as proof of concept. Chapter 4 describes the results of the case study with regard to the objectives outlined in the methods section. Chapter 5 briefly outlines a discussion chapter that will interpret the entire project and offer lessons learned. This chapter will also summarize the contributions to architecture and science and conclusions that can be drawn. A final section describes future work.

2.0 Background

A background of architecture with regard to systems science and complexity science is provided in this section. Systems science and complexity science are used as a framework for this thesis because of their comprehensive agenda. General systems theory (GST) is envisioned by Bunge (Bunge, 1977) as a *scientific metaphysics* and offers an array of processes and tools for engaging large unwieldy problems which overlap with many disciplines including architecture and design. 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). Klir offers a common sense definition of a *system* as simply a set of things and the set of relations among them (Klir, 2013).

$$S = (T, R).$$

Epistemologically, a system as defined by 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* in the following diagram (Fig. 2.0.1) (Lendaris, 1986).

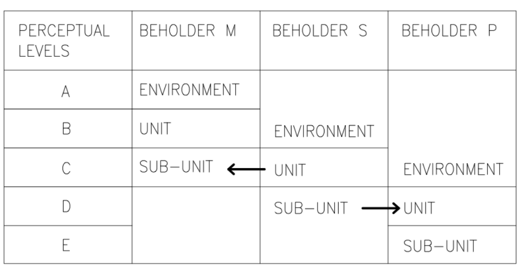

FIG 2.0.1. System diagram (Lendaris, 1986). Redrawn by author.

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. GST is concerned with pattern of relations and processes at multiple scales and over time. Complex systems are characterized by feedback loops between many variables. As such, systems approaches are particularly suited to the understanding and practice of architecture and design. Simon, in developing hierarchy theory, makes a distinction between *complexity* and *complicatedness*. To Simon, complexity represents the behavior of a structure with many levels and parts or sub-systems coordinated within an overall framework or hierarchy. 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 often having very complicated behavior (Simon, 1996). An example of complex behavior may be the traffic patterns in New York City, whereas, an example of complicatedness may be the traffic patterns in Mexico City.

Architecture is fundamentally systems oriented in the sense that it has to do with many interrelated parts over a range of scales. What is now called systems theory has been a topic at least since Aristotle's Poetics (Aristotle, Golden, 1968). In modern times artificial systems have been studied in the cybernetic project of the 1950s (Ashby, 1961), (Wiener, 1961) and Simon's, Sciences of the Artificial (Simon, 1996) to current research in complex adaptive systems (CAS) such as living systems and evolutionary programming. In today's increasingly complex world, where we face the motherlode of wicked problems, systems approaches have undergone a renaissance of sorts. Important multi-disciplinary research into complex systems is happening at the Santa Fe Institute (SFI) and New England Complex Systems Institute (NECSI) among others. This research agenda includes a variety of concepts such as: edge of chaos, emergence, self-organization and open systems far from equilibrium within the general study of artificial intelligence (AI) and artificial life (AL). Active research also includes new approaches to understanding biological and urban scaling through the application of fractal geometry (West, 2005), (Bettencourt, 2013). Fractal geometry is an important aspect of complex systems research and can in some ways be used as a precise mathematical measure of complexity in the form of Hausdorff dimension which is also called fractal dimension (FD) (Mitchell, 2009). Fractal geometry and fractal dimension is central to this thesis and will be discussed further in section 2.2. The research and theory discussed above offers many tools for assessing as well as designing systems and provides an appropriate theoretical and practical framework for investigating systems in architecture.

To borrow from the field of Artificial Life (Bedau, 2003), we may think of systems in architecture as three types: *hardware*, *software* and *wetware*.

HARDWARE: In terms of *hardware*, architecture is concerned with many inter-related physical parts (brick and mortar) and it would be easy to list examples of physical systems and subsystems which the architect must coordinate within a design. Some generic categories of physical systems in architecture are: structural systems, mechanical systems, electrical systems, plumbing systems, glazing systems, waterproofing systems etc. The physical and ecological context for a building can be thought of as a supra-system in Lendaris' terminology. Architects must integrate all these various systems together into one relatively integrated whole if a building is to function properly. Some architects have also developed meta-systems or systems of systems towards a more unified approach to managing the sub-systems within a building. One such approach was developed in the 1960's by Ezra Ehrenkrantz called School Construction Systems Development (SCSD) (Boice, 1965).

SOFTWARE: Architecture is also concerned with *software* or computer based systems. These systems include computer modeling, computer aided design (CAD) and building information modeling (BIM). These types of systems are currently developing in a variety of ways and fall under the general heading of *parametric design*. Parametric design is a manner of design where parameters and rules are encoded algorithmically and allow designers to utilize various aspects of CAD and BIM to solve complex problems. These problems are increasingly multi-variate and data driven ones that require mathematical analysis and computation based search heuristics that were, until recent times, unavailable to the architect. Genetic algorithms (GA) and evolutionary programing are examples of these types of computation based systems and have given the architect powerful new tools to invent and study form. Galapagos is one such tool and represents an out of the box genetic solver plug-in for Rhino Grasshopper tailored specifically for architects and urban designers (Rutten, 2010, 2013). Genetic algorithms and evolutionary programming will be discussed further in section 2.1.

WETWARE: Architecture is also concerned with *wetware* or the socio-technological dimension. This includes the behaviors and needs of people which has a pragmatic dimension in the sense of habitable and occupiable space as well as the historic and cultural context which can be thought of as a supra-system. I also include cybernetics in this category or the hybridization between living organisms and technology. Wetware also suggests a more ephemeral dimension in terms of: meaning, beauty, culture etc. This abstract / symbolic dimension is important to mention because it gets at some of the ontological aspects of architecture and design that are more qualitative and meta-physical. To borrow from linguistics, if the first two categories described above (hardware, software) are *pragmatic* and *syntactic*, this third category (wetware) is *semantic*. As such, the problem architecture attempts to solve is very difficult to define in concrete terms alone and must also include the intent of the designer which can be a highly subjective and intuitive aspect. Some theorists have attempted to quantify meaning in architecture using information theory and other mathematical models (Baird, 1969) (Alexander, 1964) as well as shape grammars and space syntax. This approach has met with significant pushback, with critics pointing out that the term *information* and how it is used in certain contexts does not imply semantic meaning (Arnheim, 1971). Arnheim is skeptical of advocating quantitative approaches in assessing design and emphasizes the need for the "finger pointing" critic (Arnheim, 1977). Simon's concept of partial decomposability suggests that systems with many parts and sub-systems often reside within a range of order and disorder that relies on hierarchy and modularity as organizing principles (Simon, 1996) (I may add *scale-free modularity*). This idea is expanded on in complexity theory where complex adaptive systems are theorized to move toward the edge of chaos (Kauffman, 1991). Langdon and Wolfram have studied a range of cellular automata with complex behaviors capable of universal computation within certain parameters which also suggests a zone where structure and flexibility co-exist (Langdon, 1990) (Wolfram, 2002). Mitchell and Crutchfield have demonstrated the computational potential of cellular automata to solve problems using genetic algorithms (Mitchell, Crutchfield et al., 1993).

I discussed above several broad categories of systems in architecture and a framework for approaching the design process. Next I discuss the overlap between a systems theoretic framework and architecture today. Design technology has in some ways paralleled early developments in cybernetics. Archer and others developed models of design processes in the 1960's which reflected parallel developments in systems approaches such as the systems morphology models introduced by Hall (1969). Alexander and his approach to architecture and urban planning as a *pattern language* has been influential to a generation of designers and has also influenced the development of object oriented programing. These concepts are directly related to building information modeling (BIM) and parametric 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 (CDs), 3D printed models, or directly to automated manufacturing systems and so forth. Objects are also available from manufacturers as free downloadable libraries. 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 digital technology.

Some architects and visionary designers have taken the potential of digital technology in far more exotic directions creating virtual spaces that employ algorithms to connect architecture and context in "intelligent" ways or not confined by physical constraints at all, such as the work of the firms Morphosis and Asymptote, and the work of artist / architect Marcos Novak (Judelman, 2004). A pioneer in algorithmic design is Karl Sims who developed artificial evolution in the 90s as a tool for designing virtual creatures that could respond to their environments and adapt (Fig. 1.2.1) (Sims, 1994). This work follows from earlier research into genetic algorithms and evolutionary programming which will be discussed next.

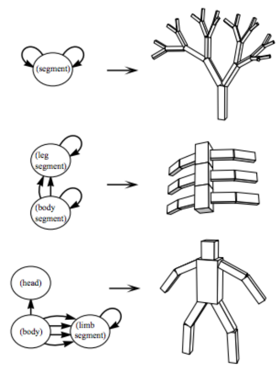

FIG 2.0.2 Karl Sim's genotype graphs and corresponding creatures (Sims, 1994). Note the fractal aspect of body type.

2.1 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 (satisficing) 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) (Mitchell, 1998). At the same time Holland was developing Genetic Algorithms (GA) which were 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 bits (strings of ones and zeros) and using the operators: crossover, mutation and inversion to "evolve" populations based on sexual reproduction. In a GA, populations evolve over time relative to some fitness criteria or objective function either exogenous or endogenous (Mitchell, 1998). Evolutionary programming was another line of research which was also developed in the 60s. 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) (Mitchell, 1998). Additional work has been done by Koza (1992) termed genetic programming (GP). Genetic programming uses a different method than the binary strings Holland uses. GP begins with parse trees (hierarchical node graphs) consisting of nodes representing various mathematical operators, variables, and logic gates: [+, –, *, / , A, X] (Figure 2.1.1). 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 programing* and has demonstrated GPs effectiveness within a variety of domains. GP's has been compared to standard search algorithms *hill climbing* and *simulated annealing* by O'Reilly and Oppacher (1994) for five problems and has been shown to be equal at best, or less effective.

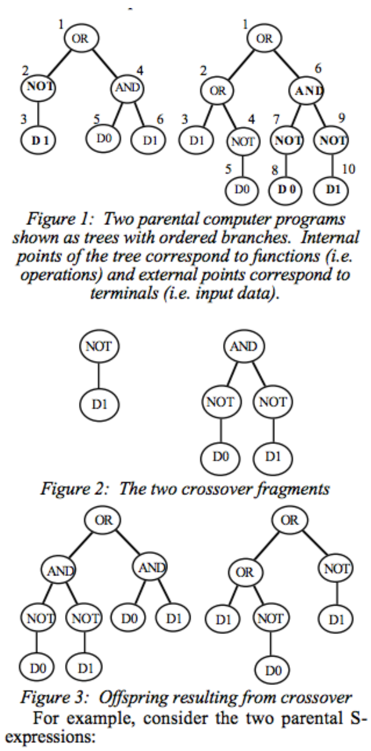

FIG 2.1.1 Genetic Programing. Parse trees showing crossover and recombination (Koza 1992).

Koza, Mitchell and Crutchfield (Koza, 1992) (Mitchell, Hraber, Crutchfield, 1993) have experimented with automated programing using GAs on evolving one-dimensional binary (black, white) cellular automata (CA). White investigates the development of a cellular automaton to model the spatial structure of urban land use over time (White, 1993). 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 GA have been discussed in terms of computational mechanics relating to concepts such as, "particles" and "particle interactions" (Fig. 2.1.2) (Crutchfield, Mitchell, Das 1996). Schelling applies CAs to models of human neighborhood segregation (Schelling, 1971).

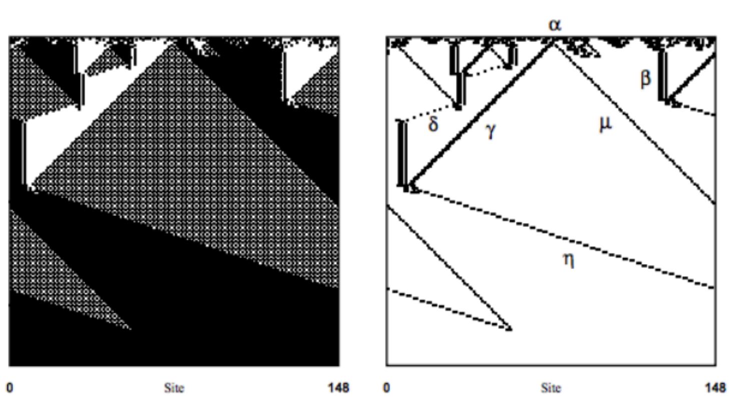

FIG 2.1.2 (Mitchell, Crutchfield, Das, 1996).

The preceding discussion 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 is tailored by the scientist / designer. 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, 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 artist 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 a GA 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 architecture.

Generative architecture grew out of the research in Cybernetics of the 1950s. Frazer developed the Evolutionary Digital Design Process at the Architecture Association (AA) as part of his work in morphogenesis in the mid 90s which has been influential. Frazer describes parametric design, or *parameticism*, 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 60s through Stafford Beer and Von Neumann's "Universal Constructors" which Pask developed as 3D building block prototypes (Frazer, 1995, 1997). Other research architects such as Coates cite Turing's early work in reaction diffusion processes (Turing, 1952) and Lindenmeyer's L-systems (Lindenmeyer, 1968) to being influential in his work on 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 GP that uses L-systems as parse trees which evolve relative to an objective function. Combining GP and L-systems is a parsimonious approach to exploring what Coates terms, "spatial morphogenesis" (Coates, 1999)[1]. Weinstock is also an important contributor to generative architecture in terms of emergence and ideas relating to evolution and form in architecture, drawing from a macro view of geology, biology and urban forms (Weinstock, 2010). 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 Mondrain paintings and then uses the GA to develop new designs that are a hybrid of both architect and artist (Fig. 2.1.3) (Gero, 1998). Patrick 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, 2012). Trends in research

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[1] One method for creating fractals is to use L-systems. L-systems are named after the Hungarian botanist Aristid Lindemayer who developed an extensive formalization of plant taxonomies using phyllotaxis (leaf arrangement) and defined the fractal structure of plants with L-systems. L- systems can likewise be used to investigate the basic properties of fractals.

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 tools are becoming commercially available for practitioners such as the Genr8 Maya plugin mentioned above as well as the Galapagos plugin for Rhino-Grasshopper. Galapagos and Grasshopper offer a visual interface for architects that allows for GAs to be experimented with in a variety of ways. 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 random curds and cellular automata (Devetakovic, 2015).

The brief background above shows 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 evolutionary processes. This process draws heavily from nature and has been termed *biomimetic* design as well as generative design. One abstract idea seen again and again in biomimetic design is fractal geometry. The use of L-systems and fractals in architecture, urban planning and biomimetic design will be discussed next in section 2.2.

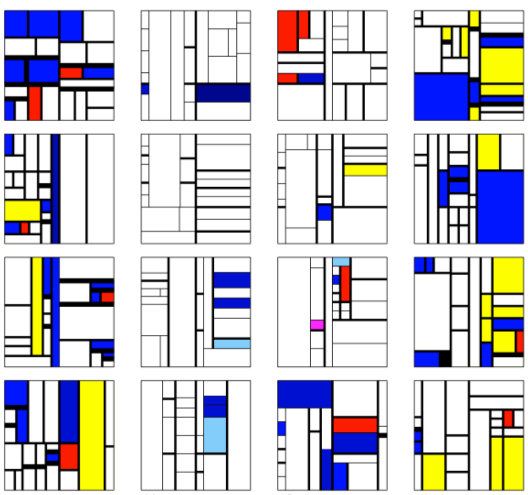

FIG 2.1.3 (Gero, 1998).

2.2 Fractals and architecture

Fractals have significance in many fields and are an active field of research. From building nanoscale fractal architectures in gold (HianáTeo, 2010) to efficient principles in programing biological form in genetic design (Weibel, 1991), to universal theories in physics (El-Showk, Poland et al., 2014), fractals are receiving much attention. Here I focus on the relationship between fractals, and architecture and the larger built environment. Fractal geometry and fractal dimension have been used in generative architecture and design and have become increasingly popular in analyzing natural and artificial objects. With mathematical tools at our disposal it is now possible to analyze the fractallity of architecture. I will review below the historical background of fractals in architecture, current research, and applications currently being developed.

Fractals are self-similar geometric patterns that repeat at multiple scales. Benoit Mandelbrot famously applied the concept of fractals to the measurement of the coastline of Great Britain. If you measure Britain's very jagged coastline with increasingly smaller measuring devices, first at the level of kilometers, then with a meter stick, and even at the level of centimeters and below, you'll continue to see a self-similar jagged structure. As you use smaller and smaller measuring devices, the length you measure gets increasingly longer.

Architecture has long employed fractals as an organizational principle. Architecture is perhaps unique in the arts in that a geometric pattern could represent something at many different spatial scales. In architecture especially, a geometric pattern may be designed to occur at many discrete scales from the pattern or motif in window muntins to the general layout of the plan and even the organization of the larger urban fabric. A good example of this idea is Frank Lloyd Wright's plan for the Palmer House (Fig. 2.2.1). In this plan the repeating figure of an equilateral triangle is evident at 7 different spatial levels (Eaton, 1998. Joye, 2011).

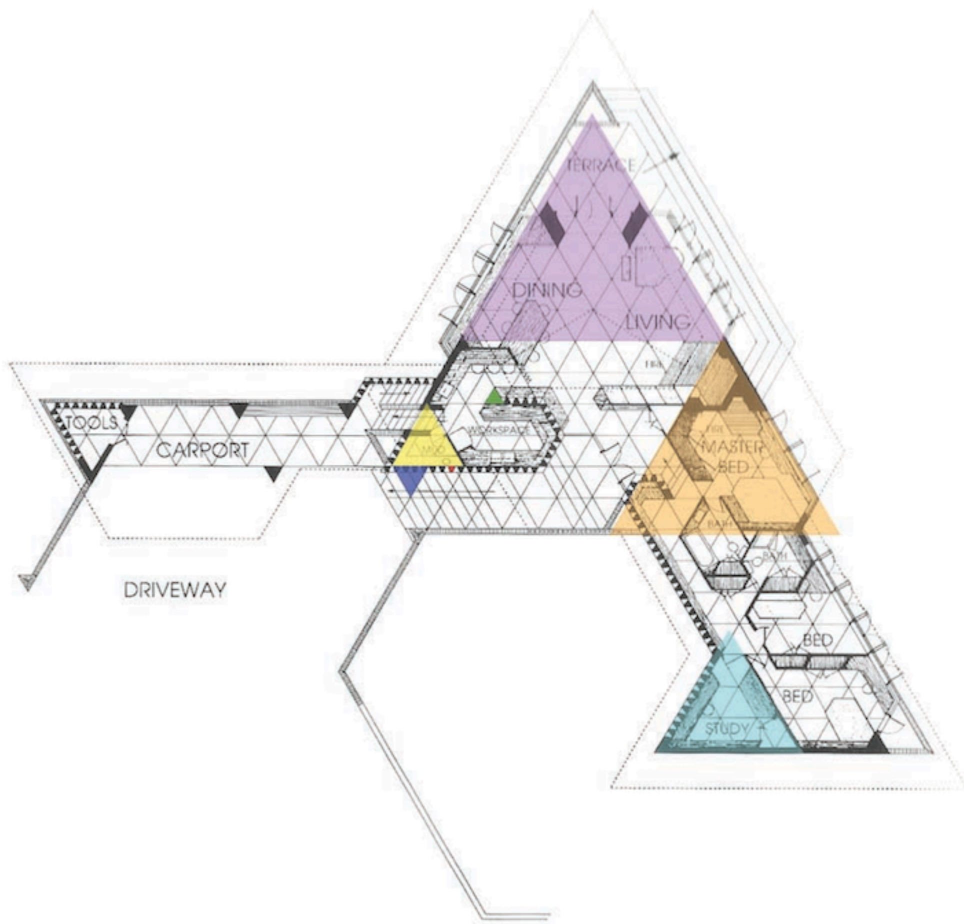

Figure 2.2.1. Palmer House plan by Frank Lloyd Wright . Colors depict 7 repetitions of nested equilateral triangles at different scales (color by author).

This technique follows patterns found in natural objects. The leaves of a fern are composed of smaller replicas of themselves for instance. Fig. 2.2.2 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 space to a dome in 3 dimensions.

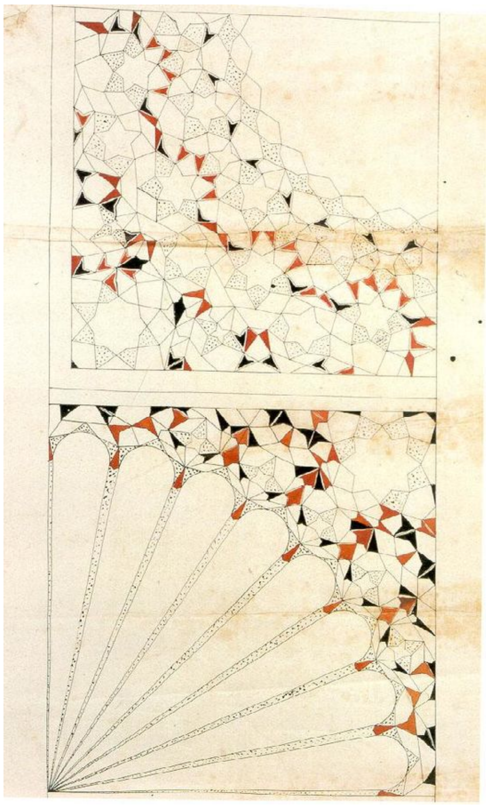

Figure 2.2.2. 15th century Topkapi Scroll showing a quarter section of a dome in plan that is further subdivided into miniature muqarnas which reflect the geometry of the whole at a smaller scale (By Unknown architect) - http://www.ee.bilkent.edu.tr/~history/geometry.html, Public Domain, https://commons.wikimedia.org/w/index.php?curid=17697287

Fig. 2.2.3 shows an example of how this technique was used to ornament the corbelling 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 a number of buildings in a complex. [2]

[2] Self-similarity might suggest a certain worldview. The idea that the whole is reflected in each part is sometimes associated with a hologram because a holographic image if shattered will re-appear complete in the broken fragments. Whereas, the notion that the whole is greater than the sum of its parts (superadditivity) is more associated with the notion of emergence, where the macro behavior of a system is different and more complex than the parts themselves or the interactions between the parts.

Figure 2.2.3. Detail of Red Mosque in Safed, Israel 1276. By Bukvoed (Wikipedia Commons).

Although multiscale self-similarity has been evident in architecture for a long time the name "fractal" and a mathematical model was only recently applied rigorously to them by Benoit Mandelbrot (Mandelbrot, 1983) although they had been studied in certain mathematical circles prior to him. Most notably by Gaston Julia who published a paper in 1918 that was influential to Mandelbrot entitled, 'Memoire Sur L'iteration des fonctions rationnelles' (Julia, 1918). This formulated the basic idea that has been influential in non-linear dynamical systems and deterministic chaos, namely that from a simple set of rules an infinitely complex object can be created. It was the advent of modern computing that gave Mandelbrot the ability to iterate the Julia set and see 'fractals' for the first time (Mandelbrot, 1979). Mandelbrot researched and appropriated many mathematical models and collected them under a common framework. One tool, which Mandelbrot borrowed from Felix Hausdorff, is a method for determining the fractional dimension of an object called Hausdorff dimension or *fractal dimension*. Another method Mandelbrot used for approximating the fractal dimension of real objects such as coastlines or mountains etc. is also based on Hausdorff dimension and will be called *box-counting dimension*. Box-counting dimension is the primary analytical tool used in this study.

Batty has explored the relationship between fractals, natural phenomena and the form of cities and has used fractal geometry to explain the form and characteristics 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. Here we measured various cities worldwide and discovered FD to peak in large complex urban environments like New York and Tokyo. FD was observed to plateau between 1.7 and 1.8 (Abundo, Driscoll et al., 2013).

Fractals are found historically in art and architecture, from before the conceptualization of fractals (Joye, 2008). Fractal geometry has likewise been used to analyze individual buildings and the architectural ideas associated with them. Bovill published a book titled, 'Fractal Geometry in Architecture and Design' in which he analyses two significant works by Frank Lloyd Wright (FLLW) and Le Corbusier respectively using box counting dimension. In Bovill's analysis he concludes that Wright's work is more complex than Corbusier's and in some ways more related to nature than modernist architecture (Bovil, 1996). These results and conclusions are challenged by Ostwald et al. who analyze five buildings by Wright and five by Corbusier and determine their box counting dimension is not as different as Bovill suggests (Ostwald, 2008) in some fashion Eaton also applies fractal dimension to the work of Wright (Eaton, 1998). Another 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 Pollack (R.P. Taylor et al., 2006). This study was tested and elaborated on by Jim Coddington et al. (Coddington, 2008). In addition to exploring the use of fractal geometry in analyzing architecture, a number of authors have also interpreted fractal geometry and made various assertions regarding its theoretical significance. Al Goldberger discusses a dichotomy between the Romanesque and Gothic styles that 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). Others have picked up this theme of linking more complex architecture characterized by fractal dimension to nature. Again the juxtaposition between Frank Lloyd Wright’s Organic architecture and the modernists is a common thread. 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, 2008). This idea is related to what has been termed ‘biophilic’ or ‘biomimetic’ design as discussed above.

A more theoretical approach to applying fractal geometry in nature and urbanism is provided by Geoffrey West (West, 2005) and Louis Bettencourt (Bettencourt 2013) respectively. 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 is inspired by Kleiber’s Law pertaining to biological allometry as well as Zipf’s Law in terms of population dynamics. Zipf’s law 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. Mandelbrot generalized Zipf’s law by adding two constants of proportionality which are parameters allowing for the fine tuning of the model to fit a particular distribution more accurately. This equation has become a standard one for comparing variables in a city such as population and area. 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 fractal structures (Fig. 2.2.4) (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. To name a few scaling laws found in cities–when compared to population density: roads, cables, numbers of gas stations and post offices are sub-linear; patents, income, real estate and crime are super-linear (Bettencourt, 2013).

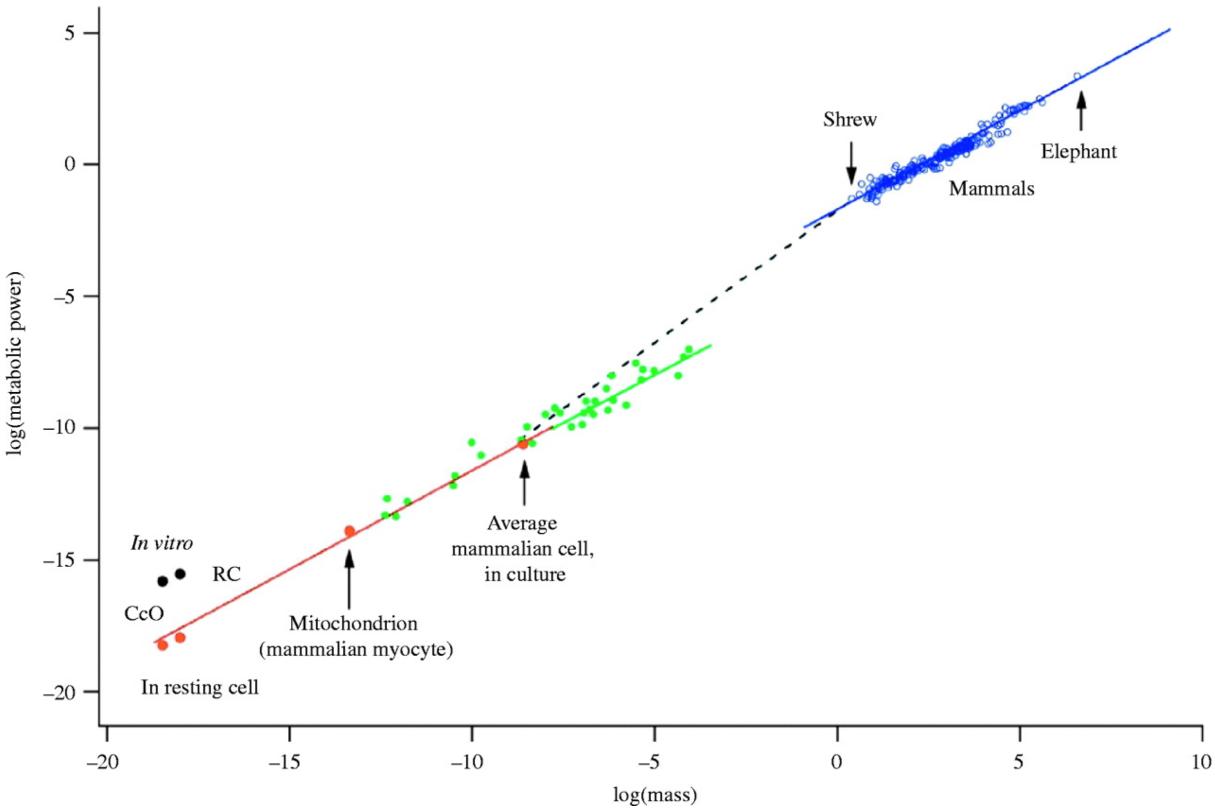

FIG 2.2.4. Biological scaling showing 3/4 power law over 27 orders of magnitude (West, 2002).

2.3 Fractal dimension

Fractal geometry is used for measuring "complexity" in a variety of ways (Mitchell, 1996). 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). Fractal dimension has also been shown to be effective in recognizing diabetic patients from retinal images (Cheng, 2003). 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).

Fractal dimension (FD) offers a measure for assessing the self-similarity of a branching pattern such as those discussed above. Self- similar patterns will generally have higher fractal dimension. This is because self-similar patterns have detail at many levels and fill the 2 dimensional plane more than a Euclidean object with comparable detail at a given level. In general, a self-similar fractal object obeys the following relation:

$$N = M^{d}$$

Where d is the fractal dimension (or fractional dimension) and M 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:

$$d = \log N / \log M$$

What this tells us is that the dimension of a fractal increases as the number of copies increases, and decreases as the scaling fraction decreases. (Note that *d* will be the same no matter what the base of the logarithm as long as the logs in the numerator and denominator have the same base.) This measure of dimension can be applied to objects that we are familiar with, such as lines, squares, and cubes, where the result is exactly as expected.

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 ration, $1/\varepsilon$ are recorded in a scatter plot. The scatter plot is a graph with $\log 1/\varepsilon$ along the x-axis and $\log N_\varepsilon$ along the y-axis. From the scatter plot a *best-fit line* or sum of least squares linear regression is drawn. The slope of the best fit line is the fractal dimension of the shape and should approximate the Hausdorff dimension.

Box-counting dimension uses the same idea as fractal dimension but applied generally to any number of scaled 'boxes' superimposed on an object:

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

Where D is the box-counting dimension and N is the number of boxes covering an object and ε is the scaling ratio.

2.4 Fractals and other information theoretic models

Alfred Renyi (Renyi, 1961) further generalized this idea and presents a model that relates a number of different measures (or dimensions) such as Hausdorff dimension and Shannon Uncertainty. This relationship is interesting because it allows for a conceptual model that coordinates spatial measures of complexity with information theoretic ones. Takayasu and Schroeder describe the relation between fractal dimension and Shannon Uncertainty through Renyi's generalization of entropy (Takayasu, 1990) (Schroeder, 1991). The mathematical relationship between Shannon entropy/ information and fractal dimension will be discussed more in section 5.0 of this dissertation and in section 7.1 in the appendix.

3.0 Method

The following chapter describes the general method and design process this research will be introducing which combines a GA with FD to produce design variants that serve as the basis for a design charrette involving a designer and juried critiques. I propose to develop and test BCD as an objective function within a GA-based design process that considers and draws from the richness of precedent. I will be using a GA to experiment with generating designs with a high degree of *complexity* as measured by the fractal dimension of their spatial configurations. Fractal dimension is a standard method for assessing spatial complexity as discussed in the literature (Mitchell, 2009). BCD has been shown to be an inexpensive analytic tool for analyzing architecture (Ostwald, 2013). As proof of concept, a case study will be developed and presented and the results critiqued by a jury of experts. I will code and employ an objective function that uses a quantitative approach (BCD) to analyze the fractality of design variants produced by a GA. Initial baseline designs will be culled from the body of work and the design methodology of the late designer and professor Dean Bryant Vollendorf (DBV) (See Appendix). Baseline designs will be modified by a GA and other tools available out-of-the-box in commercially available software such as Galapagos for Rhino / Grasshopper. The GA will be used to increase the fractal dimension of given designs by measuring each generation of design variants with BCD with respect to rules established in the methodology and a pre-defined design problem (see section 3.1). The results of this process at particular phases will be reviewed by a panel of experts in a series of juried critiques culminating with a final presentation and critique. Jurors' comments will be recorded and presented (see section 4.0). During this process, the researcher will iteratively take the output from the GA, modify (tune to fit) the output relative to the design problem and previous critique and present for jury review (pin up). This three-step cycle is represented in Fig. 3.0.0 and will iterate multiple times.

baseline –> GA –> fitting to problem –> jury review

FIG 3.0.0

MACRO PROCESS: The macro process represents the process or steps for the experiment to be conducted, which is a sub-process of a larger design process. The design process as a whole is labeled the *macro* process (macro-level). I use here Bruce Archer's design process as a starting point because it relates well with the standard architectural services defined by the American Institute of Architects (AIA) and is well known in design and creative professions (Boyd, Gristwood, 2016). In figure 3.0.1, *synthesis*, *development* and *communication* correlate with the architect's services: *schematic design*, design *development* and *working drawings*.

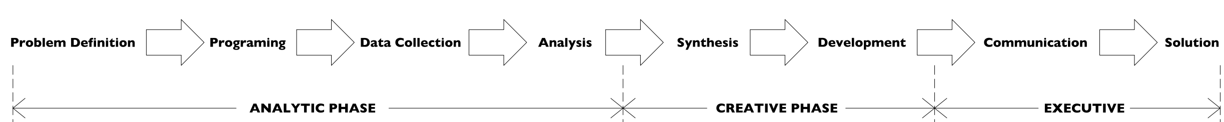

FIG 3.0.1. Diagram of design process at *macro* level.

MEZZO PROCESS: The sub-process defined within the design process expands on the schematic design phase to include an algorithmic design phase as well as a human design component. I label this sub-process the *mezzo* process (Fig. 3.0.2). The *mezzo* process (mezzo-level) has a feedback loop which is an iterative critique at milestones within the experiment where a jury of architects and other experts will respond to a selection of GA outputs and designs and offer comments and criticisms based on their expertise. There will be a number of juried critiques at various stages of the study working up to a final presentation and critique at the culmination of the study.

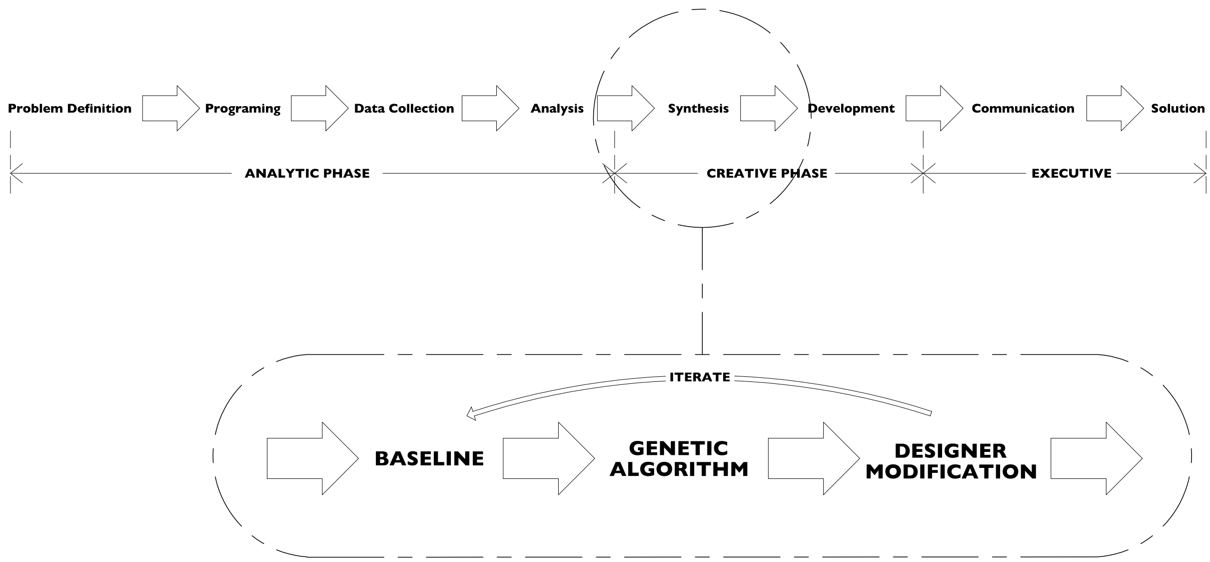

FIG 3.0.2. Diagram of design process at *mezzo* level.

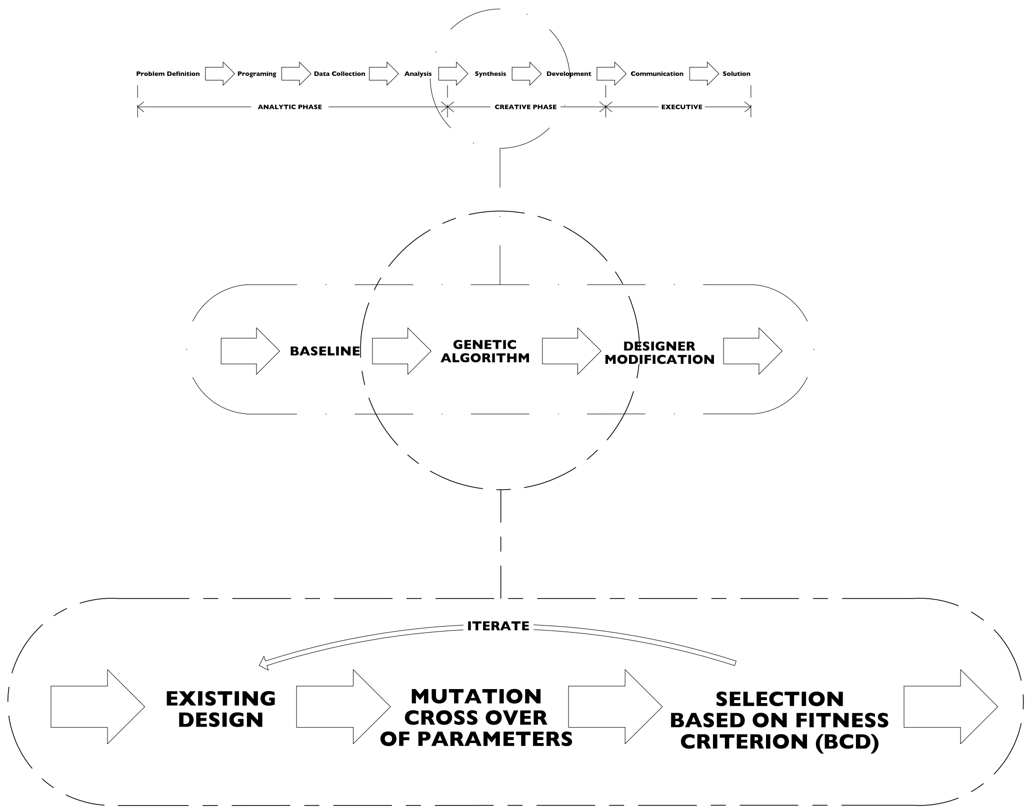

FIG 3.0.3. Diagram of design process at *micro* level.

MICRO PROCESS: The algorithmic design phase unpacks further as a *micro* process within the mezzo process (Fig. 3.0.3). The micro process (micro-level) has a feedback loop which is the iterative design generations within the GA. The micro process consists of a number of designs which are initially culled from a collection of architectural work (discussed in section 2.3). These designs represent the first generation of a genetic algorithm. The genetic algorithm creates many design variants with slight mutations and from this landscape selects a number of variants with high fitness. Fitness for this experiment is defined as high BCD. Fitness does not imply the variants are more fit designs, only that they score higher in terms of BCD. From this second generation the process repeats for a certain number of runs and then outputs one or more variants representing the highest local optima. These selected variants are then used as the initial designs at the mezzo-level. The mezzo-level uses the output from the GA as the input for a conventional design charrette where the researcher will modify designs to conform to the program and project requirements. The back and forth between these two levels will occur until the process converges on an appropriate design as decided by the jury.

This paragraph describes the objectives and evaluation for the meta-design process that will be done by the dissertation committee after the case study is complete. The design process described in Figures 3.0.2 and 3.0.3 will be developed and used for the case study described in sections 3.1–3.6. After the case study sub-project is complete the overall case study process or meta-process will be reviewed generally in terms of the efficacy of FD as an objective function for GA within a context of human-centric creative design and juried review. The objective for the macro-process, which is the efficacy and potential *scalability* of the applied design process, will be assessed by the dissertation committee after the case study is complete. Efficacy will be gauged qualitatively by the committee based on the expertise and knowledge of members. Comments will be recorded and included in chapter 5.0.

3.1 Case Study

The following sections describe the case study sub-project which will be developed and offered as a proof of concept for the design process generally outlined in section 3.0. The case study project will consist of a real world architecture project with programmatic requirements for an actual site and clear objectives. The case study will utilize the design process including the algorithmic design aspect and the human-centric design aspect as well as a sequential review by jury which will evaluate the design relative to the objectives. This research follows loosely Hall's 3D morphology of systems design process diagram (Fig. 3.1.1) (Hall, 1969). In this diagram the different steps are intended to occur within each stage of a larger process and in this sense are iterative. Hall's morphology includes general steps for a design process which is adopted for this research and refer to in the following sections.

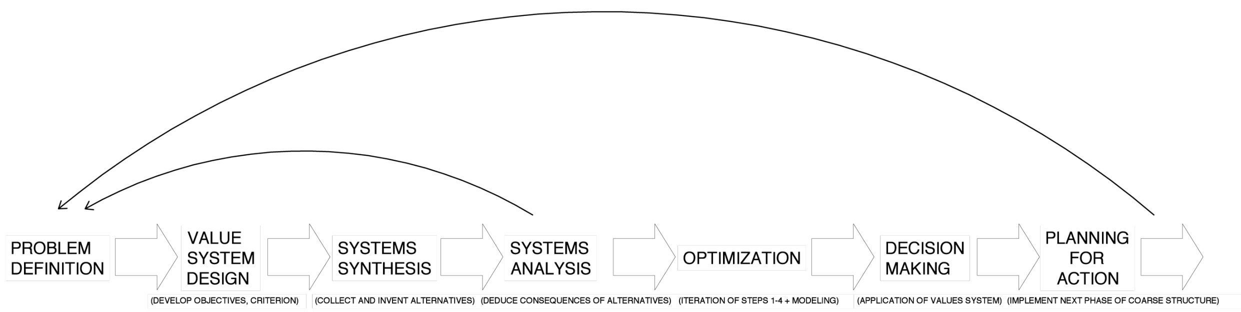

FIG 3.1.1. Arthur Hall's fine grained morphology of systems (Hall, 1969). Redrawn by author.

3.1.1 Problem definition

The problem definition is described here including the scoping of the problem. Specifically the architectural project that will be used for this research, which will include a problem statement, project program and site description. This section also describes the objectives in the form of a value statement at the beginning of the case study project.

• Problem statement: Design a pavilion representing a collaboration between man and machine. This pavilion should represent the issues discussed in the Introduction (Section 1.0), namely a building that recognizes and responds to its historical and present context. This project should address the complexity inherent in urban design such as its: urban, sociological, technological, economical and ecological dimensions.

• Project program: 2000 sq. ft. approx. Gallery space for exhibitions, sitting area. Small event space (50 people) for talks / lectures / multi media events. Public bathrooms and small staff kitchen and staff dining area and mechanical and storage area.

• Site description: Median of Park Avenue between 52nd and 53rd streets in New York City. This is presently an inaccessible median with plantings and no pedestrian access. The site is located between a: McKim, Mead and White building (Racquet and Tennis Club); a Mies Van Der Rohe building (Seagram Building); and a Skidmore Owings & Merrill building (Lever House) (Fig. 3.1.2).

3.1.2 Value System

The following paragraphs describe how the value statement for the case study project will be determined. The value statement follows from the project definition, and will be explicitly described in coordination with the dissertation

FIG 3.1.2. Picture from the median of Park Ave between 52nd and 53rd streets looking north. Racquet and Tennis Club by McKim, Mead and White is in the lower left and SOM's Lever House is in the center. Mies' Seagram building is not visible but behind the camera (photograph by author, 2017).

committee and expert panel. The value statement will include a list of project objectives to be used by the researcher and jury in evaluating design options during critiques and for the final review. Objectives will range from qualitative ones assessed by the jury to quantitative methods assessed using tools available in the software package chosen for this research and analytic tools developed by the researcher and committee.

Qualitative assessments will include: visual impact, reference to context, fractal geometry in relation to organizing principle and design methodology as well as the design in terms of a solution to the problem. The latter takes into account aspects of the physical as well as the natural and historical environment. Quantitative assessment objectives will overlap some with the qualitative objectives including the relation to the physical and natural environment.

Quantitative assessments will focus primarily on the proportional relationships of the designs and their FD. Proportional relationships will be assessed in terms of the larger body of DBV's work. Proportional relationships will also be assessed in terms of "efficiency" measures, including the relation of interior volume to exterior envelope. Other measures may include the spatial adjacencies of programatic elements similar to Boon et al. (Boon et al., 2015). The fractal dimension of design variants will be the main quantitative tool both algorithmically and analytically. FD will be measured and compared to other studies that have used FD to class aspects of the built environment and architecture (Encarnação, 2012), (Abundo et al., 2015) (Ostwald, 2015). FD has also been conjectured as a measure of genetic algorithms generally and this aspect of the study will be investigated (Kotowski, 2008).

3.1.3 Experiment (synthesis, analysis, optimization)

This section describes how the case study project will be designed and how the baseline models will be developed. Baselines will consist of three stages. The first will be 2D compositions based on DBV's design method (Appendix 7.3), the second will be in the form of 3D models based on the results of the 2D compositions extruded into the third dimension as well as a number of DBV designs that have been simplified into basic parametric models. The third baseline iteration will add programatic elements to the results of the second stage. Additional iterations will continue in a back and forth between the algorithm and designer and, less frequently, with the jury (see section 3.1.3). This section also discusses how I intend to implement the GA and FD algorithms for project as well as how the design variants will be interpreted by the researcher / designer, and how the process will iterate and I predict converge to a provocative design solution.

BASELINE: A number of architectural designs will be sampled and assessed for their use as parametric models. The catalogue of work from the late designer and professor, Dean Bryant Vollenforf (DBV) will be the sample data for this study made available to the author by the Oklahoma History Center. DBV's work will be classified based on typology and geometry. DBV's design methodology and pedagogy will be assessed and implemented as rules for the parametric model with the GA (See Appendix 7.3). A selection of DBV's work (rectilinear) will be abstracted as massing models which are simplified versions of their originals composed of lines, planes and masses. Particular designs within a class will be digitized in 3D within a CAD/BIM environment. The solid modeling software Rhino is of particular interest because it is compatible with the BIM software Archicad. Rhino can be controlled with Grasshopper and is compatible with a variety of plug-ins including Galapagos. Galapagos is a GA modeling software that is used by mainstream academics, architects and designers. From the 'real world' designs and design methodology of DBV, baseline models will be generated. Baselines will consist of three stages. The first will be 2D compositions based on DBV's design method (Appendix 7.3), the second will be in the form of 3D models based on the results of the 2D compositions extruded into the third dimension as well as a number of DBV designs that have been simplified into basic parametric models.

Baselines in stage 2 will consist of a number of schemes representing a building type. Massing models are considered compositions of various parameterized elements that will be subjected to mutation, cross over, selection, reproduction etc. in the GA. Initial massing models will be parameterized based on the x, y and z coordinates of the model's vertices with respect to the design methodology. Each geometric element: lines, planes or masses, will be variable in terms of its corresponding dimension(s) (length, width and height). Parameters may also be considered groups of vertices forming typical geometric elements such as line, planes and masses. These represent the design *vocabulary* of the scheme. An example of the parameters of a model will be the dimensions between vertices with respect to the underlying geometry of the form. For instance, if a building is designed using an underlying orthogonal grid, the dimensions will be allowed to vary only parallel or at right angles to one another (Fig. 3.1.3).

These variables will be modified by the GA to create multiple generations of variants subjected to selection and reproduction. Performance of multiple generations will be recorded and plotted with corresponding exemplar designs.

The third baseline iteration will add programatic elements to the results of the second stage. Additional iterations will continue in a back and forth between the algorithm and designer and, less frequently, with the jury (see section 3.1.4). Juried critiques will happen after each stage described above as well as a final jury.

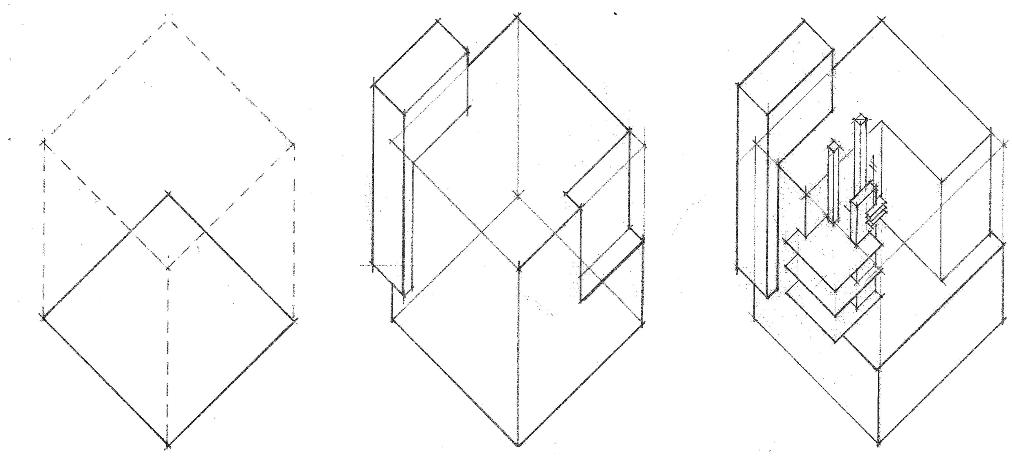

FIG 3.1.3. Diagram of parametric model showing 3 possible generations of GA output representing varying degrees of "complexity" (by author). These models are hypothetically created by a GA randomly choosing vertices in the x,y,z coordinate system and iteratively manipulating them with respect to some simple rules and the BCD objective function. BCD is a scalar measure of fractal geometry (multi-scale self similarity). Models with higher fitness have higher fractal dimension. Fractal dimension is a measure of detail at different scales. Here, the model on the left has very little detail; whereas, the model on the right has detail at 3 different scales and, therefore, a higher fractal dimension.

GENETIC ALGORITHM: Initial baseline designs will be explored using a GA to determine design variants which maximize the objective function. The objective function will be defined by the BCD of successive generations of variants. Selected designs represent local optima within a solution space defined as all possible variants within a given parametric range.

FITTING TO THE PROBLEM: The mezzo-level described in Fig. 3.0.2 involves taking the output from the GA and using it as input into a step of the process I refer to as "designer modification" or "fitting to the problem." Jorris Llarman is a well known designer who works with algorithms to aid in the design process. His exhibit, Design in the Digital Age is currently at the Cooper Hewitt Smithsonian Design Museum in New York City. Llarman refers to a similar phase in his design approach as the one I suggest. In this phase, the designer *fine tunes* in a sense the algorithmic output to fit the problem at hand. I will minimally modify the output of the GA in order to present a more compelling and convincing architectural design in terms of the material, structure and architectonics of the form. From a schematic design standpoint the design itself will be an abstract massing model only and the *fine tuning* or *fitting* the researcher engages in will be primarily to aid in the clean up and presentation of the project as a building on a site with a particular function etc.

ITERATION: The baseline for the case study will begin with a 2D composition study and rule set used as a starting point (or generator) for the GA with BCD algorithm. Iterations will help to refine the design in terms of increasing the BCD and consequently its multi-scale self similarity. Juried reviews will discuss the effectiveness of this approach and offer advice and instruction for subsequent rule modification. This process will iterate multiple times until a finished design is developed and a final presentation will then be offered for final assessment and closing remarks by the jury.

3.1.4 Decision Making (Jury Review)

JURY: Hall's morphology also includes a step he calls Decision Making where the value statement will be evaluated by a jury. A jury will be assembled to offer critiques of the above process. The jury will consist of approximately 6 professionals and academics in the field of architecture or computer science. Jurors will be asked to assess design work asynchronously through Dropbox or some other appropriate file sharing service. Design work will be in the form of digital graphics, e.g. drawings, that represent the exemplars and design modifications for both the GA phase and Fitting phase.

CRITIQUES: The jury will convene asynchronously at specific stages during the design process (see Fig. 4.0.1). Initial critiques will happen after the presentations for the three phases corresponding to baseline models and subsequent designs described in section 3.1.3. Additional critiques may be added culminating in a final presentation and critique.

OBJECTIVES: Jurors will comment relative to project objectives which are discussed here. The objectives will be generally how well the GA and BCD create effective designs in the micro process and how this is interpreted and fit to the programmatic criteria in the mezzo process (described in section 3.0). Objectives will be developed with the committee and with the jury throughout the project. Initial objectives will include both soft systems approaches and hard systems approaches. The former will be largely assessed by the jury and the latter will be assessed by the jury as well as with analytic tools. As previously discussed in section 3.1.2, qualitative assessments will include: visual impact, reference to context, fractal geometry in relation to organizing principle and design methodology as well as the design in terms of a solution to the problem. Quantitative assessments will focus primarily on the proportional relationships of the designs and their FD. Proportional relationships will be assessed in terms of the larger body of DBV's work. Proportional relationships will also be assessed in terms of "efficiency" measures (see section 3.1.2).

3.1.5 Challenges (planning for action)

This section describes potential problems that may arise in the case study project and contingency plans. An important aspect of Hall's design process and the main reason it is used here is because of its iterative set of steps that occur within each main stage of the process. The structure of the process is self-similar in this sense. Because of this structure, the process can change and adapt in terms of the problem definition, objectives and any other steps involved. The feedback loops that are shown in Fig. 3.0.1 indicate that there is feedback between steps but in reality feedback happens between every step. For this reason the process is able adjust as issues arise. Some of the potential issues that are forecasted are as follows.

The micro process as described in chapter 3 involves the design of the GA algorithm and the BCD algorithm. I am assuming that the GA will be an out of the box plug in for the software package I choose and that the BCD will be coded to work with the plug in. If this is not possible it might be necessary have to use a separate BCD tool to measure the FD of GA outputs. This would slow down the GA considerably.

The design of the GA is also a potential challenge. There are many approaches to designing GA's as we're discussed in chapter 2. Two main categories of GAs are genetic algorithms and genetic programming. The first uses linear binary strings and the second uses trees. The proposed method fits better with trees because of their obvious relationship to fractals and self-similarity. It remains to be seen what types of plug-ins will be available and to what degree they can be modified. Researchers mention that there are as many GAs as there are problems meaning that GAs are often adjusted to fit the problem (Kotowski, 2008)(Mitchell, 2009). I may have to adjust the GA significantly and a potential challenge will be whether and to what degree this is possible with out-of-the-box software.

Another potential issue is the asynchronous jury critique. The time allotted for critiques and the effort in communicating with individual jurors may cause delays. One work around here may be to simplify the critique process as much as possible. A step towards simplifying the critique will be to develop a clear set of objectives upfront. This step is critical and although the objectives can be adjusted as the project progresses, they set the stage for many of the subsequent steps.

Another more subtle challenge perhaps is where to draw the line in discussing the relationship of fractal geometry to architecture, computer aided design and design theory. As discussed in the background, fractal geometry has a relationship and significance in many fields and indeed is being actively researched for its universality. This is at once interesting and what fuels this thesis yet is also challenging in that because fractal geometry is so prevalent in so many things it is difficult to draw a boundary around where it is significant in this research and where it is not. An important aspect of the structure of the proposed research is the development of a general approach followed by a specific case study sub-project. The sub-project is intended to be focused on and only relative to the field of architecture. Larger and more broad assessments of scalability and relevance will surely come up but it is important to limit these types of discussions. For this reason, the larger implications of fractal geometry to design and CAD will appear only in the Discussion chapter 5.

4.0 Results

The results of the case study will be presented to the jury at key intervals during the design process (Fig. 4.0.1). I assume there will be 3 to 4 jury presentations culminating with a final jury review at the completion of the process. Presentations will include the GA outputs before modification or *fitting* is performed as well as the modified designs. Designs will be presented as drawings which clearly demonstrate the key aspects of the pavilion, including plans, sections, elevations and perspectives. Jurors comments will be provided in the Discussion chapter 5. Additionally, plots of the fitness for successive generations will be presented in terms of BCD showing an increasing fractal dimension and what this looks like visually. Jurors will evaluate the efficacy of BCD as a tool for generating suitable design solutions to the design problem outlined above (section 3.2). All final GA outputs and designs will be included in this section with corresponding analytic plots showing the GA maximizing BCD over successive generations along with a clear presentation of the visual designs they produced. Such presentation will essentially provide a graphic timeline of the design process and show the evolution of design variants toward the final solution.

Results for the case study will show that the use of computer-based approaches can increase the fractal dimension of design variants within the proposed process, and which will aid the designer in producing better solutions to complex architectural problems. Increasing fractal dimension will be shown to be an aid to the designer when fitting the building design to the multi-faceted and multi-scaler problem it attempts to solve. Fractal dimension is not only used in generating this solution but is part of an iterative design process including modification or fitting by the researcher / designer. Assessing the fractal dimension of design ideas will be shown to be helpful in understanding the formal implications of the final design's structure and the structure of the urban context as well.

FIG 4.0.1. Dissertation timeline.

The timeline for this research is presented above (Fig. 4.0.1). After the proposal defense on November 30, 2017 there will be roughly a 3-month period where: baseline designs will be developed, the selection of the genetic algorithm and coding of BCD tool will be done, sub-project objectives will be finalized, and a panel of experts to serve as the jury for the case study will be assembled. After this, there will be roughly 6–9 months for the case study project to be performed and reviewed, leading up to a final presentation in February of 2019, and the dissertation defense and submittal of all dissertation materials to the committee.

5.0 Discussion

The comments and analysis of the jurors will be discussed in terms of the objectives developed in chapter 3 section 3.1. Jurors will offer their assessments of both the micro process and mezzo process phases in terms of analytic criteria and qualitative criteria based on the experience of the juror. Comments will be documented and compared and contrasted during the case study experiment as well as in the discussion. Comments will be discussed relative to the question asked at the outset of the research as to whether or not computer based search heuristics using fractal geometry might reflect the increased efficiency or *economy of scale* we see in cities and at the same time retain the role of the creative architect and the spirit of architecture. Jurors comments will speak to both criteria.

Fractal geometry and fractal dimension have significant overlap with many aspects of architecture and cities as well as within the rubric of systems science and complexity science. The Background section of the proposal touched on some of these aspects. Fractal dimension has been shown to be a helpful indicator and objective function in a GA based generative design process. The process developed is a step towards understanding and incorporating self-similarity as a principle of design in nature and artifice, essentially a scale-free module. Such a principle has the potential to help designers produce more efficient buildings and urban environments. Also discussed will be fractal dimension in terms of other complexity measures such as algorithmic complexity and thermodynamic depth as discussed in the literature (Mitchell. 1996). Fractal dimension will also be discussed in terms of its relation to other entropy measures and possible equivalencies with these models and the implications for spatial data (Takayasu, 1990) (Schroeder, 1991). More general theoretical assessments of fractals in relation to complexity will then be discussed, touching on themes in systems science and complexity science. These themes are: complexity vs. complicatedness, hierarchy vs. holarchy, fractals and emergence and fractals and self-organized criticality. Remarks will be made about non-spatial ideas associated with fractals such as the notion of attractors and repellers and how the work above might inform this larger discussion in systems science.

5.1 Contribution

The proposed research will be an important contribution to architecture as well as evolutionary computing. Fractal dimension offers a relatively lightweight objective function for GAs and will be shown to indicate the complex organization of form in a helpful way for architects to use. Fractal dimension, as discussed in the Background section, indicates more developed and effective solutions in architecture and city planning. Generally, fractal dimension is an indication of the complexity of a form, or in Jacob's opening quote, its *organized complexity*. Not simply the superficial complicatedness of a particular object but rather its deep organizational structure at many different levels of scale. Higher fractal dimension indicates detail at many scales. For this reason, fractal geometry and fractal dimension have potential in a variety of environments such as: feature selection in machine learning, dimension reduction in assessing large data sets such as bio-informatics, character recognition, biological scaling, city scaling and many other scale-free types of behavior. In addition to these discriminative applications, fractal geometry and fractal dimension have been shown in this study to aid in assessing generative modeling processes, namely algorithmic design. This research will significantly close the gap between Machine Learning techniques and contemporary architecture practice.

This study will also demonstrate a process of algorithmic design using fractal dimension as an effective means for assessing complex organization in a GAs design output. This process is essentially an extension of the architectural process in that it incorporates historical precedent and the 'eye' of a designer. In this sense it represents an important departure and contribution to the field of computer aided design and building information modeling.

5.2 Conclusion

Researchers are rising to Jacobs' description of architecture and cities being examples of "organized complexity", and increasingly consider our built environment not in reductive terms but in terms of being a complex, non-linear and multi-variate problem. This study represents a step forward in how such problems can be better understood and solved for in today's rapidly changing landscape. Architects and designers are beginning to use data mining techniques and analytic computational approaches to help solve these "wicked" problems. This study extends architectural research further into the realm of dynamical systems and fractal geometry.

This study also outlines a clear design process and provides tools towards integrating mathematical and computational approaches with traditional architecture and design fields. Through the use of mainstream digital modeling and drafting tools I have shown how GA and BCD might be effective in design strategies to address the ecological, economical, social and technological dimensions called for by our built environment. This research has added clarity to the larger shift in design paradigm away from traditional design to more generative approaches that work with emerging technologies. As we enter into an increasingly automated and autonomous era, my hope is that this work will help guide technological development in positive directions that retain the architect within the design process and increase his or her capacity for rich and provocative design via appropriate technologies. To put it another way, *I hope this work emphasizes the need and value for human creativity within the design process*. It is reasonable to think that the design process proposed here using both the power of the computer and the creativity of the designer and jury within a rubric of fractal geometry and fractal analysis may provide insight into the dichotomy between order and disorder that purely quantitative analyses or purely qualitative assessments fail to reveal.

It is valuable to explore how approaches across disparate disciplines and from multiple perspectives may be applied and developed in an effort to tease apart thorny issues pertaining to the analysis *and* design of the built environment. This dissertation has shown one example of how soft systems approaches may be combined with hard systems approaches to improve design outcomes.

5.3 Future Work

Future work will be to scale up and generalize fractal dimension as feature selection in Machine Learning. Future work will also include developing the BCD objective function tool to make it widely available to architects and designers.

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7.0 Appendix

7.1 General notes on fractal geometry, fractal dimension and architecture

Artificial and natural systems are often complex ones. Adjectives such as — rough, irregular, convoluted and fragmented apply, as well as — dynamic and non-linear. Such systems are difficult if not impossible to analyze formally. One method for understanding and measuring these types of complex systems is by fractal dimension. Melanie Mitchell, in her book ‘Complexity, a Guided Tour’ explains one metric for complexity in terms of fractal dimension, “One description I like a lot is the rather poetic notion that fractal dimension ‘ quantifies the cascade of detail’ in an object. That is, it quantifies how much detail you see at all scales as you dive deeper and deeper into the infinite cascade of self-similarity” (Mitchell 2009).

Benoit Mandelbrot coined the term ‘fractal’ in the 70’s and was instrumental in synthesizing literally centuries of exploration by such notable mathematic and scientific luminaries as DaVinci, Newton, Liebnitz, Sierpinski, Cantor, Dedekind, Julia, and Hausdorff, just to name a few. Until Mandelbrot's work, which was supported by the advent of modern computing, much of the previously discovered material related to fractals had to be intuited: the discoverers of such strange mathematical marvels had no way to visualize the infinite detail and variation contained within fractal patterns. That fractals are indeed strange is confirmed first, by the fact that they are based on sets that are everywhere continuous and nowhere differentiable and second, by the fact that our typical notions of dimensionality (topological or Euclidean space) do not necessarily apply to fractal “space” (Schroeder 1991). Until the advent of modern computing much of this material had to be intuited by its discoverers, as there was no way to visualize the infinite detail and variation contained in fractals.

Typical notions of topological and/or Euclidean space do not necessarily apply to fractal space. A general notion of spatial dimension is simply how many basis elements are necessary to describe it, i.e. a line is one dimensional, a plane is two dimensional and a solid object is three dimensional.[3] Fractals however have a fractional dimension, one that lies in between integers, such as 1/3 etc. (although fractal dimension may also be a whole integer). A fractional or fractal dimension is more like a measure of density or a rate of growth towards infinity than a conventional description of space. A fractal such as the Koch curve (Fig. 10.1.2) has a fractal dimension of roughly 1.26. The Koch curve becomes infinitely long as the number of iterations approaches infinity and thus fills the plane, or at least part of it. *In an intuitive sense, the Koch curve lies in an in-between dimension somewhere between a line and a plane*. The Koch curve is composed of line segments, which are (topologically) one-dimensional, “embedded” in two-dimensional space (a plane). As the line segments increase in number, they fill the plane more and more yet never become two dimensional; they always remain between one and two dimensions, ever approaching a dimension of about 1.26. Fractal geometry is a generalization of Euclidean geometry in that the standard 3 dimensions of space are special cases of integer dimensions in a spectrum that includes fractional dimensions. As we

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[3] The dimension of Euclidean n-space E^n is n. When trying to generalize to other types of spaces, one is faced with the question “what makes E^n n-dimensional?" One answer is that to cover a fixed ball in E^n by small balls of radius ε, one needs on the order of ε^{-n} such small balls. This observation leads to the definition of the Minkowski dimension and its more sophisticated variant, the Hausdorff dimension. But there are also other answers to that question. For example, one may observe that the boundary of a ball in E^n looks locally like E^{n-1} and this leads to the notion of the inductive dimension. While these notions agree on E^n , they turn out to be different when one looks at more general spaces.

just mentioned, a straight line is one dimensional but as soon as it starts to curve it describes a plane but does not completely fill in the plane and is in a sense a fractional dimension between one and two. Fractals generally have dimension greater than their topological dimension and less than their embedded dimension (Mandelbrot, 1983). Fractal dimension is a different measure for an object than its mass, density, position, velocity etc. In addition to these, all objects have a fractal dimension as well, which speaks to different traits than these types of measures. Fractal dimension is a measure of an object's multi-scale complexity. Detail at many different scales will have a higher FD than detail at only some scales. In this sense, fractal dimension is a measure of self-similarity, although the specific shape that is repeated is not represented in its FD and indeed different scale invariant structures can have the same fractal dimension. Self affinity is a property of fractals that do not strictly repeat at different scales but have some proportional re-scaling. Allometric scaling relationships in biology are often self affine.

Fractal dimension is based on Hausdorff dimension developed by the German mathematician Felix Hausdorff. The diagram below (fig. 10.1.1) illustrates the relationship of Hausdorff dimension applied to general dimensional space. A line segment or *initiator* with divisions r in one dimension, $D = 1$, has a partitioning of N where $N = r$. In two dimensions the number of partitions increases to N^2 or *4*, this second order operation is termed the *generator*. Likewise in three dimensions, D = 3, the number of partitions increases to N^3 or *8*. This relationship is generalized to any geometric condition where $N = r^D$. Dimension can be determined by creating a 'geometric structure from an original object by repeatedly dividing the length of its sides by a number x. Then each level is made up of $x^{dimension}$ copies of the previous level' (Mitchell 2009).

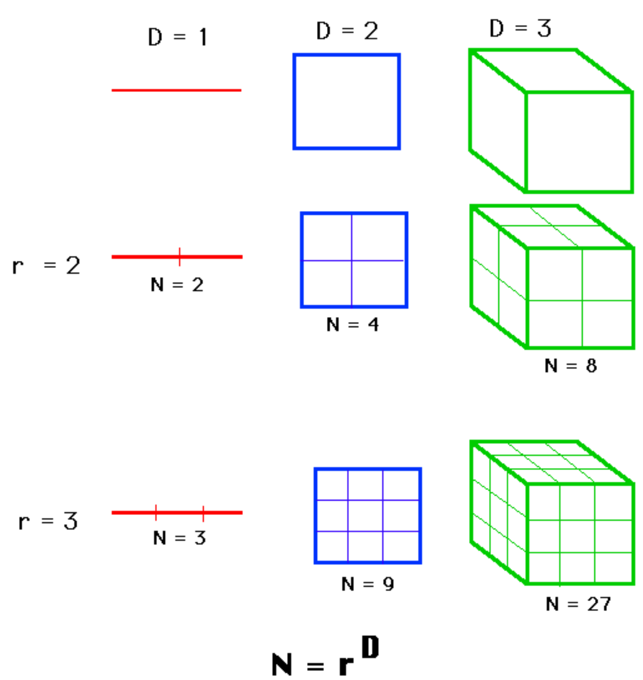

FIG. 10.1.1 Illustration of Hausdorff dimension. The exponent D is the dimension which may be a fraction as well as a whole number (Fractal dimension. (2017, October 5). In *Wikipedia, The Free Encyclopedia*. Retrieved 17:37, November 7, 2017 (https://en.wikipedia.org/w/index.php?title=Fractal_dimension&oldid=803864188).

If D is not an integer the resulting operation will have a fractional or *fractal* dimension. First, an initiator is segmented into a number of pieces related to the number of pieces in its generator. Non-integer dimensions result when the *log* of the generator is not evenly divisible by the *log* of the initiator — a fractional or fractal dimension is the result. The fractal dimension *Df* is the same as the Hausdorff dimension described above: equal to the ratio of the log of the number of elements (line segments) in the generator over the log of the number of elements in the initiator.

$$D = \log n / \log r.$$

To derive this equation, simply take the equation in figure 10.1.1, $N = r^D$, take the log of both sides, $(N) = D \log (r)$. Solving for D yields the equation for fractal dimension, $D = \log (N) / \log (r)$.

Here is an example of fractal dimension using the Koch curve shown below (fig. 10.1.2). The initial line segment is called the initiator and its corresponding shape at step 2 is called the generator. In the case of the Koch curve, the initiator is partitioned into three and the generator is partitioned into 4. The fractal dimension for the Koch curve is:

$$D = \log 4 / \log 3$$

This is equal to 1.26... Subsequent iterations run the original operation at 1/3 the size for each new line segment formed. This process can be repeated indefinitely with the fractal dimension always remaining 1.26... This number is the limit of the space filling properties of the fractal as its length approaches infinity. The Koch curve is composed of one dimensional line segments yet it is embedded in a two dimensional space — a plane. As the line segments increase in number, they fill the plane more and more yet never become two dimensional, they always remain between one and two dimensions ever approaching a dimension of 1.26...

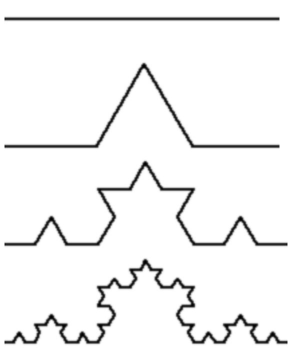

FIG. 10.1.2 Koch curve construction.

BOX-COUNTING DIMENSION: The method that will be used to determine the fractal dimension of design variants for this research is a common technique for determining the fractal dimension of an object that is not a simple construction like the Koch curve called box-counting dimension (BCD). BCD is often used for spatial data that is not defined with pure geometry but rather consists of idiosyncratic shapes of all kinds such as those found in nature and in complex, hard-to-characterize forms such as buildings and cities. A useful way to visualize fractal dimension is helpful in understanding BCD. In figure 10.1.2 above, instead of partitioning the initiator three times, $r = 3$, think of the initiator as one unit divided by three or 1/r. This is the scaling ratio. At the second iteration the generator now consists of not *4* but 4 * 4 or $N = 16$. The fractal dimension is then:

$$D = \log N / \log 1/r, \text{ or for the Koch curve: } D = \log 16 / \log 1/3$$

This gives the same dimension only negative, $D = -1.26...$ where the number of elements in the generator N is a function of the scale r of the iteration. This is the form used in box counting dimension. BCD is the same fractional relationship between initiators and generators only using boxes N representing the number of elements necessary to cover a shape at a particular scale. The properties of a fractal is that the generator is infinitely recursive and scale invariant and therefore self-similar at different scales. Using a variety of different sized boxes gives fractal dimensions at different scales. Plotting these measurements reveals the correlation between the different scales and fractal dimension of the overall form. BCD 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 and the relationship of the log of the number of boxes N_r and the log of their scales, 1/r are recorded in a scatter plot. The scatter plot is a graph with $\log 1/r$ along the x-axis and $\log N_r$ along the y-axis. From the scatter plot a *best fit line* or sum of least squares linear regression is drawn. The slope of the best fit line is the fractal dimension of the shape and should match the Hausdorff dimension described above (Schroeder 1991). Fractal dimension is useful for determining the raggedness or fragmented quality or relative smoothness of a shape or boundary condition.

INTERPRETING FRACTALS IN CITIES AND ARCHITECTURE: Fractals are useful in analyzing deterministic and 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 briefly. The railway system of Paris has been shown to have a fractal dimension of 1.47 (Fig 10.1.3) (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). A perhaps important caveat however, is that there are also lateral loops or rings that cross between tracks at various distance from the city center which we don't see in DLA. For this reason, Batty's simulations of cities and central place systems using DLA is not ideal (Batty 1987). Alfred Hubler develops models using both ramified particle aggregates under high voltage and minimum spanning trees (Fig. X2). These models also do not show lateral connecting rings (Hubler et. al, 2008).

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.

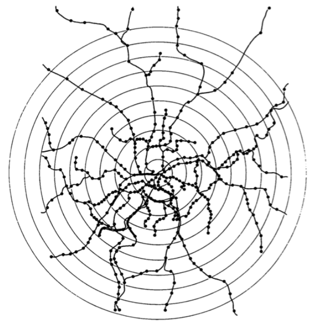

Fig. 2. Sketch of the Railway Network of the Greater Paris Area. This includes the R.E.R. and S.N.C.F. systems.

FIG 10.1.3 (Benguigui, Daoud, 1991).

"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).

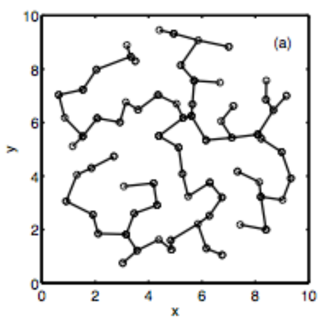

FIG 10.1.4 (Hubler et. al, 2008)

This idea is challenged in Hubler's minimum spanning tree model, where a random distribution of nodes are connected using a minimum spanning tree and the result is compared to DLA and shown to be similar in terms of degree distribution of the nodes. (Fig 10.1.4) (Hubler et. al, 2008). A random distribution of nodes would suggest more of a homogenous field rather than a geometry that is inherently fractal. The fractal pattern results from the efficient connection of the nodes. This is a more compelling case for the fractal character of city networks than Benguigui and Daoud's. Batty suggests that fractal patterns are associated with efficient space filling networks which are used as uptake and distribution networks such as the case of Parisian rail lines. Batty writes:

"In particular, the way cities fill space is by delivering energy in the most economical manner to serve large areas and the dendritic, branching patterns or transport networks that result can be proved optimal in many contexts" (Batty, 2012).

FRACTALS AND INFORMATION: Fractal dimension offers a crude measure for assessing the self-similarity of a branching pattern such as those discussed above. Self-similar patterns will generally have higher fractal dimension. This is because self-similar patterns have detail at many levels and fill the 2 dimensional plane more than a

Euclidean object with comparable detail at a given level. Fractal dimension is Hausdorff dimension and is defined by:

$$D_c \equiv \frac{\log N}{\log \varepsilon}$$

Where *D* is the fractal dimension and ε is the number of segment in the initial object, called the initiator, and *N* is the resulting number of elements produced, called the generator (see appendix).

ε is also considered a scaling ratio, in which case the expression becomes:

$$D_c \equiv \lim_{\varepsilon \to 0} \frac{\log N(\varepsilon)}{\log 1/\varepsilon}$$

Separately, Takayasu and Schroeder have shown a relation between fractal dimension and Shannon Uncertainty through Renyi's generalization of entropy. Here *q* represents the order of the system (Eq. 1) (Takayasu, 1990) (Schroeder, 1991). When *q* is 1, the equation becomes the familiar Shannon Uncertainty (Eq. 3). When $q = 0$, the probability of an event is simply the number of events, where ε is a scaling factor. Equation (Eq. 2) then becomes the fractal dimension (Hausdorff dimension) (Eq. 4). Takayasu writes, "Suppose that points are distributed randomly in a d-dimensional space. Divide the space into d-dimensional cubes of side ε. Let P_i denote the probability that a point belongs to the *i*th cube. For an arbitrary positive number *q*, we introduce a new quantity $I_q(\varepsilon)$ given by the following equation:

$$I_q(\varepsilon) = \frac{1}{1-q} \log \sum_i P_i^q$$

Eq. 1

We define the *qth-order fractal dimension* as :

$$D_q = \lim_{\varepsilon \to 0} \frac{I_q(\varepsilon)}{\log(1/\varepsilon)}$$

Eq. 2

The quantity I_q is often called the *qth-order Renyi information* and we can easily show that I_1 coincides with the usual information:

$$I_1(\varepsilon) = \lim_{q \to 1} \frac{1}{1-q} \log \sum_i P_i^q$$

Eq. 3

$$I_1(\varepsilon) = \lim_{\delta\to 0}\left[\frac{-1}{\delta}\log(1+\delta\sum_i P_i \log P_i)\right] = -\sum_i P_i \log P_i$$

As a consequence D_i coincides with the information dimension D_1. The dimension D_q is also called the qth-order information dimension. Consider the limit q -> + 0; we can show that D_0 agrees with the capacity dimension, D_c. from the following equation:

$$\lim_{q\to +0} P_i^q = \begin{cases} 0, & P_i = 0, \\ 1, & P_i \neq 0, \end{cases}$$

It is not difficult to understand that:

$$= \lim_{q\to 0} \sum P_i^0 = N(\varepsilon)$$

is equal to $N(\varepsilon)$, the number of cubes which include at least one point" (Takayasu, 1990). Hence $D_0 = D_c$.

Eq. 4

" (Takayasu, 1990)

7.2 L-systems

L-SYSTEMS: A method for generating and/or modeling fractals is to use L-systems, named after the Hungarian botanist Aristid Lindemayer. Lindenmayer developed an extensive formalization of plant taxonomies (phyllotaxis) and defined their fractal structure with L-systems. L-systems use a basic grammatical language consisting of an invented semantics (the meaning of words or symbols) and syntax (the rules for constructing relationships between words or symbols). Semantically, alphabetical symbols are used to refer to certain procedures and syntactically, sets of procedures ('sentences') are formed which consist of strings of these alphabetical symbols. In L-systems then, a 'sentence' is a meta-procedure – a set of individual procedures (alphabetical symbols) that are strung together to form a larger procedure which is then iterated viz. some scaling factor. Lindenmayer was able to use L-systems to categorize a variety of plants and subsequently they have been used to describe and code for a varaiety of fractal geometry.

7.3 Excerpt from the unpublished writings of Dean Bryant Vollendorf, "Organic philosophy in architectural education", Collection of the Oklahoma History Center

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.

The introduction of the basis of composition.

The doors to old Lee Hall at Clemson University are an example of the principle in function. Thus in 15 minutes the student is involved in architecture.

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 base relief thinking. The purpose of the requirement of the line stopping at a line or edge is to create the circumstance for the student to discover by the lines (see figure 2) form individual blocks or surfaces.

These problems would be done on a opaque white paper 8 1⁄2 x 11 and developed into a portfolio for presentation.

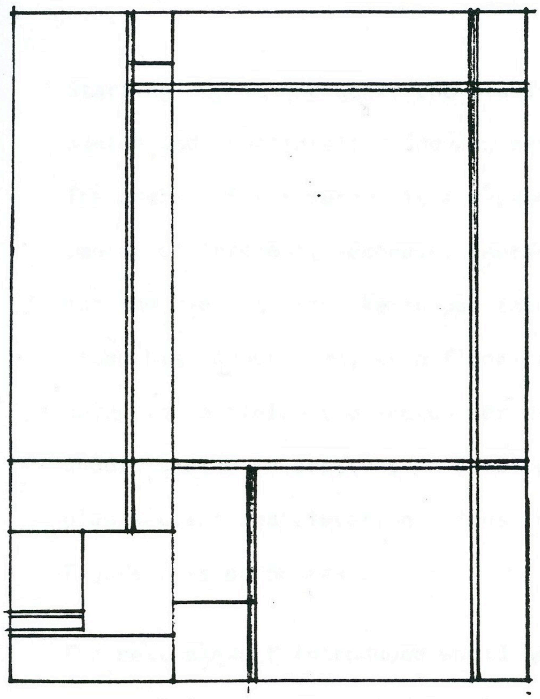

Figure 2. Rectangular Composition

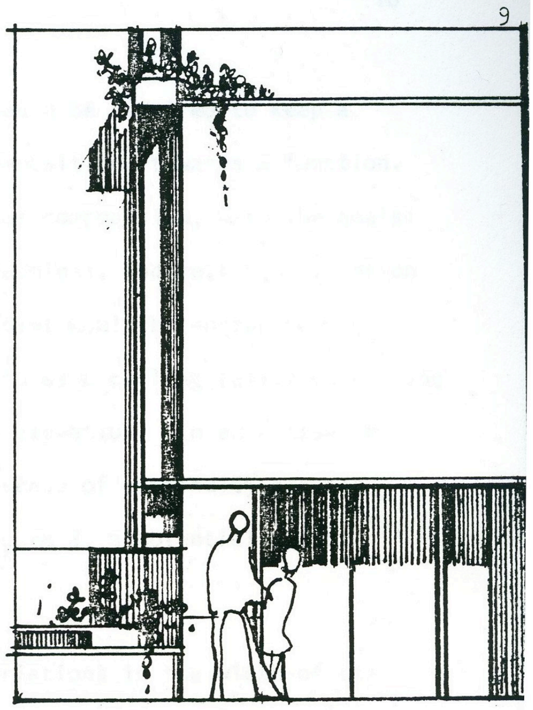

Figure 3. Relief Study

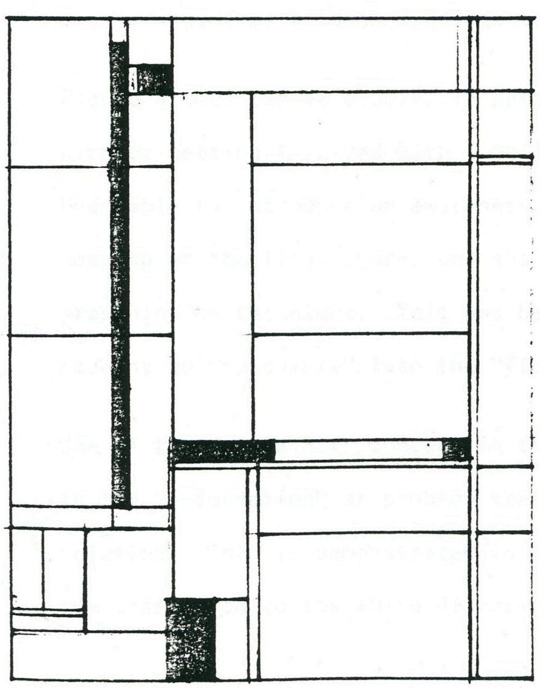

Figure 4. Plane Study

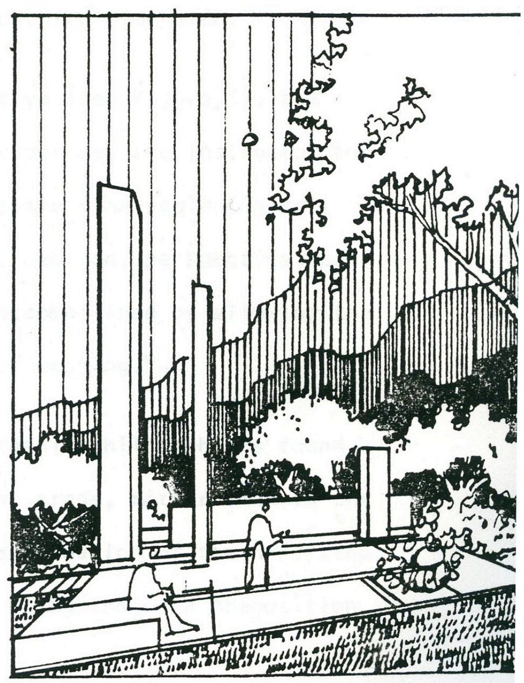

Figure 5. Persepective of Figure 4

Starting the second week, the student would be required to keep a sketch pad, continually studying their compositions towards a function. The problem for Figure 2 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. Thus in Figure 3, a potential use of Figure 2 is demonstrated.

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.

Figure 4 thus can be studied in perspective (See figure 5); and without getting involved with a building per se, the instructor has been able to introduce an awareness of scale (the scale figure), meaning of the line, shades and shadows, section, perspective, and presentation technique. This has been accomplished by allowing the student to "speculate" into the "field of meaning".

Use of the "explainer" concept in the organic philosophy is found in the "information" or problem statement stage, rather than in the solution. This is demonstrated in the explanation of the next step, the transition to the third dimension. Using the word preposition (over, under, or to), the instructor can explain the factors that function to delineate space. To get the student to work towards these words, the concept of the reflected ceiling plan is introduced. Thus Figure 6 is a start toward a rectangular propositional composition. In using this technique of introduction, the student would work in plan and section. In other words, there should be another drawing between Figures 6 and 7.

Figure 6 should be studied in relation to the potentials of both plan and reflected plan, thus section cut that will delineate the final forms will be about one-half way up the elevation. Using the resulting space awareness gained in previous problems, the student begins to see plan relationships that begin to suggest the generator of the final design.

There is another way of expressing the concept of "code", and for this reason also the plan is left unfinished. Perhaps the most difficult area to explain in architecture to a student is in the crystallization of the idea, from concept to statement, or where the true "field of meaning" takes form. As Frank Lloyd Wright has stated it, "There is the fluid, elastic period of becoming, as in the plan, when the possibilities are infinite".

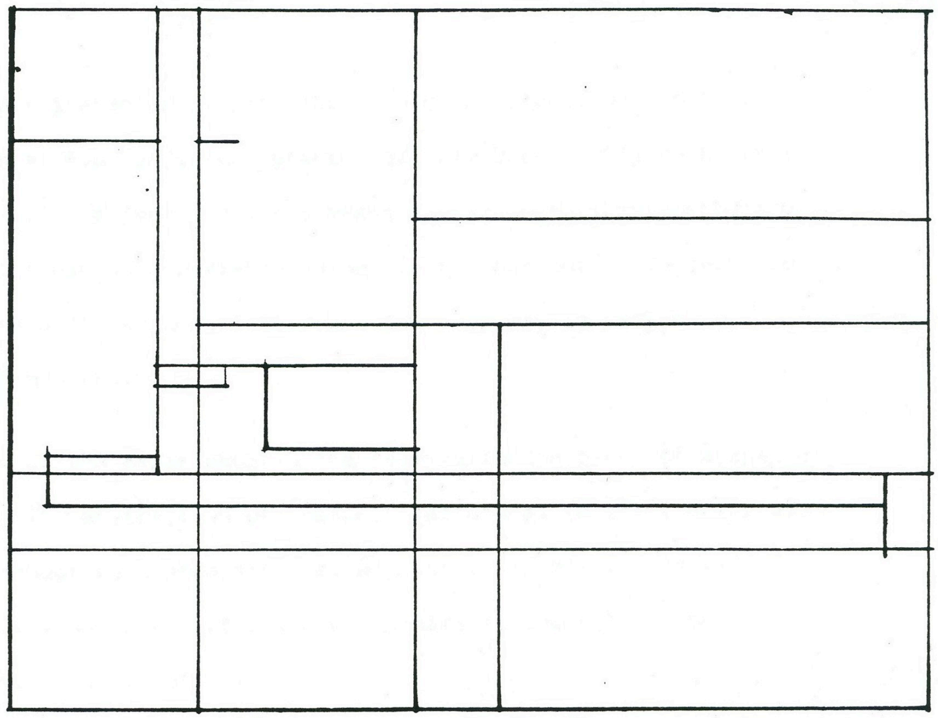

Figure 6. Plan Composition at Generator Stage

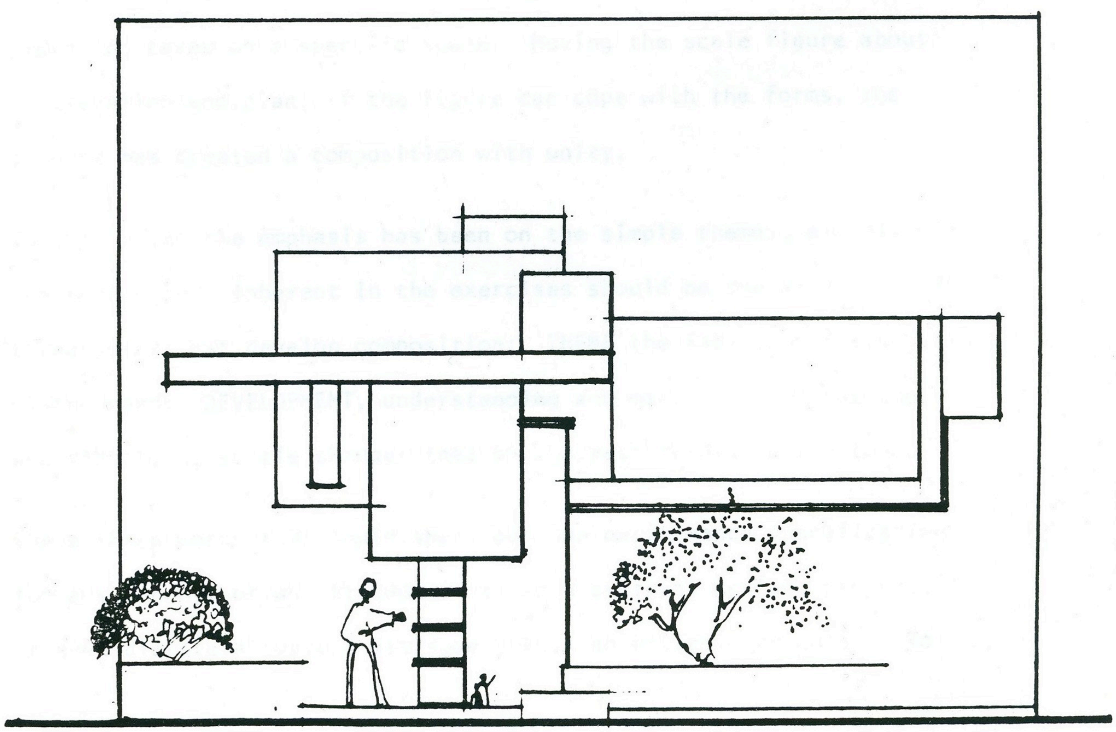

Figure 7. Elevation Composition.

There are infinite possibilities: and to make the student more aware of this factor, one of this series of problems would require that they look at their elevation as plan and develop an elevation from it. If one looks at Figure 7, then glances quickly back to Figure 6, this potential can be seen. By this means the student forms vocabulary, expands through an experience gained in their work. To see into and extend one's own work is perhaps the best way to extend the "field of meaning".

The total of the experience is the realization on paper of a special concept. The abstraction of space is introduced to the student as a tool through this prepositional approach. In Reitveld's view, "the reality which architecture can create is space", the most fundamental reality of all.

A good composition has unity, which might be described as a scale dedicated to itself. When a scale figure is added to Figure 7, the elevation takes on a specific scale. Moving the scale figure about in elevation and plan, if the figure can cope with the forms, the student has created a composition with unity.

To this point the emphasis has been on the simple themes, exploring the rectangle. Inherent in the exercises should be the awareness of three words that develop composition: THEME, the idea, a representation of the need; DEVELOPMENT, understanding and making use of the theme; and VARIATION, subtle changes that by contrast reinforce the theme.

These three words thus could spell out the performance for a symphony, or an attitude in an architectural design, project, or even dictate a logical attitude toward an entire curriculum. To fully understand these words, the working of the organic philosophy again plays a part. The student is encouraged to listen to music as part of a continuous experience that education should be. Looking at Figure 5 and 6 while listening to Beethoven's "Eroica", I believe the meaning in this design truly becomes apparent. The lesson is that Beethoven looks at the theme in many directions. Rotation of a design does not mean that necessarily a design conceived in one direction should be turned on its side, or upside down. Looking at the design out of context, however, con often make one more aware of the interrelation of parts.

Moving from the simple rectangular themes again, music can be most useful in the explanation to a student of the word counterpoint, a disturbance designed to announce and explain the theme. Using Ravel's "Piano Concerto for Left Hand", the thematic announcing qualities of counterpoint come alive, and at the same time the student is introduced to programmatic architecture, by programmatic music.

Paul Wittgenstein, an Austrian pianist who lost his right arm in the 1914-18 war, commissioned ravel to do this work for him. Ravel's response is beauty from within the problem, a totality that grasps time and place. Referring back to architecture, one might say, where Beethoven projects a mass-like quality in his music, Ravel has a tensile dynamic. Ravel in the "Left Hand" uses a multi-theme technique as counterpoint; this can be seen as a tool in the built-form in the following examples.

In the Octillo Desert Camp by Frank Lloyd Wright, one is first aware of the organic relation of the buildings and the site. The horizontal boards reflect the desert floor, and the occupiable spaces reflect the mountain shapes. On closer examination in the plan, one sees the basic rectangular unit rotated

freely, this being reflected in the structure of the camp walls and major room bays. This plan motion is then announced in the off-centered pitch of the tent roofs.

The "code" orientation of the desert camp use of counterpoint becomes more obvious when compared to a combination of "code" and "message" counterpoint used by Le Corbusier in the Villa Savoye. As a rectangular structured and expressed form, the circular forms are obvious "code" counterpoint. The functional use of these forms is what gives credence to the "message". The size of the oval on the first floor as an external form is oriented to the speed scale of the automobile; the inner circular form that eventually pops through the roof is dedicated in scale to man in motion. The fast repetition of the mullions of the lower level entry generate the oval while at the same time announce the fact that you are to go up into the living space. On arrival at the second level, the counterpoint quality of the triangular opening in the ramp area is reinforced now by horizontal mullions, the mullion relating the viewer to arrival.

The thought of this being pure functionalist thinking and not counterpoint is dispelled when one is made aware of the original color scheme of the house; lower level columns are orange, the exterior walls forest green, the main level pink, and the top sky blue.

Mies van der Rohe's Tugendhat House uses "message" if explained in terms of counterpoint. First the upper level is almost totally conventional, with the exception of the entry stairs sheathed in frosted glass and circular form, the theme is thus privacy. The lower level is literally and open terrace for living, the exact opposite them of the upper level. The stair form on the upper level becomes counterpoint in that it is completely concealed on the lower level. Through the stair from functions in expressing motion, on the lower level the form is used as a gathering, joining form, in the dining area. Thus, counterpoint in the Tugendhat his found in the multi-theme use of form and space. The latter part of this remark is born out in the plan of the lower level, with five different space themes in one room: library, cave live; music area closed, open feeling with form forced into it; living, an open terrace of rectangular splendor; dining, form responding to need; and pantry, a denial of form.

Another way of looking at counterpoint is to simply refer to it as noise. In explaining this concept at a children's concert, the director of the New York Philharmonic said, "each culture has a different noise level". If one looks at our society that we live in today, it seems we are trying to equate mass production, the Parthenon, evolution, and automobiles with an expectation of beauty. Omitting counterpoint from the equation, the results as a built-form would be exemplified in the Illinois Institute of Technology by Mies van der Rohe. But taking the same equation, education, student, and machine, with the understanding of the principles of counterpoint, one sees in the built form a potential of reality in Leicester University Engineering Building, by James Stirling and James Gowan.

By stating the examples above, from Octillo the Leicester, one might say this theory could be presented in a lecture course. The product of this approach is "the threshold of minimum awareness", the idea becomes a fact, which it is not, instead of becoming a tool discovered by the student. The organic and creative way of involving the student in this area would be to state the problem in terms of a composition, explaining the basis of the counterpoint concept, without using specific examples. On

completion of the project, the student would then be introduced to an architect whose work demonstrates a similar attitude in the built form. Presentation of this project would be in plan, perspective, and model. As the purpose is to move the student forward in architecture, the student is encouraged to design the project on paper, and then do the model. In building the model, the student is encouraged to study the project with a model scope, checking and correcting the design from within.

The purpose of this model is not just a study in exterior form and mass. Through the use of the model scope, the student discovers they can get inside the model, that the exciting exterior forms are a result of active interior space. This is, of course, the central meaning of the organic philosophy, obviously explaining the "within" concept.

The example, Figures 8 and 9, is a rectangular composition disturbed by circular forms. It was designed to explore the principle of counterpoint, but also to introduce rhythm. The title might be the result of doing the project while listening to music, or found in the "field of meaning." If this were a student problem, they would be encouraged at this stage to research the following people: Aldo Loris Rossi, house at Ercolono, Naples; George Fred Keck, house at Green Bay; Ralph Rapson, Hope Lutheran Church, Minneapolis.

The goal, of course, is to excite the project with the awareness of function, but at the same time the student's awareness of the built world is growing. The reasoning in this attitude becomes even more apparent in the following remark by Bruce Goff. "I tried to teach the students to learn from what had been done, but more important to think their own way as much as possible. It is hard for students to distinguish between inspiration, influence and limitation".

Organic philosophy in architectural education is thus not a system, but more an attitude on how the system will be used. The dedication of the philosophy above all is to help the individual understand themselves.

It becomes increasingly difficult to achieve this quality of understanding within the modern educational system. It is obvious by the numbers of students, activities of both faculty and students whose efforts are frustrated in this direction. If one were to look at the Baird diagram again in the light of the student- faculty relationship entering to a creative experience, it appears that one cannot omit architectural criticism from this discussion.

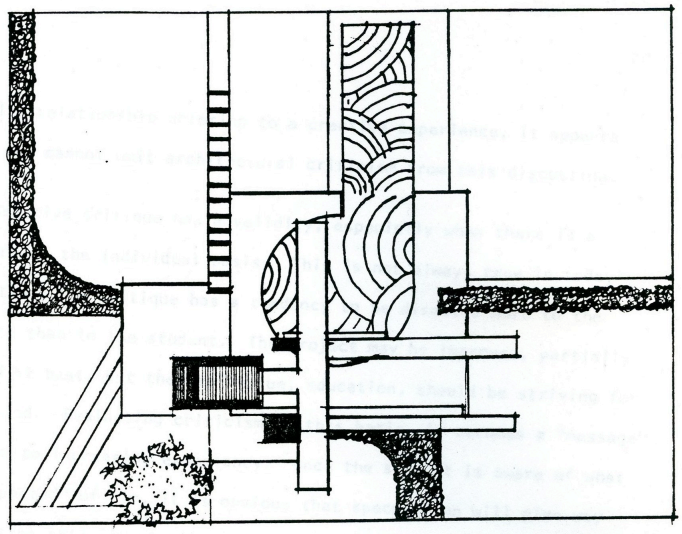

Figure 8. Composition with Counterpoint Landscape for a Memorial to Paul Wittgenstein

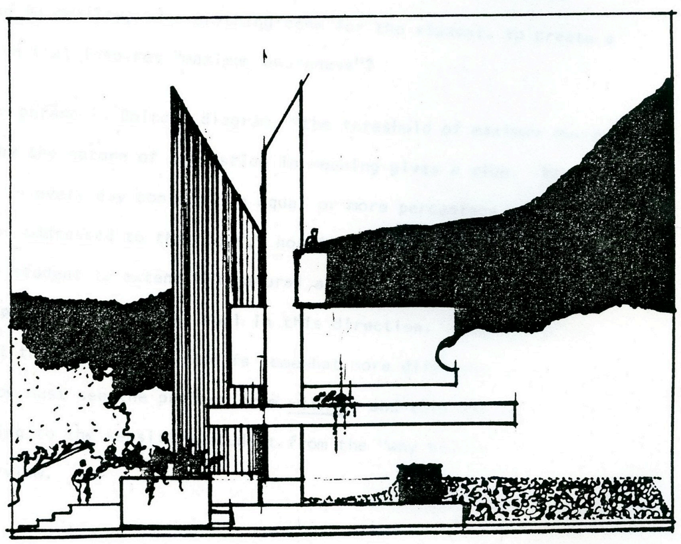

Figure 9. Elevation of Composition