Self-Organizational Architecture:
Design Through Form-Finding Methods

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Self-Organizational Architecture:
Design Through Form-Finding Methods

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SUMMARY

Form-finding in Architecture looks at processes in nature to discover a more correct way in which to organize building. It is a study into the capability of discovering optimum form, dynamic adaptability, and exposes a set of unique relationships not relevant to Architecture previously. The beauty of these objects does not have to be designed. It is an emergent property of natural form. However, the wonder lies not in aesthetics, but in the manner in which natural forms come into being… seemingly without a plan, at a multitude of scales, and in a vast array of materials. Alone, pattern in nature opens a vast array of potentialities for the study into new methods of architectural design. It is important to note that this inquiry will not be into the aesthetics of self-organized pattern, but the mathematical and procedural processes of formation itself.

This study forms a set of principles, methodologies and tools for structuring a full-scale form-finding inquiry through the self-organization of pattern in nature. Following this inquiry one should be able to apply the organizational principles of patterning in nature, specifically breakdown patterns, to inform the programmatic design and layout of shopping malls. The rules set forth outline the formation of breakdown patterns, and the ordering of shopping malls. Through the use of parametric modeling software and computer programming language, sets of digital models efficiently explore of the vast number of potential pattern organizations by mimicking their formation in digital space. Through computational scripting, digital models also reveal formation changes due to the adaptation to site, circulatory loads, and spatial distribution, while still maintaining the laws of pattern formation.

Introduction

For many years, architects have looked to self-formation processes in nature to discover a more correct way in which to organize architecture. The most prominent of those architects are Antonio Gaudi, to some extent Luigi Nervi, and of course, Frei Otto, and, just to name a few. The richness of these formations are some the most beautiful objects found on this earth. However, the wonder lies not in the aesthetics, but in the manner in which they come into being… seemingly without a plan, at a multitude of scales, and in a vast array of materials.

The self-organization of pattern is dynamic and adaptive, capable of producing form that is not necessarily expected. Like patterning in nature, a building should be capable of taking up any internal forces without giving up function, being able to exist in a perpetual state of emergence, yet always complete. Form finding is an organizational method through which a building can escape being a fixed organism with a predetermined form. By using a bottom-up method of design, there is a forever-embedded set of rules in place for expansion or reorganization of that building.

Part I:
THEORY AND ARGUEMENT

2.1 Beauty in Architecture

"Beauty is that reasoned harmony of all the parts within the body, so that nothing may be added, taken away, or altered, but for the worse" -Leon Battista Alberti [1]

Nature does not care about aesthetics. Her only concern is with the optimal and perfect ordering of systems. It is filled with variation and complexity that architecture has yet to fully explore. Nature doesn't care about form following function, or function following form… her constructions arise through optimization, iteration, mutation, and feedback, all of which produces formations which are as elegant as they are robust. It is this endless interaction of component parts that give rise the unprompted patterns that are at the same time complex and beautiful.

Pattern is often mistaken for some sort of repeating array of identical units. In its simplest terms, pattern should be defined as 'symmetry with the proper harmony of component parts to each other and to the whole, defining a kind of beauty.' This means the pattern can include arrays that are not necessarily identical, and repeat in a manner than is not necessarily regular or with well-defined symmetry. Pattern in nature embodies this concept. Through its dynamic characteristic, it is able to absorb changing conditions, alter its visual appearance, all while remaining topologically the same.

We discover that Nature's patterns recur again and again in situations that appear to have nothing in common with one another. How so then, does a drainage network begin to resemble a bolt of lighting, a fractal pattern

1 From On the Art of Building: Book 6, 155-7.

in a digital model, a system of blood vessels, or a tree? (Figure 2.1).

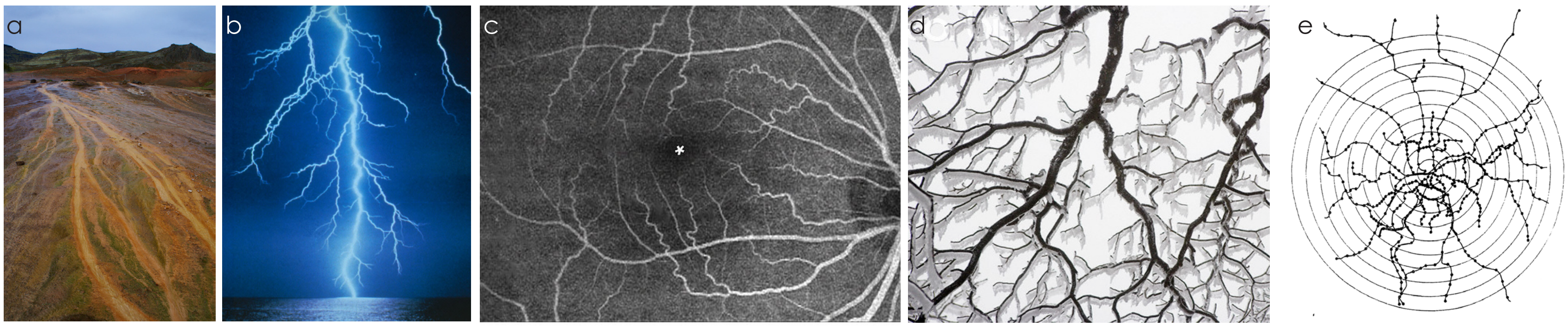


Figure 2.1 Self-Organizing Patterns of the Same Type Occuring Under Different Circumstances
a. Sulfur drainage from an Icelandic geyser; b. Lighting; c. Blood vessels in the htuman retina; d. Tree branches; e. Diagram of the Paris Metro System,

If nature is at all economical (and we should assume that this is usually so), then we should expect that she will not construct complex form through a series of laborious processes, but by using some sort of organizational and pattern forming phenomena. This means that growth and form need not be mysterious and that the rules for generating them are generally of a simple nature. Mathematics enables us grasp the essence of pattern and form. It is the means of description at its most fundamental level, and thereby be facilitates our seeing what features need to be reproduced by an explanation or a model. [2]

Leon Battista Alberti, probably the most influential Renaissance theorists of Architecture, prefered the Platonic

2 Phillip Ball. The Self-Made Tapestry, 8-15.

belief that there is a higher reality to the physical or phenomenal world. He was certainly correct in doing so in regards to the formations in nature. More importantly, to the subject of this inquiry, he accepts that art and architecture can symbolize these higher ideas through their adherence to universal mathematical laws or harmonic proportions. In his treatise, *On the Art of Building*, he states:

> "The three principal components of that whole theory into which we inquire are number, what we might call outline, and position. But arising from the composition and connection of these three is a further quality in which beauty shines full face; our terms for this is ***concinnitas***…It is the task and aim of *concinnitas* to compose parts that are quite separate from each other by their nature, according to some precise rule, so that they correspond to one another in appearance… Everything that Nature produces is regulated by the law of *concinnnitas*, and her chief concern is that whatever she produces should be absolutely perfect."

It only makes absolute sense that everything in nature is perfect, (relevant to its environment and time). If it was not perfect, it would not have been selected. It is important to note, that thus far in Alberti's statement, beauty is not mentioned. *In nature, beauty is the emergent property*. He goes on to say:

> "Beauty is a form of sympathy and consonance of the parts within a body, according to definite number, outline, and position, as distacted by concinnitas, the absolute and fundamental rule in Nature. This is the main object of the art of building, and the source of her dignity cahrm, authority, and worth." [3]

3 Leon Battista Alberti. On the Art of Building: Book 9, 301-3..

If beauty is the emergent property of *concinnitas*, (the proper arrangement of parts), then it is the goal of the architect to first be concerned with finding the most correct organization scale of elements. In establishing the most correct form, the architect will have discovered the most beautiful one.

2.2 Form-finding in Architecture

Form-finding falls somewhere in between the theory and practice of Architecture. It can be described as *the study of emergent properties of complex system to establish a more intelligent, correct, and robust form.* The practice itself demands drastic changes both in the way one thinks about architecture and how one produces it. It ignores the architect's tendency towards conceptual ambiguity. It is not inspired by the arts; it is not a piece of poetry or a metaphor. Form-finding is part of an answer to the question, "what is architecture and how do we go about designing it?"

Bubbles, shells, sand dunes, and the like are not architecture, of course. Architecture is the set of objects and environments in which we go about our day-to-day lives. It is mankind's greatest impact on this planet, how we measure a society's greatness, and that which we leave behind. Alberti describes an architect as, "who by sure and wonderful reason and method, knows both how to devise through his own mind and energy, and the realize by construction, whatever can be most beautifully fitted out for the noble needs of man, by the movement of weights and the joining and massing of bodies" [4] By now, the idea of constructing work in a durable and convenient manner should be self-evident. As the human population continues to increase across the globe,

4 Leon Battista Alberti. On the Art of Building: Book 1, 3..

it is increasingly imperative that architecture seeks more minimal impact on the environment. Frei Otto calls for an architecture of necessity, saying, "Good architecture is more important than beautiful architecture… The ideal is ethical architecture that is also aesthetic." [5] He felt that mankind squandered space and energy and destroyed nature. In his search for a more natural architecture, the possibilities are extended, not restricted. The goal is to not find an answer immediately, but to see out the most optimal solution that is suitable for the time. In form-finding, nature is not copied, but used to inform a more intelligent method of integrating built structure into the landscape. This does not mean that a building should look like a bubble, a tree, or a termite mound. The emergent properties in form-finding are studies of minimal systems, whose forms originate passively to their most optimum state. These emergent phenomena are often the unexpected and nontrivial results of simple interactions between simple components.

Form-finding is only one of the many ways in which to go about designing architecture and being an architect. However, it would only seem wise to explore it as a design tool… especially since one only has look out a window to see it working so seamlessly, not to mention beautifully.

2.3 Birth of Form-Finding- Antonio Gaudi

"The straight line belongs to man, the curved line belongs to God," –Antonio Gaudi

While Gaudi could not have directly asked God to draw the curves of his pinnacles and arched constructions,

5 Frei Otto. Finding-Form, 13.

he could allow the correct form to emerge though gravity.

Gaudi was the first form-finding architect, and the first in modern history to employ an analog computer in the designing of shell structures. He demonstrates a clear influence of Gothic tradition of material testing and non-linear engineering. Gaudi employed physical models with weights to determine the correct construction of efficient shell forms (Figure 2.2). His Masterwork, the Sagrada Familia (1882-present, Figure 2.3), and the unfinshed Colonia Guell were designed in this way. Throughout the structure, networks of arches converge and bifurcate, forming what resembles branching assemblies. Ornament is generated through the definition of edges, lofting routines, and aggregation of those elements at various scales. It is an architecture that evokes nature, but cannot be described by nature alone. It ascends to something more, somehow capturing brutality and grace at the same moment. It is not purely excessive, nor purely efficient. Performance is everywhere, but it articulated through the language that elevates it to the level of art.

Figure2.2 Antonio Gaudi- Model for Colonia Guell

a b

Figure 2.3 La Sagrada Famila- Antionio Gaudi
a. Exterior view of the Passion facade; b. Interior detail of column network

2.4 Frei Otto

While Gaudi originated form-finding in architecture, it was Frei Otto that perfected the process. One only has to see the work of Otto to understand that beauty can be found without having been necessarily designed.

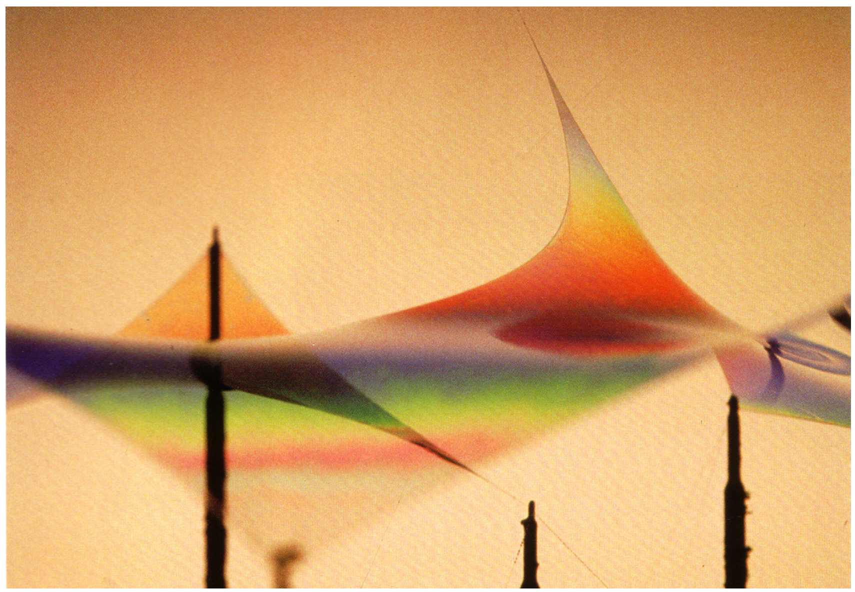
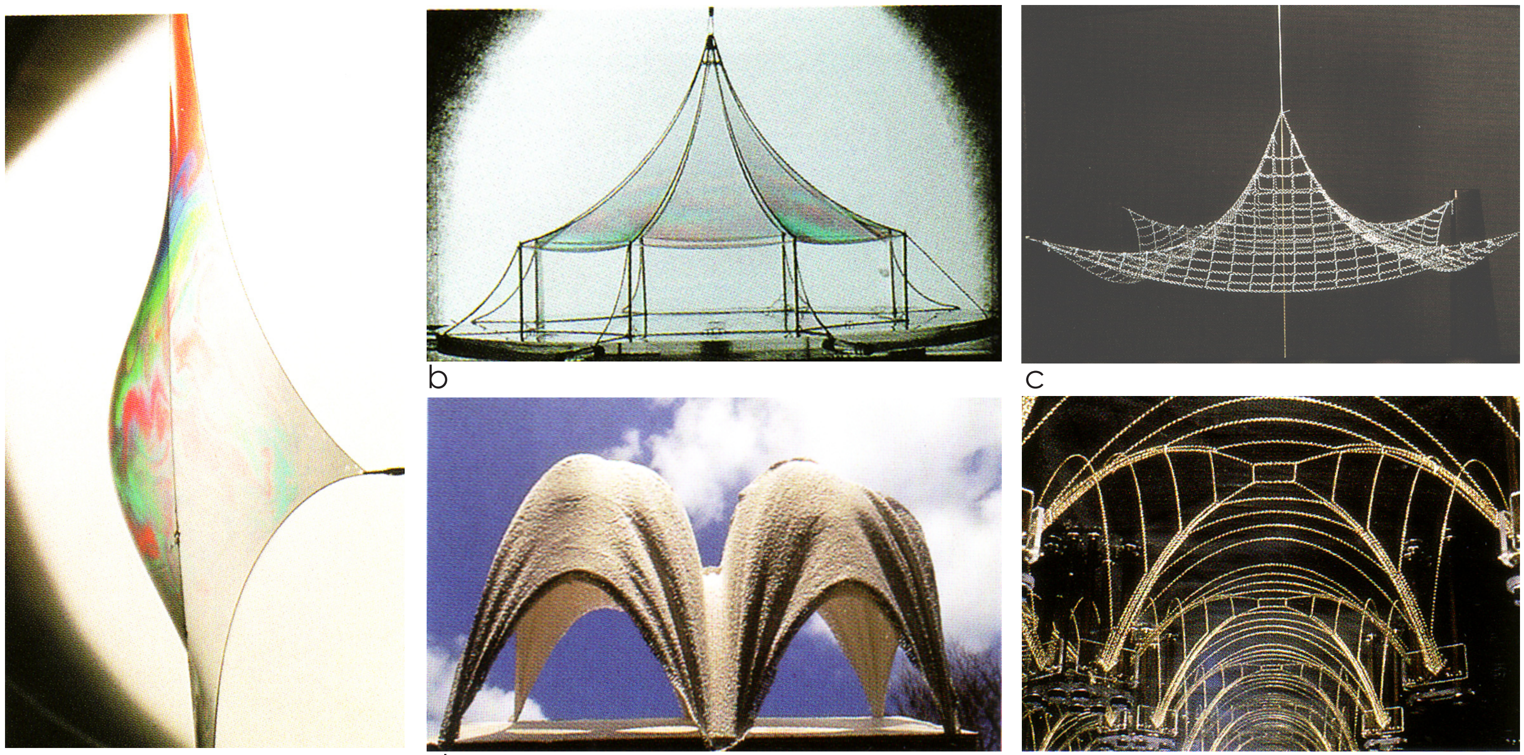


Figure 2.4 Frei Otto- Soap Film Model For a Tent
(Image: Freo otto & Bodo Rasch. Finding-Form, 44.)

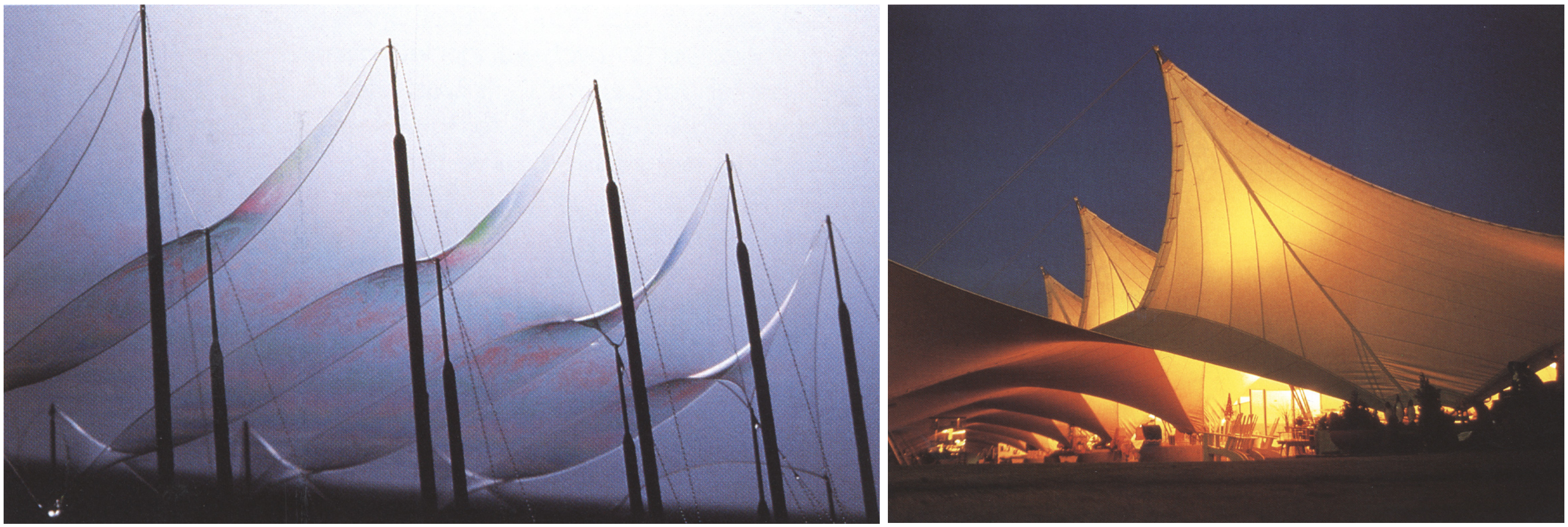
Frei Otto regarded form-finding as a method of research and design of the emergent properties of natural systems, through which buildings will become less unnatural than in the past. This is a large step in lessening the impact mankind has on the planet.

The work of Otto;s practice, The Institute for Lightweight Structures, is based around process of seeking form for large engineering constructions through careful constrcution and documentation of experimental phyiscal models. Every experiment conducted by the group serves as a model for the future explanation of forces and force transpositions of the particular form in question. They are the first stage in the explanation of the origin of form. Otto deems it absolutely necessary that Form-finding Architecture be an interdisciplinary pursuit, made up of architects, engineers, biologists, philosophers, physicists, and synergists. It is the ethical task of the group to fit every unavoidable new structure into its environment with a minimum of materials and energy consumption, eventually in such a way that it becomes part of an ecological system.
The scope of his investigation includes soap-film experiments for producing minimal surfaces, pressure-loaded vault forms by reversing tension-loaded suspended forms, optimized path systems, pneumatic structures, and branched constructions (Figure 2.5). The range of possible forms is determined by the choice and definition of the conditions under which the form-finding process takes place. Uniting the logic of material and of structure makes it possible to form-find certain kinds of structures at all stages, from the beginning of the design processes to full-scale construction.



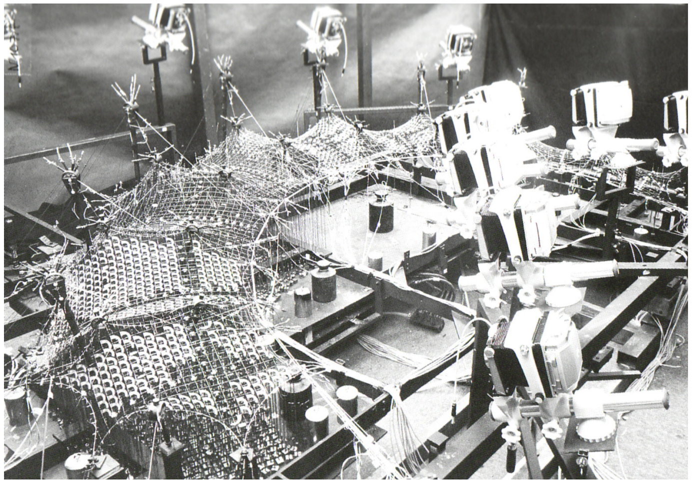
b c a d e

Figure2.5 Form-Finding Experiments Conducted by Frei Otto and Bodo Rasch at the Institute for Lightwieght Structures
a. Soap film in a wind tunnel; b. Pointede Tent Soap Film; c. Suspended Net Model d. Plaster and Fabric model (inverted) for vault formation; e. Chain inversion for the formation of groin vaulting. (Image: Freo otto & Bodo Rasch. Finding-Form, 58-63.)



a b

Figure 2.6 Greate Wave Hall- Internationl Garden Exhibition at Hamburg- 1963.
a. Soap film model for parrallel wave tent;   b. Photograph of finished constrcution. (Image: Freo otto & Bodo Rasch. Finding-Form, 78.)



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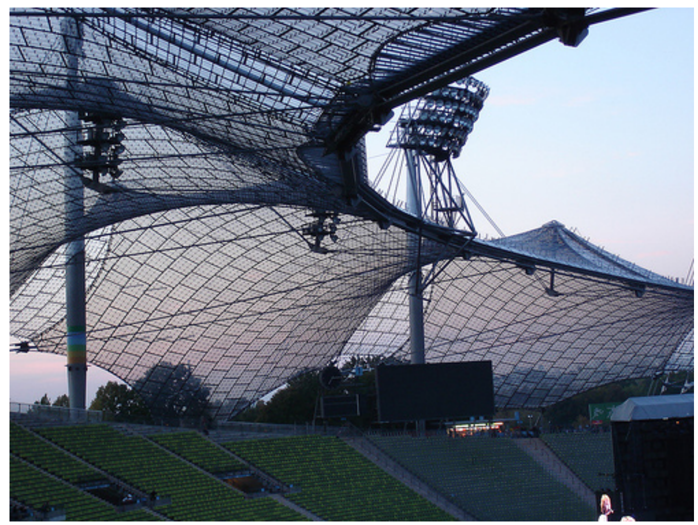

d

Figure 2.7 Olympic Roofs, Munich-Frei Otto,1968
a. Experimental model to determine structure b. Full construction c. Detail photograph; d. Detail photgraph

a

b

Figure 2.8 Proposed Train Station in Stuttgart, Germany- 2001
Frei Otto, structural advisor; Christoph Ingenhoven, architect

3.1 Design Selection

Which came first, the chicken or the egg? In this inquiry it's hard to say. The only requirement for selection (pattern and architecture) is that the one is not chosen completely independent of the other. In this case, the patterning-mechanism and building type were selected simultaneously as a matter of personal preference. Hence forth, the inquiry will be specifically concerned with the study of breakdown patterns such as cracking and branching processes. These will be used to construct a spatial organization for shopping malls.

In choosing a horizontally propagating pattern, it was required that building type be, for the most part, horizontal in conceptualization as well. It was also a matter of personal preference to construct an inquiry into movement and circulation. Breakdown patterns are characterized by the movement of forces by the process of least work. Shopping malls are successful on basis of the movement of people in order to distribute commodities.

For this inquiry, the patterning mechanism is the literal generator of the spatial concept of the mall. In shopping malls, modifications are the order to the day. There is a constant shift of spaces as venues, open, close, expand, change store layout, and display seasonal merchandise. The building should be capable of taking up all internal forces without giving up function. This is not so when the building is a fixed organism with a predetermined form. The building exists in a perpetual state of emergence, yet always complete. Therefore, <u>the spatial concept becomes the more enduring structure for a more changeable infill.</u>

4.1 Shopping

Shopping traces its relationship to the city back to Greek agora, wherein public life emerged beside the market-place (Figure 4.1). Much later, in 19th-century Paris, the arcade redefined the experience of the city by creating a level of connectivity. The arcade functioned as version of the city street, forming a conduit between previously disconnected portions of the city (Figure 4.2). The next great shift occurred with the suburban shopping mall, which was and is completely disconnected from the city and public life. Its visitors enter a vast interior space where time and reality are no longer present. Over time the suburban shopping mall has made its way back into the city, bringing its suburban ideals of bland un-authenticity with it (Figure 4.3).

The delineation of the "urban" realm has become synonymous with the provision of spaces of shopping. Shopping has encroaches onto so many new territories that is has become the defining way the majority of the population experiences public life. They have invaded many of our cultural institutions, such as museums, churches, sporting and musical events, and the like. In many cases, these convert hybrids average far better in sales than the average shopping mall. (The MOMA store averages $1,750 per square foot; London's Heathrow airport averages $2500 per square foot; Mega-Malls average $600 per square foot; Regional shopping malls average $250. [1])

Shopping malls continue to draw on the notion of the spectacle. In many instances, the mall is just as much an entertainment center as a shopping destination. These often fall into the category of the Mega-Mall, (over 1

1 Sze Tsung Leong. Project On The City 2: The Harvard Design Guide to Shopping. 147.

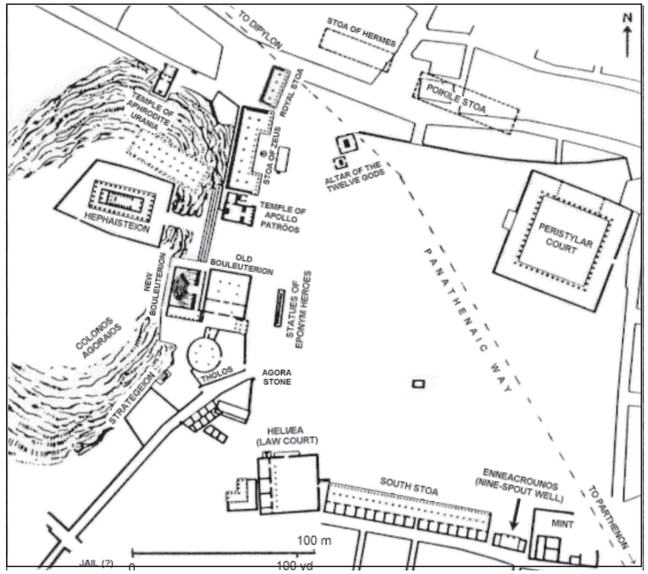

Figure 4.1 The Greek Agora

Figure 4.2 Typcial 19th-Century Parisian Shopping Arcade- Gallerie Vivienne

Figure 4.3 Typical Suburban Shopping Malls

Figure 4.4 Mall of America

million square feet) (Figure 4.4). Like the airport and the museum, it sells itself as one thing but in the end is just as functional just as successfully as a shopping mall.

One thing is for certain, shopping is continually being reinvented, reformulated, and reshaped to keep up with the subtlest changes in consumer pattern. This is evident in the multitude of forms it has taken throughout history.

4.2 The Escalator

The success of the shopping mall is dependent on the ease of movement of the consumer. No other architectural invention has been so indispensable to shopping as the escalator (Figure 4.5). Unlike its cousin, the elevator, the escalator is a significant importance to the formal development of the shopping mall. The elevator is limiting, only carrying a set number of people. The occupants have to know exactly where they are getting off and on. It is a halting process. The escalator, on the other hand, is fluid and efficient… there is no starting and stopping. People transition environments effortlessly, blurring the difference between sections and levels. It denies relevance of departments and floors. Combined with air-conditioning, the escalator allows more depth to be accessible to the consumer. If travel is so effortless, the consumer is more likely to circulate more through the space, and ultimately, to buy more goods. And because

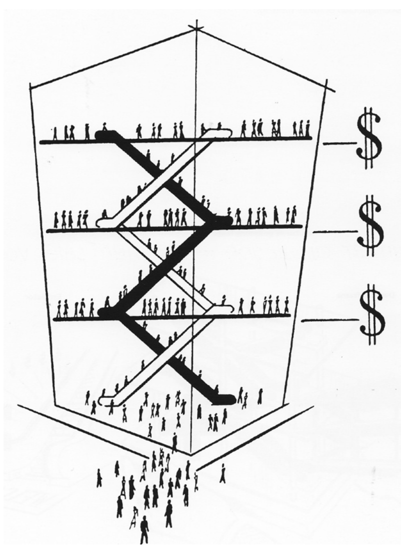

Figure 4.5 1946 Otis Escalator Advertisement

the escalator offers a wide, unobstructed view of one's surroundings, visitors often stray to look at adjacent merchandise instead of heading straight to their prior destinations. The escalator has helped blend shopping into other architectural models, mall into museum, downtown and airports into malls. The escalator is present in all… silent, and unnoticed.

a b c

Figure 4.6 Escalator Mazes
a. Siam Paragon, Bangkok; b. Bullring, Birminfham, UK; c. Golden Terraces, Warsaw

4.3 Space

> "Space is more of an idea than a delineated concept…though space has liberating effect, it is not freedom. Freedom is unbridled, unlimited release. Space is ordered, targeted, even if that order is emotional by nature and impossible to define. Freedom is virtual, existing only as something in the distance that is not part of you, such a horizon, that shifts when you think you have gotten closer to it... Freedom is something you feel when it is not yours." [2]

These are the words of architect Herman Hertzberger in his text _Space and the Architect_. He describes freedom as something that is intangible, disappearing around the next corner, hovering just over the horizon. At the point when one finally rounds the corner, all there is more space… leaving one constantly searching. Freedom is intangible.

Shopping malls are dependent on this notion of freedom. They invoke this ever-illusive notion through their series labyrinthine spaces and generous spaciousness. The mall is an accommodation of unregulated desire. Around every corner, at the end a vanishing point is something else tempting you, as if the multitude of objects flittering by you at the moment is not good enough? It is a glittering fantasy in a world suspended in time. The goal of the mall is to lure the consumer into wandering aimlessly through its vast corridors, forgetting all that goes on beyond its walls. It is a mirage of a beautiful form of existence… selling a life that one can never quite capture.
Its illusion of spaciousness only increases the desire for more things to fill it with.

2 Herman Hertzberger. _Space and the Architect_. 14.

4.4 Space As Experience- The Dérive

As much as the architect may try, he/she can never fully define a space. It is defined by those who use it. The architect can attempt to define that space in one manner, through a number of drawings, dimension, and material. However, its descriptions are infinite. They depend on the time of day, the noise, and number of people. Therefore it can be said the space cannot be defined, only described. At best the architect can only design the scaffold for change.

No other architectural idea embraces this notion quite a fully as the work of the Situationists in the mid-twentieth century, particularly Constant Nieuwenhuys' *New Babylon*. *New Babylon* began with the notion of the 'dérive'. The dérive, (literally - 'drift'), is described by Situationist founder Guy Debord, as:

> " a technique of transient passage through varied ambiances…
>
> In a dérive one or more persons during a certain period drop their usual motives for movement and action, their relations, their work and leisure activities, and let themselves be drawn by the attractions of the terrain and the encounters they find there. The element of chance is less determinant than one might think: from the derive point of view cities have psychogeographical relief, with constant currents, fixed points and vertexes which strongly discourage entry into or exit from certain zones." [3]

The earliest physical example of the dérive is Debord's map of Paris, titledt'The Naked City' (Figure 4.7).

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3 Guy Debord. From *Internationale Situationiste* #2, 1958.

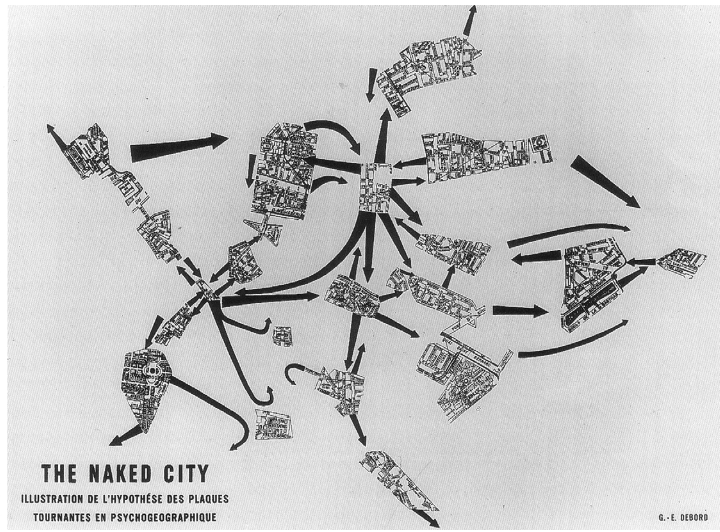


Figure 4.7 The Naked City- Guy Debord and Asger Jorn- 1567
(Image: Mark Wigley, Catherine Zegher. The Activist Drawing, 2001. p. 96s.)

Starting with tourist maps, the late-night drifts of groups were traced through the city. Large red arrows link the sites, cutting through parts of the city as if they didn't exist. All that was then left of the city were the dérives made by these wanderings of desire. Constant redraws these maps with his scissors, transforming these maps of old cities into his World-Wide City of the Future- *New Babylon* (Figures 4.8-4.12). In its final stage, the plan is a three-dimensional collage of tourist maps from many different cities. The element of collage is the central core of the project.

New Babylon is a seemingly infinite playground. Its occupants continually rearrange their sensory environment,

Figure 4.8 New Babylon, Amsterdam
Ink on map. (Image: Mark Wigley, Catherine Zegher. The Activist Drawing, 2001. p. 58.)

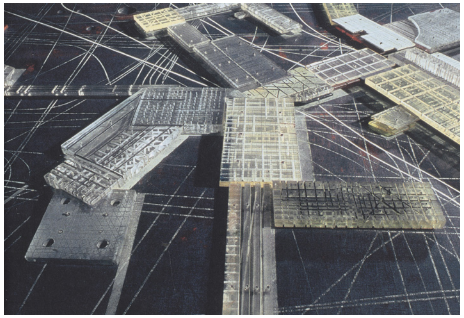


Figure 4.9 New Babylon- Group of Sectors
Ink on Plexiglas, oil on wood. (Image: Mark Wigley, Catherine Zegher. The Activist Drawing, 2001. p. 57.)

redefining every micro-space within the sectors according to their latest desires. In a society of endless leisure, workers have become players, and architecture is the only game-in-town, a game that has few limits. "The inhabitants drift through the huge labyrinthine interiors, perpetually reconstructing every aspect of the environment by changing the lighting and reconfiguring the mobile and temporary walls…For this homo ludens, social life becomes architectural play and the multiply interpretable architecture becomes a shimmering display of interacting desires" [4] Each sector of the city is served by automated machines hidden underground that take care of all of the work, while the people spend their lives wandering the vast corridors of the interior, suspended high in the air. The 'Architect' merely sets the scaffold for change, the mechanisms of the process, and then has to relinquish control.

There are very few other types of architecture that serve as a metaphor to the shopping mall through such a form of utopian fantasy than New Babylon.

4 Catherine de Zegher. The Activist Drawing. 10.

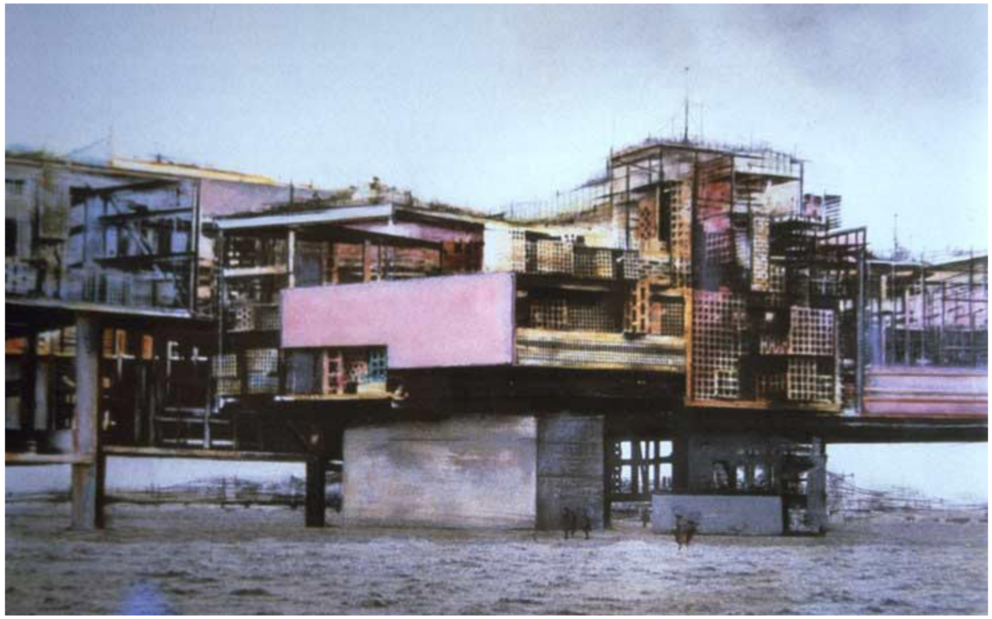


Figure 4.10 New Babylon- Sector Construction
Metal. (Image: Mark Wigley, Catherine Zegher. The Activist Drawing, 2001. p. 119.)

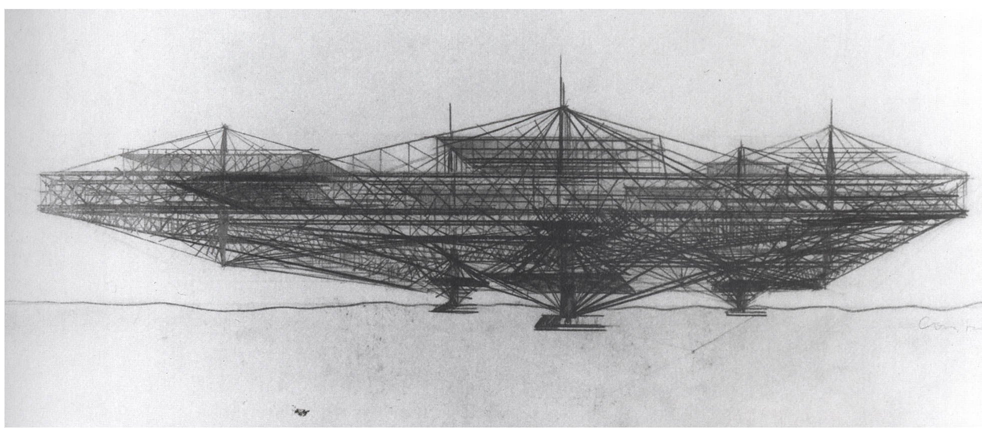


Figure 4.11 New Babylon- Sketch of Self-supporting Sector Constrcution
Pencil on paper. (Image: Mark Wigley, Catherine Zegher. The Activist Drawing, 2001. p. 105.)

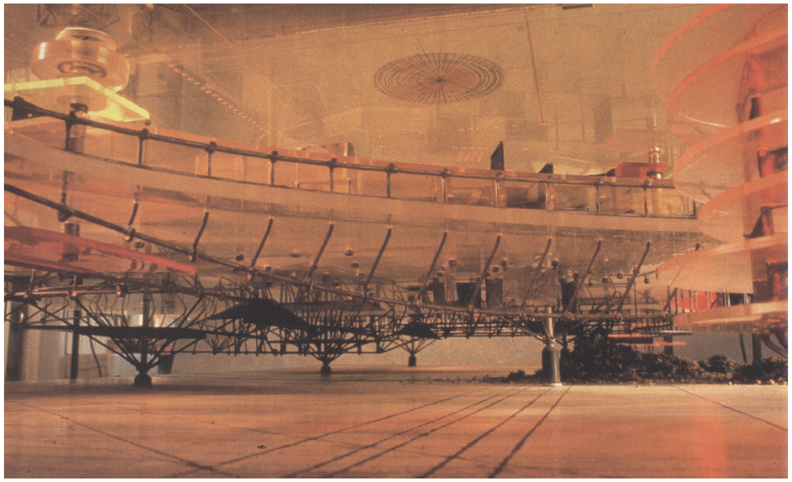


Figure 4.12   New Babylon- Yellow Sector
Metal, ink on plexiglas, oil on wood. (Image: Mark Wigley, Catherine Zegher. The Activist Drawing, 2001. p. 108.)

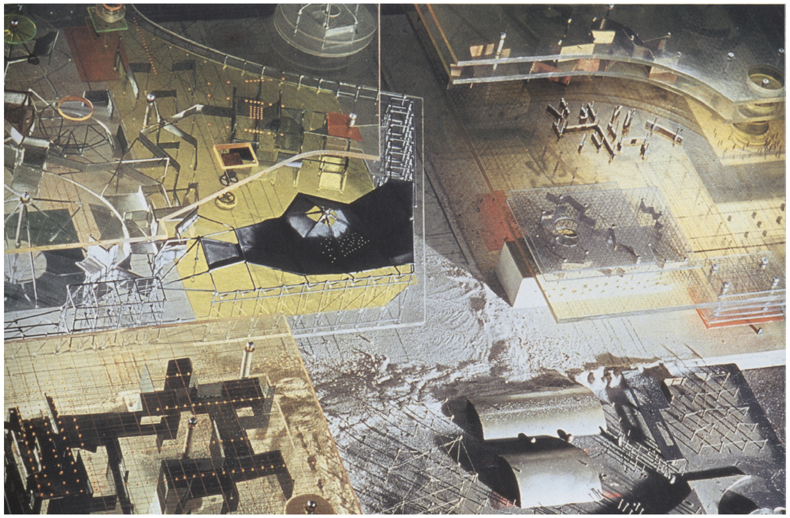


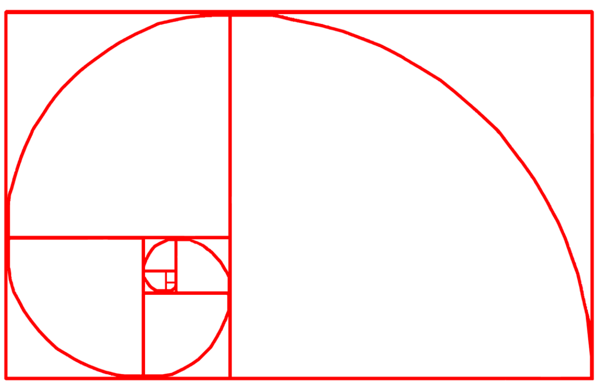
Figure 4.13 New Babylon- Combination of Sectors
(Image: Mark Wigley, Catherine Zegher. The Activist Drawing, 2001. p. 113.)

Part II:
Methodology

Chapter 5:

5.1 Patterns in Nature

It was Plato's belief tha there existed a perfect model for everything . Mathematics is the key that enables us to grasp the essence of pattern and form. It is our means of describing the Platonic ideal. We assume that nature is economical, and therefore will not construct complex form through a series of laborious processes, but by using some sort of organizational and pattern forming phenomena. This means that growth and form need not be mysterious and that the rules for generating then are generally of a simple nature. Pattern is rarely reflective of the forces that generate it. It is one of the few cases in which the effects are greater than the case… for the better of all.



a

b

Fig. 5.1 The Famous Golden Section
a. Mathematicial Construct; b. Section through a nautilus shell

5.1 Drainage Networks

Drainage patterns are patterns of movement, kinetic energy. They are fascinating in that they are dependent on one drop of liquid behaving in the identical manner as a million of the same. They always seek the path of least resistance. It is the combination of these small behaviors that produces these patterns, some of the largest, most visible, and life giving of our planet.

Drainage networks can be described as slowly propagating cracks, which grow in the opposite direction of the movement of the water that they carry. Wherever the amount of rain hitting the surface of a landscape is greater than its rate of removal, a gully is formed, deepening the volume in which the water can retreat. The water then causes further growth as it erodes away sediment along its journey.

Fig. 5.2 South Yemen from Space- Typical Dendritic (Branching) River Network

Branching river systems are true fractal networks (Figure 5.1). The following rules are really expressions of self-similarity and consist of the barest ingredients when comparison to the dynamicism of the natural processes. Yet somehow, almost all river networks come to obey them, as if by magic.

5.2.1 Scaling laws of Branching River Networks

In 1952 A.N. Strahler classified the elements of the drainage network into 'stream orders', which indicated their position with the network   (Figure 5.3).

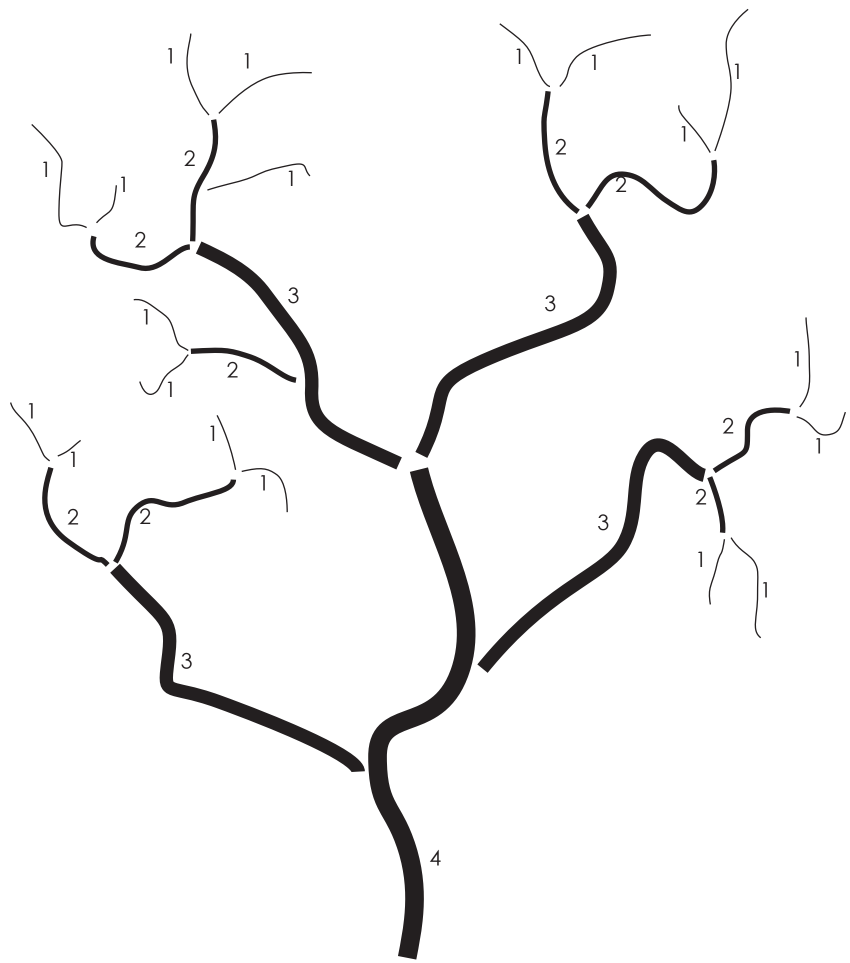


Fig. 5.3 Hieracrical Ordering of Drainage Network (Image: Peter S. Stevens, Patterns in Nature).

According to Strahler's classification system, first-order streams, are those with no tributaries. When two first-order streams converge, they form a single second-order stream, and so on... A single lower-order stream can flow into a higher order, but it will not change the order of the stream into which it merged. [1]

In the 1930's, American engineer Robert Horton conceived a set of numerical scaling laws that describe the properties of drainage networks. By viewing Figure 5.1, one could probably deduce that the first scaling law of drainage network composition is that there are more lower-order streams than higher-order. Horton was able to describe this in mathematical terms, which is the first of his three scaling laws.

$$N_x = constant * N_{x+1}$$

The average number (***N***) of streams of order X, is a constant times the number of the next highest order, X_{+1}. In nature this constant is found to average somewhere between three and five.

In the second of the scaling laws, Horton also mathematically quantified the rule for stream lengths.

$$L_x = constant * L_{x+1}$$

The average length (***L***)of streams of order X, is a constant times the number of the next highest order, X_{+1}. Thus,

1 Phillip Ball. The Self-Made Tapestry. 153.

higher-order streams are longer than lower-order ones.

The third scaling law of drainage network is that the length of the principal (that is highest-order) river in a network is proportional to the drainage basin area.

$$L=1.4Area^{2/3}$$

It is argued that the exact numerical values of the formula vary in comparision to that of actual river basins. The factor of 1.4 fluctuates between 1.0 and 2.5, while the exponent of 2/3 fluctuates between .50 - .70. [2]

5.2.2 Topological Ordering of River Branching

The topological ordering of branching patterns can be described by the following formula, with J representing junctions of branches:

$$1J_1 + 0J_2 - 1J_3 - 2J_4 - \ldots = 2$$

It is implied by the above formula that two-way junctions (J_2) do not change the outcome of the pattern and need not be accounted for. Furthermore, it is recognized that junctions with three streams converging into one rarely exist in natural river branching patterns, (J4). Taking these two factors into account, the formula simply reduces to the following:

2 Phillip Ball. The Self-Made Tapestry. 153. & Peter Stevens. Patterns In Nature.110.

$$J_1 - J_3 = 2$$

J_1 is the number of one-way junctions, plus the exit; therefore, being the number of first order streams plus one. Following this formula, a river network of 40 sources, would have 40 first-order streams and 39 triple junctions. A 60 source network would have 60 first-order streams and 59 triple junctions, and so on... [3] The distribution of triple junctions in a branched river system is the determining factor in the ordering of the network, (the number of first-order, second-order, etc). Published in study by Ronald Shreve in 1966, the number of possible distributions of triple-junctions in a stream network is finite, increasing with the number of first-order streams. Each possibility has an equal chance of being chosen, with natual stream networks supporting this conclusion. A visual explanation of Shreve's distribution law is given in Figure 5.4. Each individual network possibility is defined by having no amount of distortion that will transform it into another network. Shreve's rule of topological ordering also confirms Horton's scaling law for stream numbers as the ratios from each subsequent stream order are three to fives times than that of the next highest order. This describes the bifurcation ratios of the streams in most of thepossible network configuations in Shreve's model.

3 Peter Stevens. Patterns In Nature.114-116..

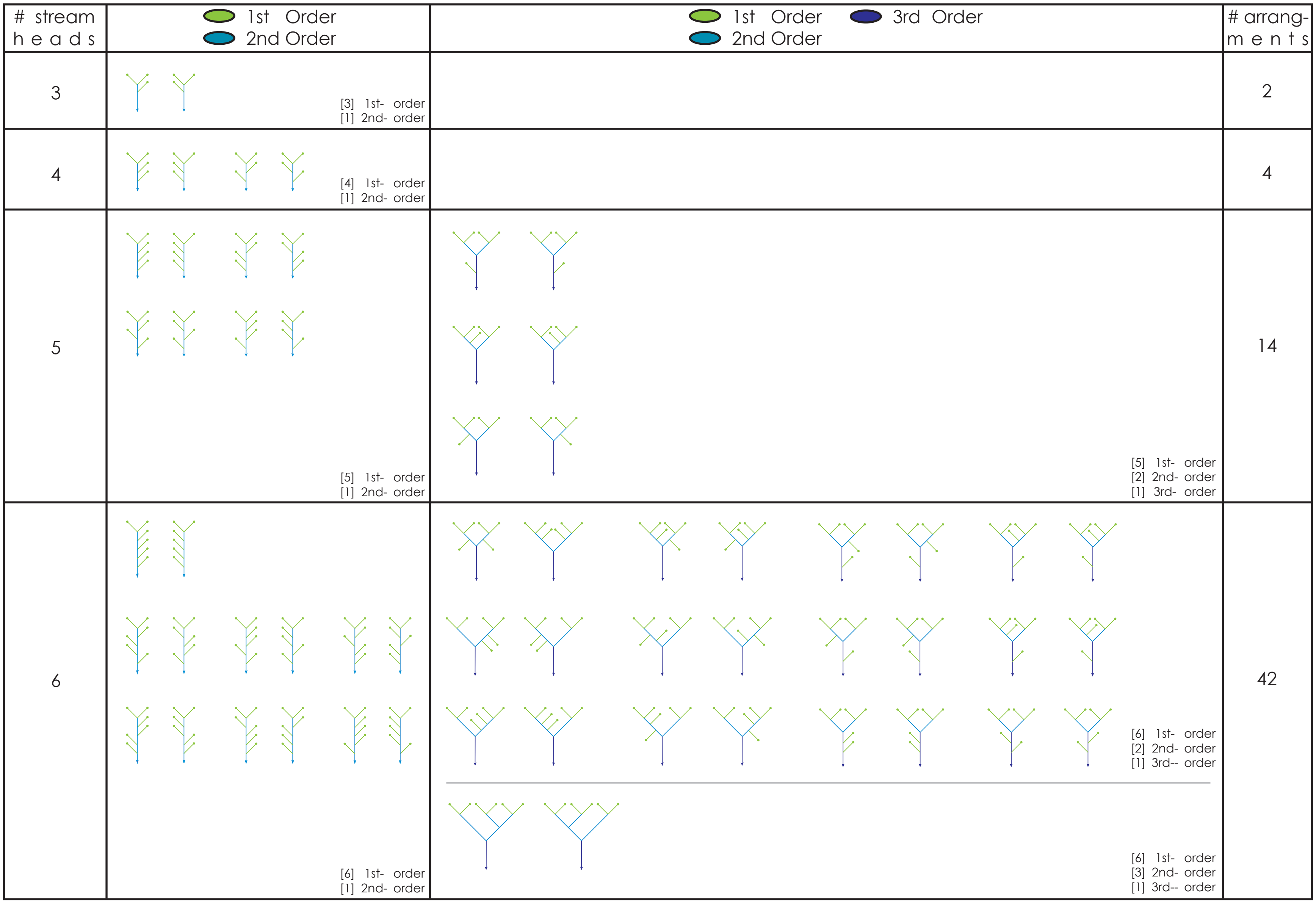


Fig. 5.4 Topological Arrangements Of Streams With Three To Six Sources

All organizations fall within Horton'scaling law of stream numbers, and within the formula relating triple junction and number of sources (J_1 - J_3 = 2).

5.2.3 Other Laws Governing Branching River Networks

The previous laws regarding scaling and topological relationships showed clear characteristics of self-similarity and fractal dimensioning. The following laws are not so explicit in their relationship to the ordering of drainage networks, but important none the less.

<u>*Law for Stream Width to Length Ratios:*</u> No river runs straight for more than ten times its width. [4] In simple mathematical terms:

$$L_{straight} <= 10 * W$$

<u>*Principal of Least Work*</u>*:* One would think that the sum of the width of all of the tribuaries at a singluar section of the drainage network would be equal to that of the width of the highest-order stream. However, this is not the case. This is due to resistance flow. Movement of material through a narrower passage has higher friction, therefore, the width of the branch must be greater to counter this effect. [5] The mathematical representation of this notion is as follows:

$$W_0 \wedge 2.5 = W_1 \wedge 2.5 + W_2 \wedge 2.5$$

<u>*Rodriguez- Iturbe's Claim:*</u> Streams flow as to minimize the total rate at which the mechanical potential energy <u>is expended</u>. The network's shape will change until it finds that for which the total rate of potential-energy dis-

4 Peter Stevens. <u>Patterns In Nature</u>.110.

5 Peter Stevens. <u>Patterns In Nature</u>.116-121.

sipation is as small as possible. In other words, natural drainage networks are optimal channel networks that have 'sought out' a form that minimizes the rate of energy expenditure. [6]

Law of Braching Angles: If two branches of the same width converge at a point onto a higher order stream, they do not alter the angle of that stream and will tend to favor entering at an angle of 75 degrees to the higher order (Figure 5.5 a). If one stream enters onto a higher order stream, it has the capabiliy to alter the path of that stream. The smaller the amount of energy the entering stream possesses, the closer to 90 degrees it will be in relation to the higher order (Figure 5.5 b). [7]

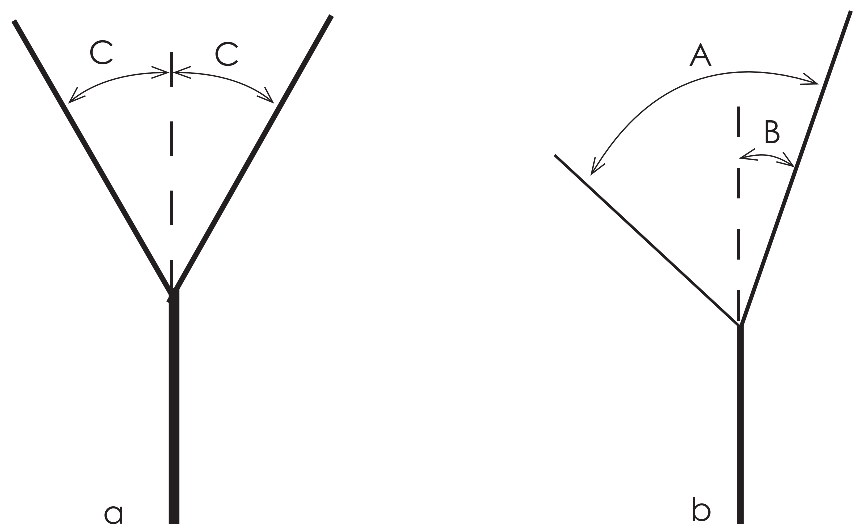
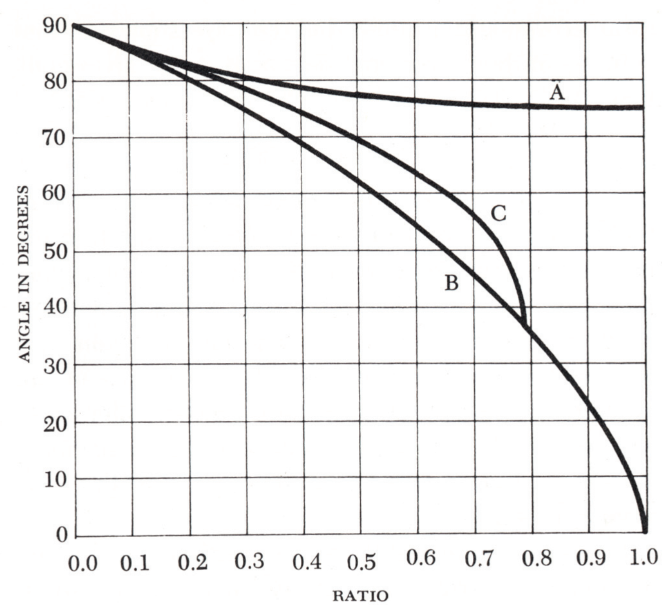


Fig. 5.5 Branch Angles Concerning Least Work Principles
(Image: Peter S. Stevens, Patterns in Nature).

6 Phillip Ball. The Self-Made Tapestry. 156.
7 Peter Stevens. Patterns In Nature.116-121.

Table 5.1 charts the average realtionship of these deflection angles.

Table 5.1 Angles For Branched Networks
Enter the ratio between the two branches and note the angle listed at the left for the desired branch type from Fig. XX (Image: Peter S. Stevens, Patterns in Nature).



Property of Self-Avoidance: A stream will hardly cut back across itself to create islands or loops. As a stream head advances towards an existing channel, the volume of water feeding it diminshes as the existing channel starts to cut off the supply from surrounding ground.

5.3.1 Fracturing Processes

Cracking in nature is an attempt to relieve as much stress as possible from a material while doing the least amount of work. This means to maximizing the area-to-fracture length ratio. Since the goal is to do this with the least amount of effort, one would guess that the cracks would take on the most efficient arrangement of tiling a plane: hexagons. However, occurrences of perfect hexagonal cracking are extremely rare, and only occur in three-dimensional columnar crack formations (Figure 5.6).

Crack angles have to do the rate at which they are formed. In networks where stress grows slowly over time, crack angles tend to be near 90 degrees (Figure 5.7 a). Such networks include mud, spalling paint, and ceramic glaze. This origin of the networks is no mystery… if one has enough patience, their formation can be observed. Rapidly fractured networks, such as glass tend to bifurcate at angles of no greater than 60 degrees (Figure 5,7b). Columnar cracking, which is the rapid cooling of homogeneous lava, is the only cracking formation that nears the 120-degree angle ideal (Figure 5.7 c). [1]

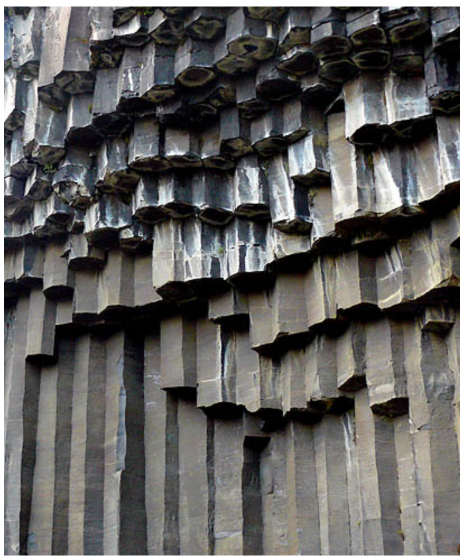


Fig. 5.6   Columnar Cracking
Svartifoss, Iceland

1 Norman H. Gray. "Symmetry in a Natural Fracture Pattern: The Origin of Columnar Joint Networks", 536.

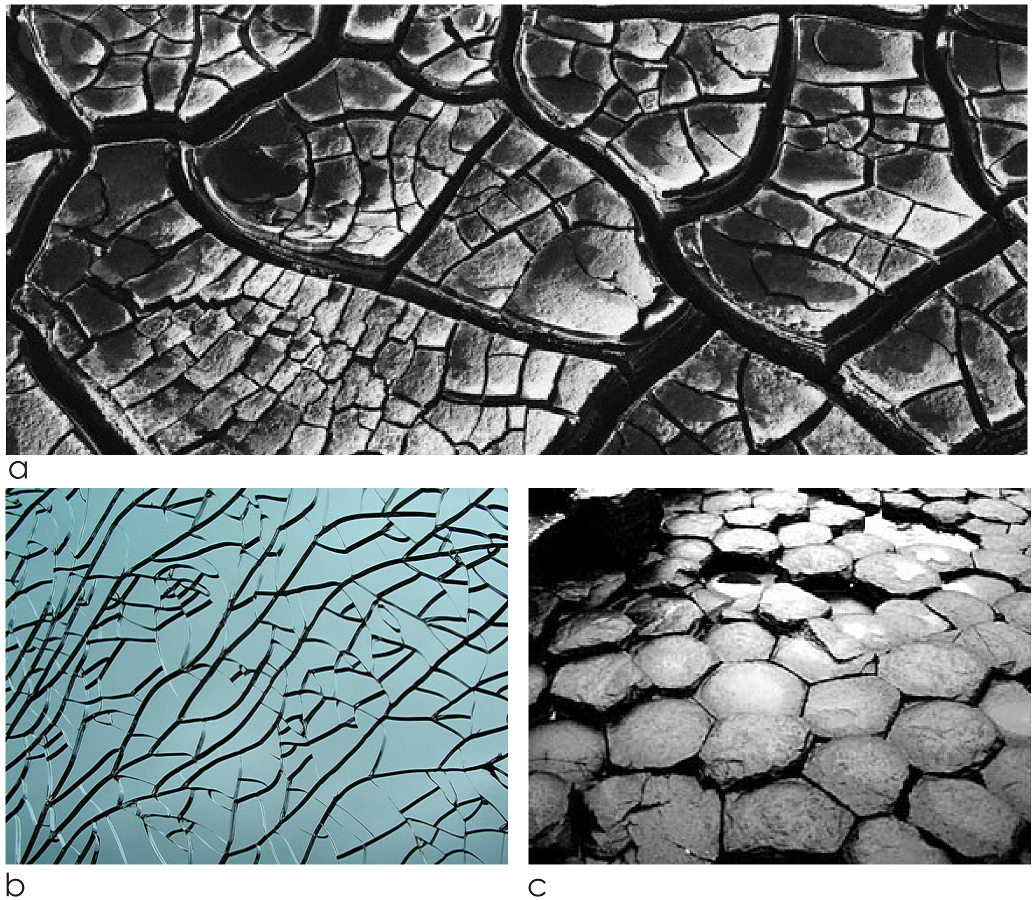


Fig. 5.7 Cracked Networks
a. Mud- note the tendancy towards right angles; b. Glass- note the tendancy of the bifurcations of 60 degrees or less; c. Columnar Joints at The Giant's Causeway, Ireland- note tendancy towards 120-degree angles

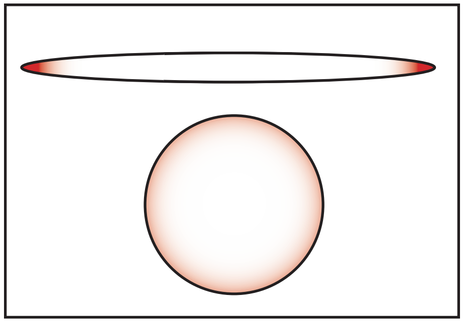


Fig. 5.8 Stress Levels Of Imperfections In Brittle Materials
Red indicates areas are higher stress.

Fig. 5.9 Multiple Branch Cracking

Fig. 5.10 Thermally Cracked Pattern

5.3.2 Brittle Materials

The rapid fracture of brittle materials is a non-linear phenomenon, meaning the effect is not proportional to the cause. Fracture is caused by stresses within the atomic structure of the material. This could be from an internal imperfection, or from external forces (impact, pressure, etc.). The resultant visible effects vary widely, due the fact the cracking is a very unpredictable and uncontrolled phenomena. Typically the details of the cause are too numerous, or too small to trace. The brittleness of a material is caused by the singular fact that there is a much higher stress concentration around an imperfection. Furthermore, the stresses are higher around more acute angles of imperfection, than broader ones (Figure 5.8). At a small point of imperfection, the material is more likely to produce a singular branching pattern, while a thrown object will more likely produce multiple branches emanating in all directions from the point of impact (Figure 5.9). Uniform thermal stresses are more likely to produce a network of cracks, with no particular directionality or origin (Figure 5.10).

Regardless of the pattern, the determining factor for the formation process is that the stress at the tip of the crack is enough to break the molecular bond holding the material together. The stress at the tip of that crack is two-hundred times greater than elsewhere, increasing as the crack grows over time (Figure 5.11).

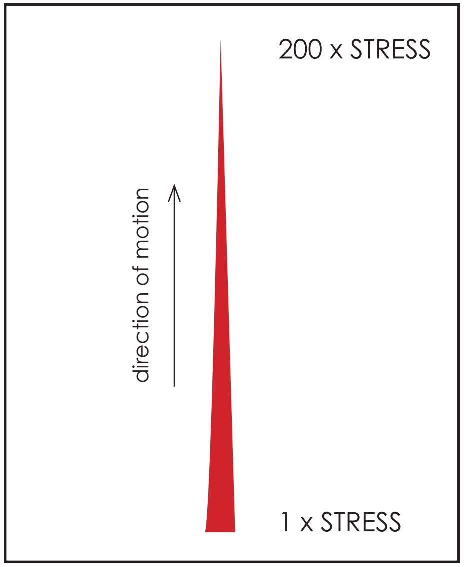


Fig. 5.11 Crack Tip Stress

This suggests that the slower the crack speed, the less powerful. In crack formation, after reaching a certain speed, the tip goes into a state of chaos and forms off-shoot cracks. In turn, if these cracks continue through the same process, a network takes on the characteristics of self-similarity. At more in-depth explanation is offered in Figure 5.12.

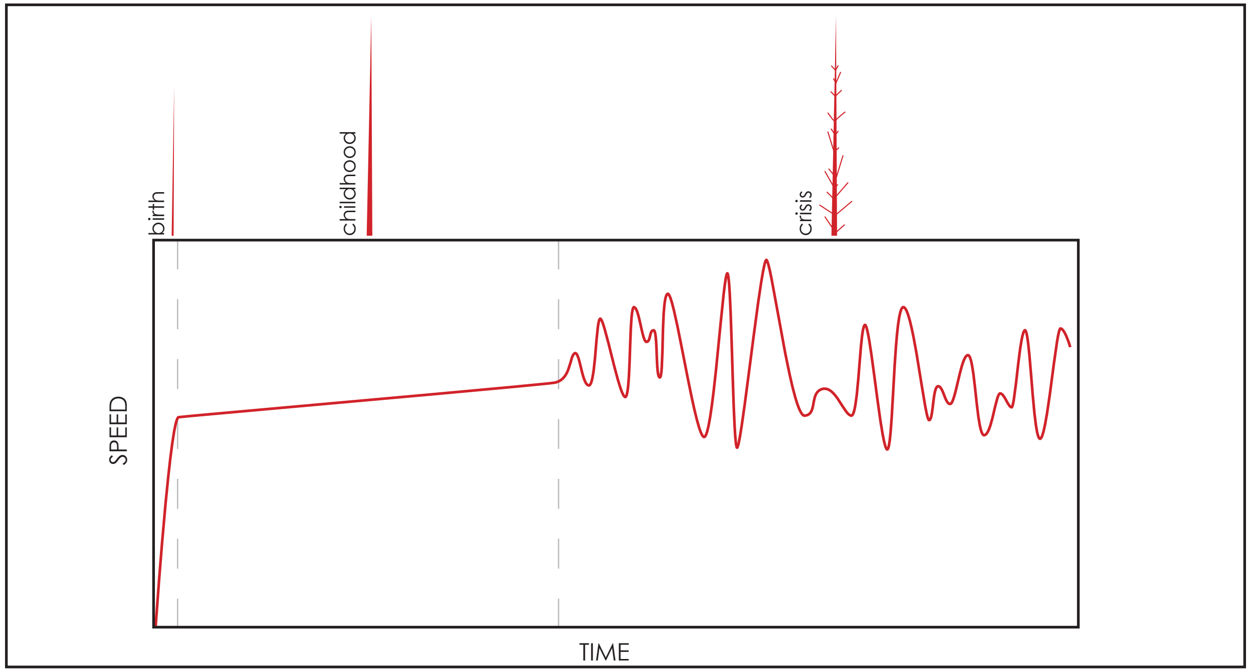


Fig. 5.12 Crack Tip Speed Over Time
At 'birth', in a matter of a millionth of a second, the crack tip has reached a velocity of 200 metres per second, a significant portion to the speed of sound. During 'chilhood' crack continues to pick up speed smoothly, while staying straight. The fracture surfaces are therefore straight and smooth as well. Once the crack tip reaches a certain velocity, its speed starts to fluctuate unpredictably causing the tip to veer from side to side. This movement causes the fracture surface to become rough and sprout new crack tips at angles 0-90 degrees to the orignal path of travel (Reference: Phillip Ball, The Self-Made Tapestry)

Fig. 5.13 Cracked Mud
© neil talley

5.3.3 Mud Cracking

Two-dimensional cracking is an operation that relieves surface tension caused by uniform shrinkage or expansion. In mud cracking, water evaporates from the top layer of mud, causing it to contract. The displacement of the top layer then creates internal stresses at all points within the network by trying to stay attached to the lower surface. Eventually, the tension in the top layer is so much, that to minimize displacement and relieve the stress, a crack is formed.

Geometrically, crack formations in such types of networks can be described as:

"…homogeneous infinite mosaics of convex polygons, which fit together perfectly so as to cover this whole plane just once. Each linear element within the net is a side of two contiguous polygons and each vertex is shared by three neighboring polygons." [1]

One would assume that since most vertices are three-connected, that the mean number of sides for the polygonal areas is six. In this case, the junction is described by the letter " *Y* ", having three linear elements converging at that junction. However, in mud cracking networks, the average number of sides of a polygon is less than six. Instead of having three linear elements converging at a junction, mud cracks tend to truncate one another in the same fashion as the letter " *T* ". The emergent differnce from these two types of junctions is in the number of vertices shared by the polygons sharing the juncnion. In the *Y*-junction, the vertex is shared by all three polygons. In the *T*-junction, the vertex is only shared by two of the polygons (Figure 5.14). This is the cause of the change in

1 N.H. Gray, Topologicla Properties of Random Crack Netwrks. 617.

the average number of sides for mud-cracking networks.[2]

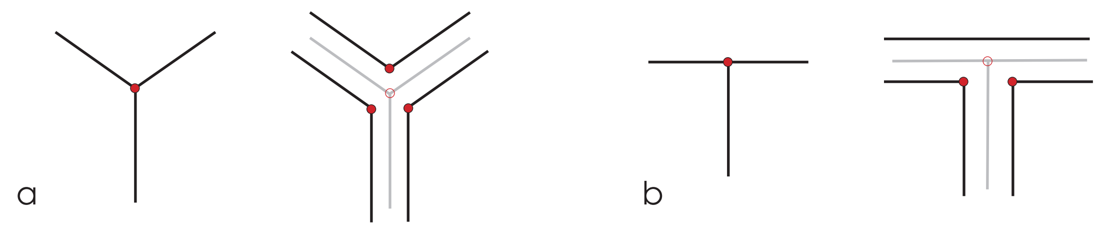


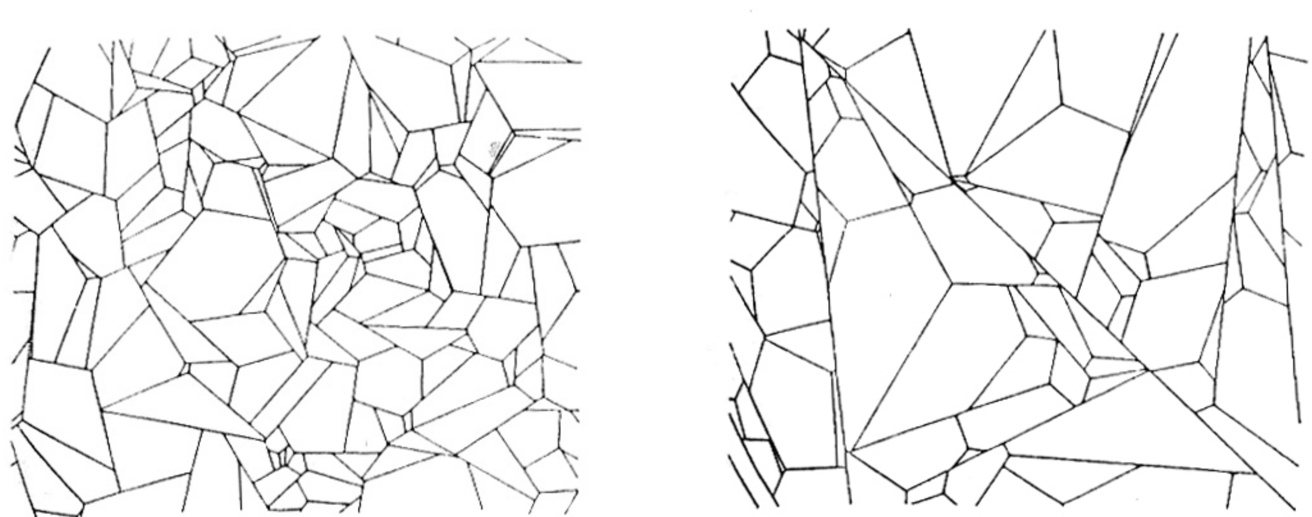
Figure 5.14 Y & T Junctions in Crack Networks
a. Y-junction. note that the vertes is shred by all three neighborhong polygons. b. T-juntion. note that the vertex is shared by only two of the three polygons.

The rare occurrence of four sided junctions, or "*X*" junctions in two-dimensional cracking networks can be attributed to their truncation property, where only one of two cracks will continue on after their intersection.

Cracking operations are difficult to accurately represent in digital space because their ordering ultimately depends on time. Simulations of cracking operations (either drawn by hand or in digital space) rarely look like the real occurrence because they assume homogeneity of material and operate without a sense of time or hierarchy. For instance, if one crack grows at a faster rate than a second crack, then latter would be the crack that would be truncated. If the second grew faster than first, then the opposite would occur. If this operation were drawn by hand, how would one determine the rate at which each crack originates, and thus the final outcome of the

2 N.H. Gray, Symmetry In a Natural Fracture Pattern, 534. (Fig. XX)

procedure. The outcomes of different ordering caused by time is demonstrated in Figure 5.15.



a b

Figure 5.15   Y & T Junctions in Crack Networks
a. Junctions nucleated *simulatneously* and grown at a uniform rate until truncated. b. Junction nucelated *sequentially* and grown until truncated. (Image: N. H. Gray. "Topological Properties of Random Crack Networks," published in Mathematical Geology, Vol. 8, No. 6, 1976. pg. 625.)

Chaper 6

6.1 Typology of the Mall

The goal of design in this case is not to reproduce an existing building typology of the mall. If a typological arrangement works, chances are an architect would produce a good design through accurate understanding and reproduction. However, what characterizes remarkable design is a thorough exploration of a narrative. In physical (tangible) terms the narrative of a mall is about movement, infinite space, and separation from the outside world and its responsibilities. In the more elusive sense is should invoke fantasy, expectation, and something that is just out of reach… a shimmer that disappears right before it is obtained, a life that could only be had if you could ensnare it through something around the next corner. However, as enrapturing as the narrative may be in comparison to the typical study of program, layout, and adjacencies, that study is still necessary in order to design a functional building.

Malls are generally formed from two types of organizations. The first type of plan is the cluster organization. This type is characterized by having the building masses bundled into groups, while the circulation occurs at the intersections of the groups. (Many outdoor shopping complexes exhibit this type of planning). The second type is the dumbbell plan in which the building masses are separated with circulation connecting them along more or less linear pathways. Building masses tend to be the anchors of the mall, (i.e. department stores, movie theaters, activity centers, hotels, etc.) While some are exclusive to one type, most exhibit charactersitics of both. Figure 6.1 depicts the general layouts of some of the more popular malls in the United States, chronologically organized by type.

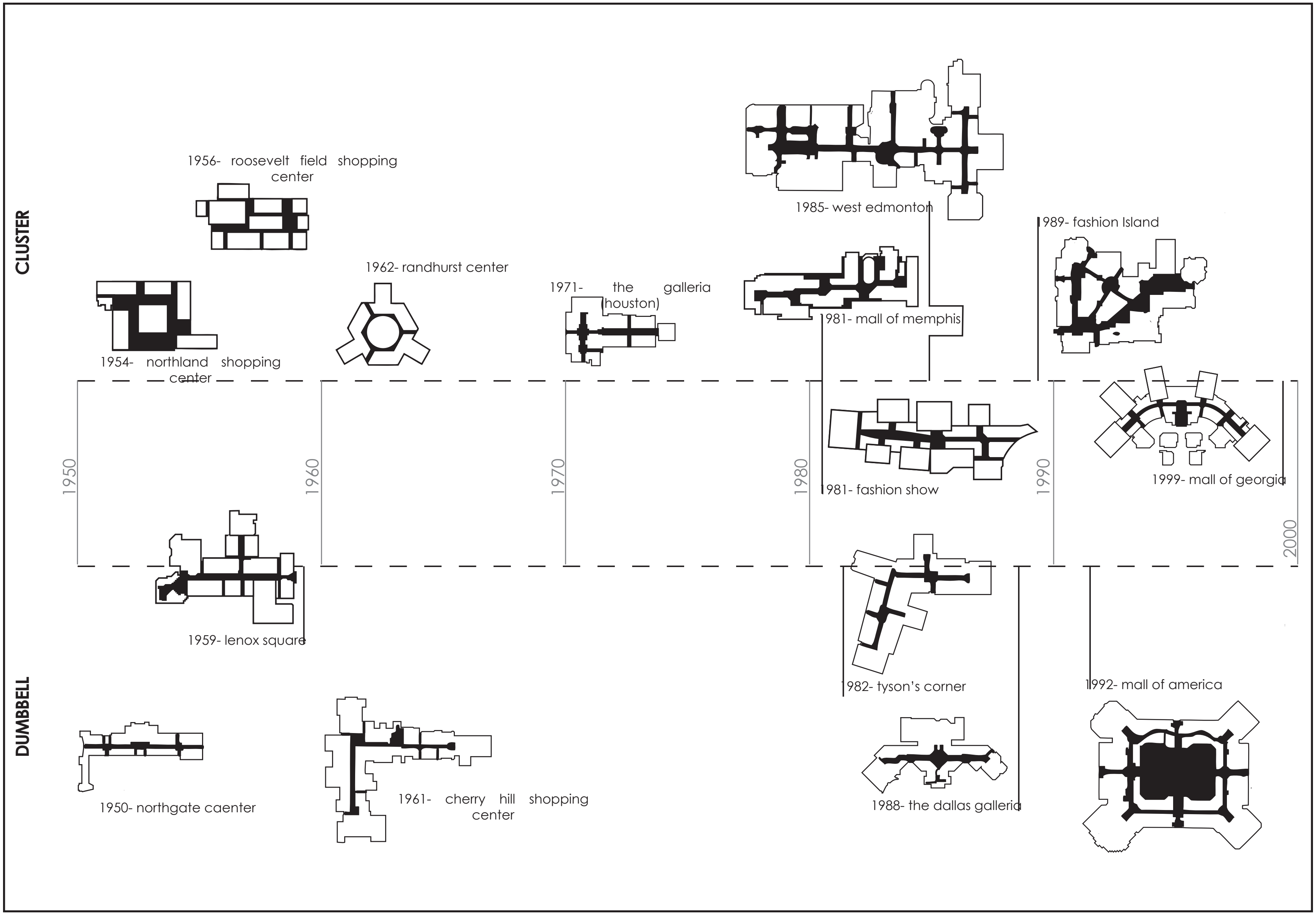


Figure 6.1 Malls Organized By Chronologically By Type

The next set of Figures, Figure 6.2, is a series of diagrams demonstrating the relationship of the various components of the mall: building masses, circulation, and stream order classification.

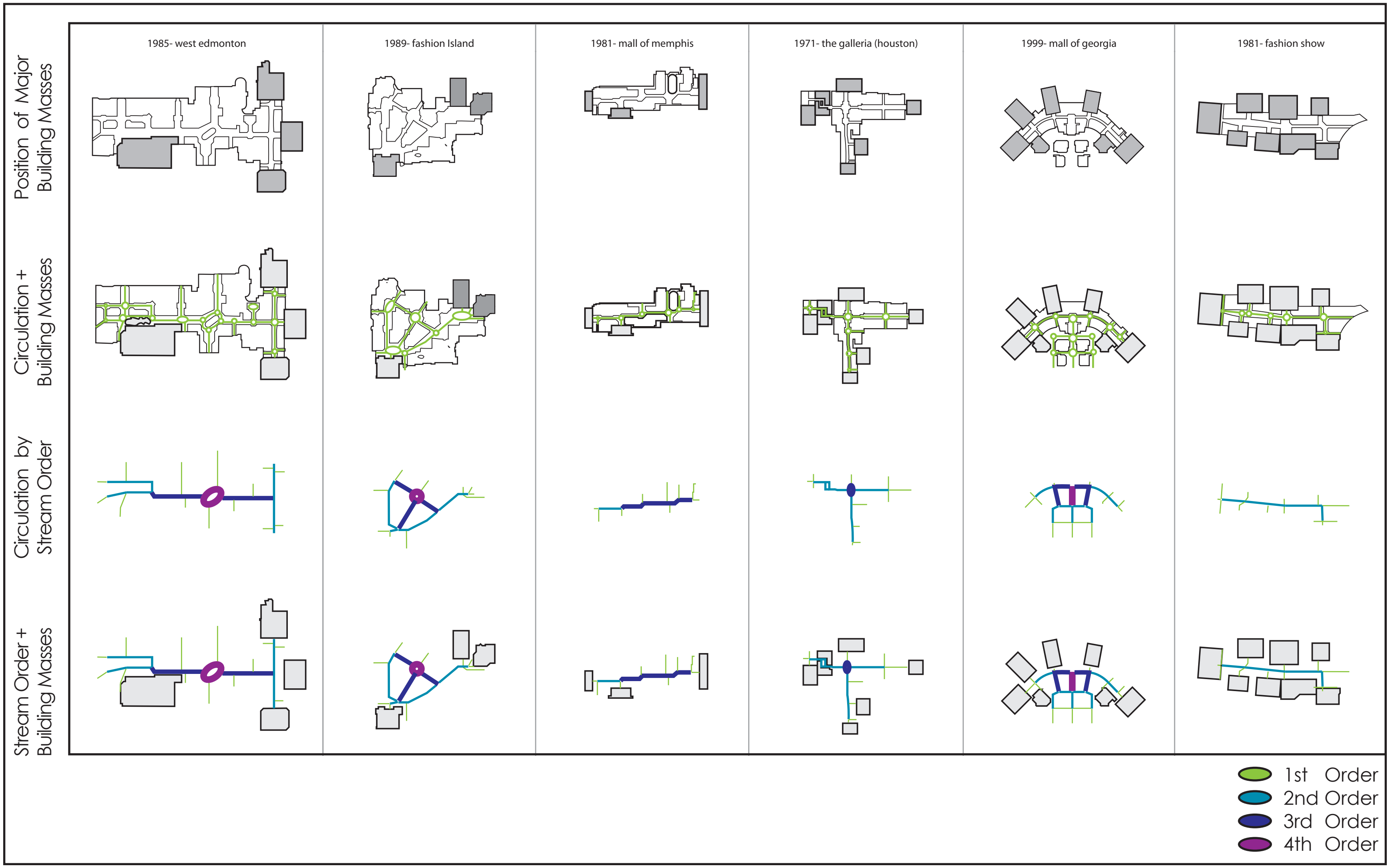


Figure 6.2 Diagrams showing relationships between Building Mass, Circulation, and Stream Ordering

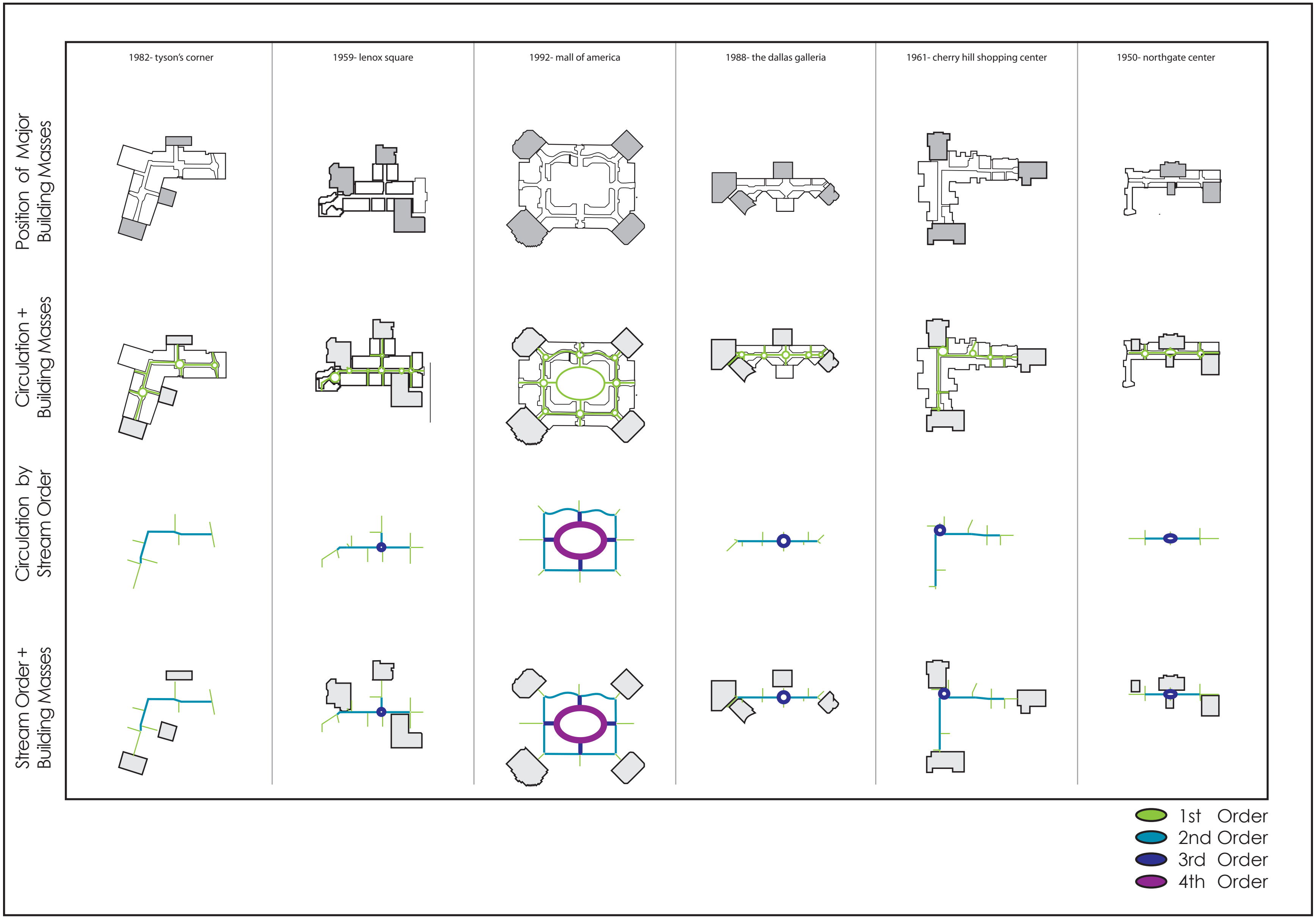


Figure 6.2 (cont'd)

There are a few things to be concluded from Figure 6.2. First, is that the circulation of all malls has a stream ordering classification of at least two and that higher or lower stream ordering is not specific to the type of plan. Second, is that building masses tend to occur near first-order circulation. The higher order circulation tends to be adjacent to smaller specialty stores. This would infer that building masses tend to be more destination shopping than to draw the random drifter. Smaller stores, which fall into the heterogeneous portions of the mall, (along higher order circulation), depend on luring passers by as they wind their way to other destinations.

PART III
METHODOLOGY OF DESIGN

Chapter 7

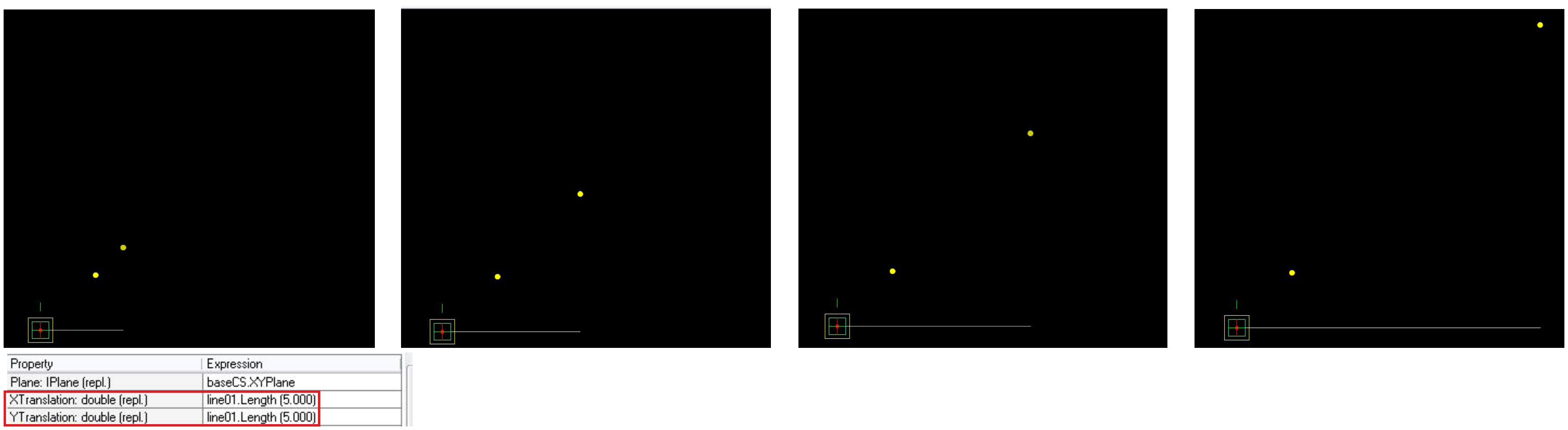
7.1 Process of Exploration of Infinite Possibilities

The number of possibilities of the constructions of pattern is so visibly and unimaginably vast that new thought models must be utilized to organize and explore the immense quantity of configurations. At this point in the design process the processing power of computers grows to be advantageous. For the human mind to calculate the possible quantity algorithms, both systematically and correctly would take a very long time indeed. A computer possesses the speed and processing power to be able to explore new permutations in what seems like an instant. Presently, architects have begun to explore more of these possibilities where physical models fail, or are simply too process heavy to be timely and/or economically feasible.

The algorithmic process for generating drainage patterns, cracks, etc. is performed in digital space when more efficient. When the programming language of the algorithms becomes too overbearing for the architect, (typically untrained in computer language), a return to the drafting table is useful. A feedback loop is created, where the architect uses the computer to inform the hand, then uses the hand to inform the computer. (The hand of an architect is often smarter than the eye and sometimes smarter than the brain.) The hand in turn may discover a shortcut in an algorithm, or may inform a design decision that simplifies or eliminates portions of the programming aspect of exploration.

7.2 Bentley's Generative Components

Bentley's Generative Components (GC) software possesses the capability create relationships between geometrical elements within digital space (in lieu of discretely modeling each element). The software can be described as a bridge between programming and discrete three-dimensional modeling, (where all code happens in the background). GC best exploited through the use of relational modeling and is especially helpful for those who are not familiar with programming language (most architects). Instead of placing and manipulating geometric components by discrete Cartesian coordinates, GC allows the user to define associations from one element to the next. An example of a simple relationship would be: Point A is to be x units in the y-direction from Point B. The number x units should be the same as the length of Line C. (Figure 7.1)



Property	Expression
Plane: IPlane (repl.)	baseCS.XYPlane
XTranslation: double (repl.)	line01.Length (5.000)
YTranslation: double (repl.)	line01.Length (5.000)

Figure 7.1 Example of Relaional Modeling in Generative Components
The dynmaic relationship shown above is dependent on the X and Y translation of the right-hand point being a function of the length of line01. The code for this in GC is line01.Length (as highlighted by the red box).

The previous is an example of a very basic relationship. The software is used to its full capabilities when the user is capable of defining very complex relationships. These can begin to generate pattern, dynamic constructions, or entire building systems.

Another simple capability, yet helpful to those non-programmers, is the use of what is called 'graph variables." Instead of calling out a discrete value for data, the user can replace it with a placeholder name. In GC, a placeholder name is attached to a slider that is allowed to vary between a defined set of limits. Figure 7.2 provides an example of simple graph variable appearance, coding, and resulting relationship.

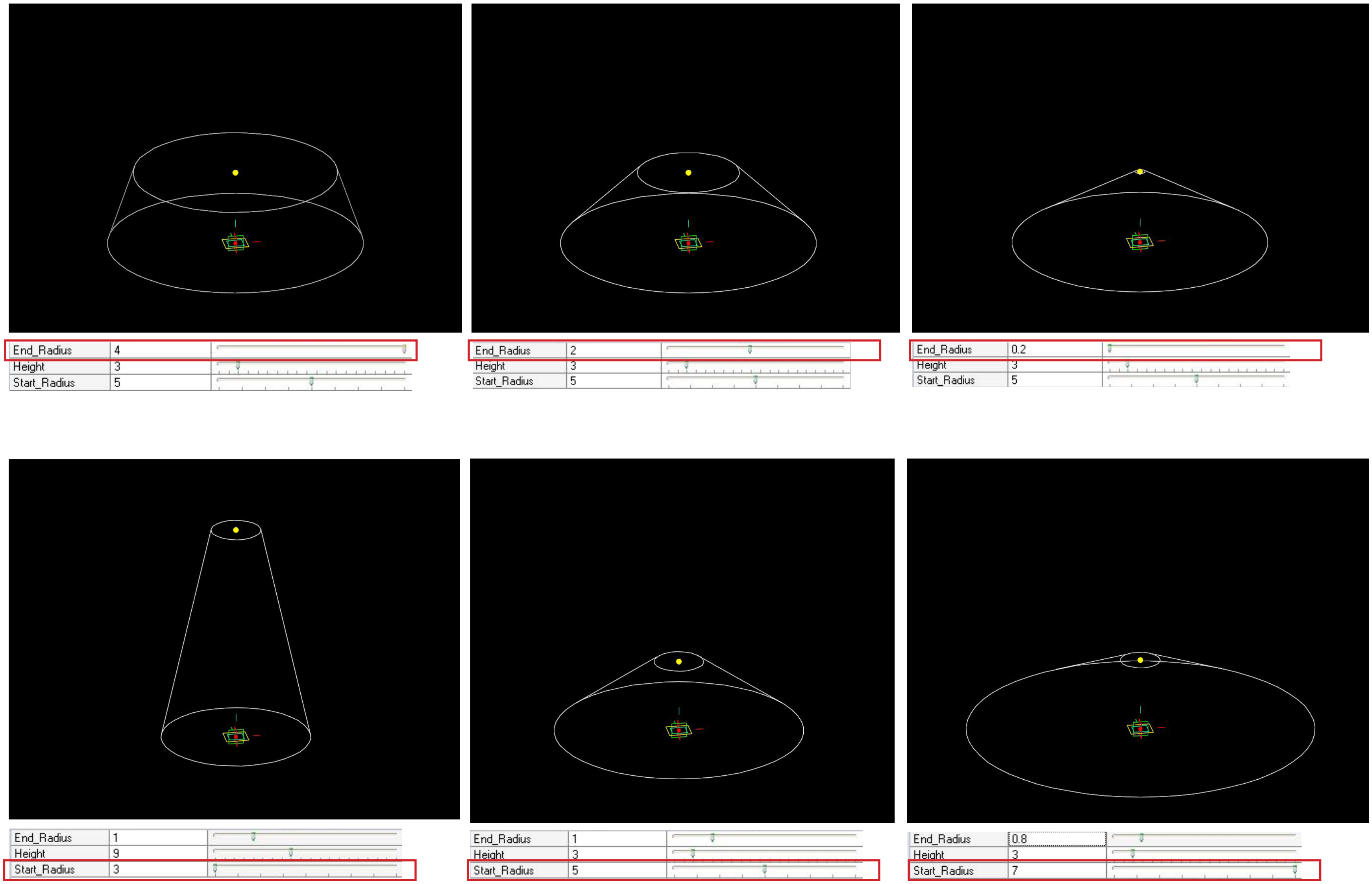


Figure 7.2 Example of Parameterization Through Graph Variables
The change in shape of the cone is mapped through the designates graph varaibles.

7.3 Constructing an Intelligent Form Generator

If the rules of pattern formation were simply followed, an architect would end up '*designing*' a river, a nautilus shell, or a spiral of rose petals. The role of '*design'* is to then, at the point when understanding of the expanse and formation of possibilities has been explored and desired rules have been established, is to fit them to a building or a landscape. How can they be applied to the scale a site? In order to use form-finding as a method of designing architecture, one must determine which rule sets apply to the process of architectural design, and which are no longer relevant or applicable.

The use of relational software, such as Generative Components allows the desirer to parameterize any inputs neccessary to the inquiry. Therefore, the designer can change the requirements of the system on a whim, without spending an exorbitant amount of time and effort.

7.4 Construction of a Digital Drainage Network

In Generative Components, digital representations of streams with sources ranging from three to ten are constructed, each obeying the laws of branching river systems, (i.e. scaling, topological properties, width, etc.) The first step in the digital formation of drainage network is the topological ordering of the branches. Shreve's findings on the topological variations of branching river systems demonstrate that all arrangements are equally possible, (Figure 5.4). In the digital form of representation, the computer is allowed to pick whichever arrangement is chooses for an infinite number of trials. This means that for a given site, with a determined number of streams sources, the computer can first generate the finite set number of topological possibilities. Each topological arrangement is then capable of deforming into an infinite number of visual configurations, simply based on the construction of controlled noise (randomness), and controlled variation of the fractal values (scaling laws) through the definition of graph variables.

Each order was programmed with its 'startpoint' at the 'endpoint' of the next highest order, with the angles of the branches controlled by cylindrical coordinates (Figure 7.3)

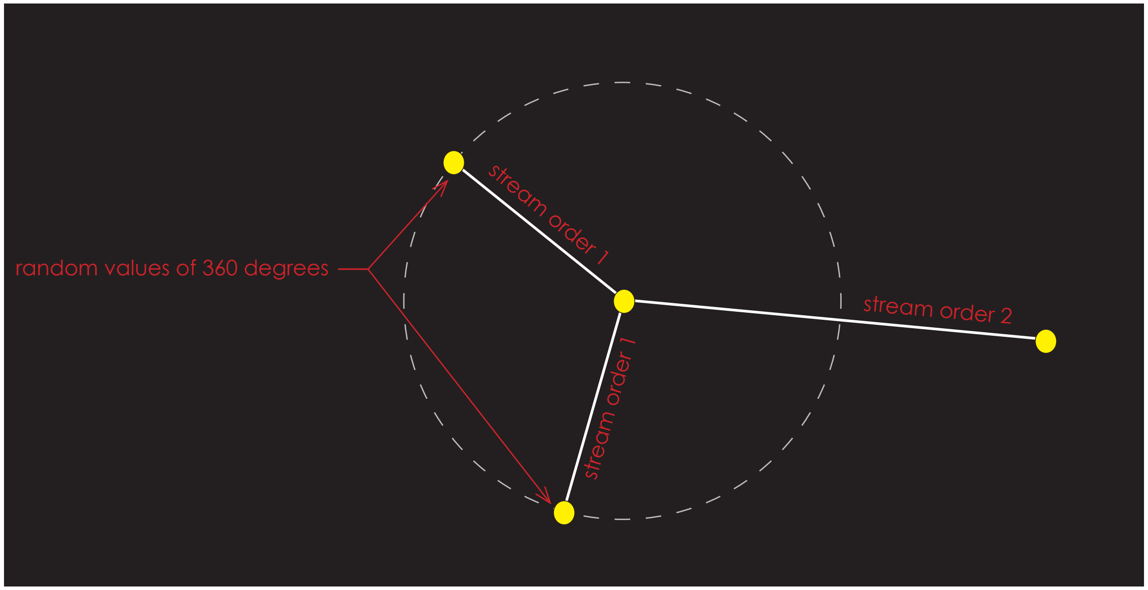


Figure 7.3 Cylindrical Coordinates
In order to achieve a degree of randomness, the distance of a particular stream-order head in relation to that of the next highest stream-order were based on random values of a 360 degree circle. Meaning that, one stream head was controlled by being constrained on a circle of a determined radius, with the center of that circle being the stream head of the next highest order

Horton's scaling laws were followed through the inclusion of algorithms into the scripts describing the length of each order in relation to its adjacent next highest order, with parameterized values of the scaling laws defined as graph variables inside the algorithm.

The ability to switch between topological configurations is determined by the addition of 'conditional' and 'swtich' statements within the programming language of the digital model. A 'conditional' statement functions by declaring, "x is something to y… if true, do this, if false- do that" By carefully structuring and nesting these statements, the series of topological configurations is made possible (Figures 7.4, 7.5, 7.6).

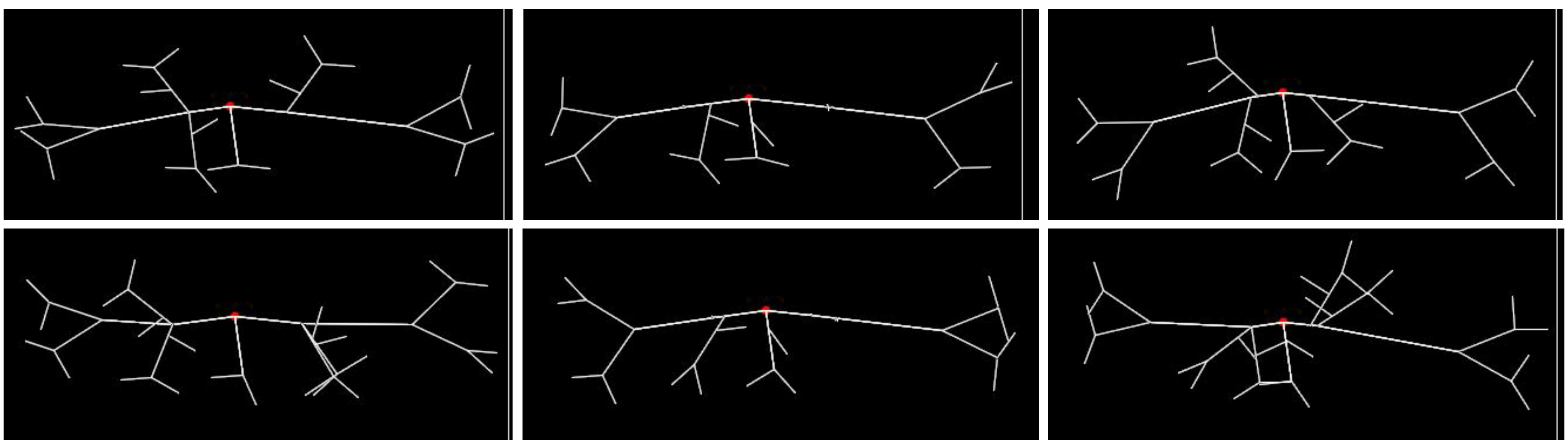


Figure 7.4 Random Variaion
By re-running the script, Generative Components will generate a different organization for an infinte number of trials. The variation is acheieved through controlled randomness and the additon of conditional statements. Each iteration obeys all of the rules of branching river system described in Chapter 5.

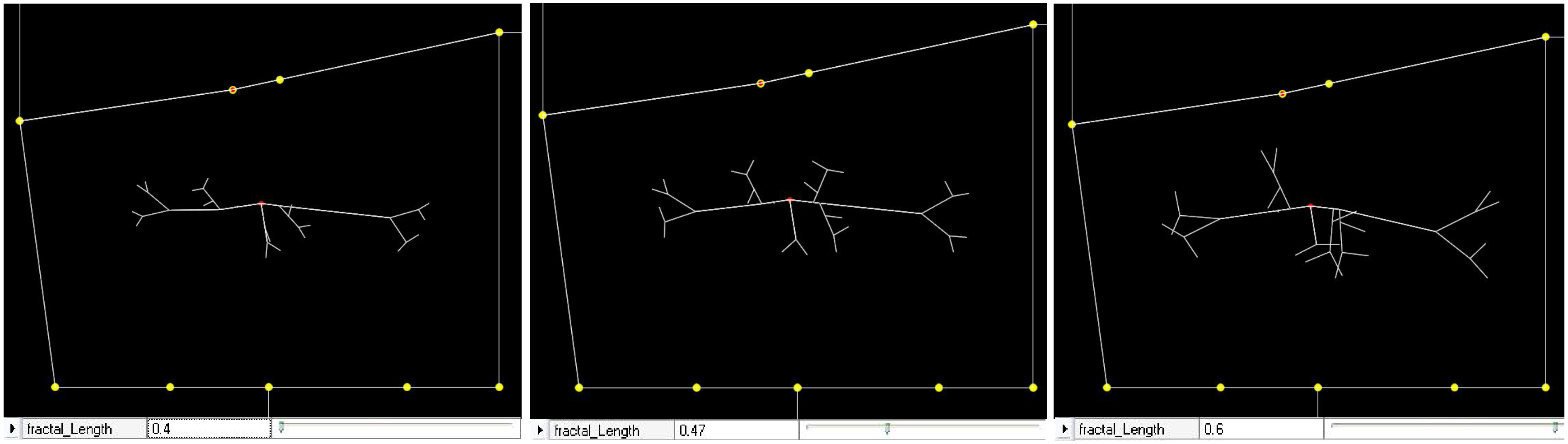


Figure 7.5 Scaling Law For Stream Lengths As Achieved Through Graph Variables
Each branch of the network is scaled by a factor 'fractal_length' in respect to the adjacent branch of the next higest order. From the left the scaling factors of the networks depicted above are .40, .47, and .60.

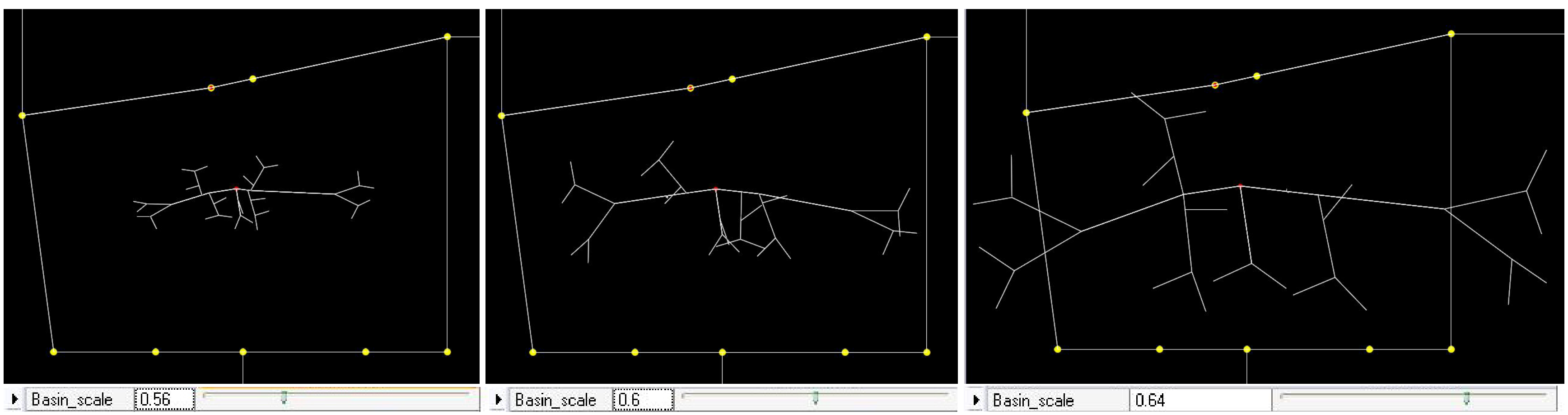


Figure 7.6 Scaling Law For Drainage Area As Achieved Through Graph Variables
Each network is scaled by a factor 'basin_scale' in respect to the adjacent branch of the next higest order, adhering the formula L=1.4Area^2/3
From the left the scaling factors of the networks depicted above are .60, .60, and .64.

Figures 7.4, 7.5, & 7.6 portray an accurate model of drainage networks in nature. However, in order to elevate these formations to the level of architecture, it must first respond to a site. Figure 7,7 shows how the system can begin to respond to chaning site conditions.

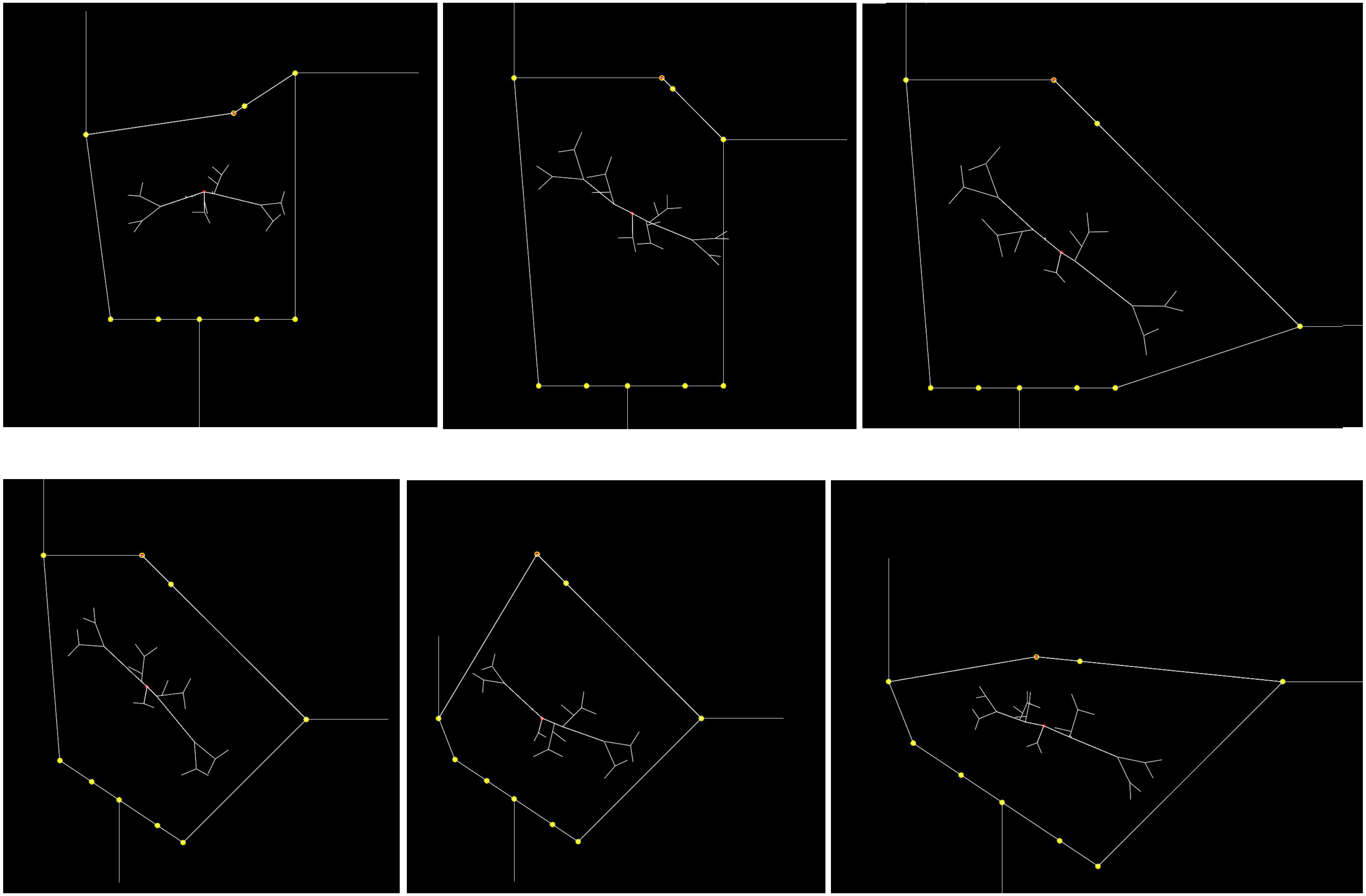


Fig. 7.7 Series Demsonstrating Response To a Site
By the vertices defining the area of the site, the network is capable of rearranging itself, seeking out its optimum form.

8.1 Conclusion

Complex networks and numerous relationships, like those demonstrated in Chapter 7, produce pattern that can behave in the manner of branching river networks, shell spirals, bubbles, and the like. They are capable of generating finite sets of topological arrangements, as well enabling as each arrangement to absorb changing forces and condtions. These reactions produce a seemingly infinite amount of visual variations.

However, these steps are just the tip of the iceberg when it comes to the full out design process of form-finding in Architecture. It is a process that not only involves understanding, modeling, and finally producing the correct form. It involves material testing, engineering, cost calculation, environmentaltesting, and sometimes a bit of luck. In the end, it is a process that takes, at the very least, months to perform, and years to perfect.

However, by studying the self-formation processes of natural constcutions, an entire world is opened to the Architect. Not only one of optimum characteristics and dynamic adaptability, but one that is full of beauty and of life.

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