Algorithmic Landscapes
Computational Methods for the Mediation of Form, Information, and Performance in Landscape Architecture

Algorithmische Landschaften
Rechenmethoden zur Vermittlung zwischen Form, Information und Performance in der Landschaftsarchitektur

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Abstract

Recent design discourse in landscape architecture has shown a prejudice against rigid formal systems and has advocated systems that promote self-organization, emergence, and indeterminacy, as well as non-linear systems and thinking. A growing number of landscape architectural practices have seized upon the thinking and tools associated with dynamic systems in order not only to create new types of formal expression, but in the hope that more performative landscapes can be conceived and implemented. The role of the designer in such projects shifts from that of the artist who gives concrete form and definition to a project, to the engineer of a system, who sets in motion a process or series of processes that will ultimately lead to a range of possible futures and associated forms.

The development of algorithms, in the form of scripts and codes, presents a way for the designer to more rigorously study the behavior of complex systems and the formal, spatial, and evolutionary implications of dynamic processes. Already, disciplines at the edges of landscape architecture, from the natural science such as geomorphology and botany, to the applied sciences such as environmental engineering and planning, have expanded their thinking through algorithmic simulations and models, in order to answer fundamental questions concerning the behavior of dynamic systems and the emergence of form in nature. Computer scientists have been particularly interested in an algorithmic description of nature for ends ranging from improving graphical representation, to generating believable artificial worlds, to improving artificial intelligence. For landscape architects and designers, applying such algorithmic processes and thinking allow the designer to use the computer not only as a tool of production and representation, but as a potential tool for analysis and design. While the holistic approach of Landscape architects should not require the same training and approach as that of the engineers and coders of complex systems, in order to fulfill the high ambitions of recent design discourse in a meaningful way, landscape architects should reassess their relationship with computational processes and tools and engage them in a new way.

As such, this thesis engages the role of algorithms in landscape design in terms of three fundamental categories. First, the role of algorithms in generating form in the landscape. Second, how information can shape and enrich algorithms, and how algorithms can mediate between complex data sets. Third, the role of performance in the contemporary landscape and how algorithms can be used to make landscapes that respond better to change through time and which better reflect underlying processes.

The categories of algorithmic form, information, and performance are explored in this thesis through three lenses and in three parts. Part I introduces algorithms and algorithmic design in the context of landscape architecture, and then provides a historical underpinning describing how formal systems used in design contexts emerged and later developed through various periods of human history, ultimately being automated through computation. Formal systems did not emerge in a vacuum and they are useful only insofar as they mediate between layers of natural and cultural information and describe the structures and patterns observed in nature and in culture. These observed structures and patterns are explored in more detail through specific algorithmic patterns and paradigms in Part II of the thesis. In Part III, the patterns are combined into specific design case-studies of landscape architectural projects developed by the author. The historical background in Part I, the computational experiments of Part II, and the projects presented in Part III contribute to an overall picture showing the potentials and difficulties with adopting algorithmic methods to simulate, model, and design landscapes in complex contemporary contexts.

Keywords:

Algorithmic Design, Digital Landscape Architecture, Form in Landscape Architecture

Kurzfassung

Der landschaftsachitektonische Diskurs der letzten Jahre hat gezeigt, dass es deutliche Vorbehalte gegenüber formalen und starren Systemen gibt. Gleichzeitig wurden zunehmend Systeme die sich durch Selbstorganisation, Emergenz und Unbestimmtheit auszeichnen und mit nichtlinearen Denkweisen verbunden sind gefördert. Eine wachsende Zahl landschaftsarchitektonischer Theoretiker und Praktiker haben diese Denkansätze und Werkzeuge im Bezug auf dynamische Systeme aufgegriffen, immer verbunden mit der Hoffnung neue Formen des formalen Ausdrucks sowie performative Landschaften zu konzipieren und umzusetzen. Dadurch verändert sich die Rolle des Entwerfers: er wird vom Künstler, der ein Projekt definiert und ihm eine konkrete Form gibt, zum Ingenieur eines Systems, der einen oder mehrere Prozesse in Gang setzt, die letztendlich zu einer Reihe von möglichen Zukunftsszenarien mit ihren dazugehörigen Formen führen.

Die Entwicklung von Algorithmen, in Form von Skripten und Codes, bietet dem Entwerfer die Möglichkeit das Verhalten komplexer Systeme sowie die damit verbundenen formalen, räumlichen und evolutionären Implikationen dynamischer Prozesse genauer zu untersuchen. Bereits zahlreiche andere sich mit der Landschaft beschäftigende Disziplinen, von den Naturwissenschaften wie Geomorphologie und Botanik bis hin zu den angewandten Wissenschaften wie Umwelttechnik und -planung, haben ihr Denken durch algorithmische Simulationen und Modelle erweitert um grundlegende Fragen des Verhaltens von dynamischen Systemen und der Entstehung von natürlichen Formen zu beantworten. Informatiker waren besonders an einer algorithmischen Beschreibung der Natur interessiert, die von der Verbesserung der grafischen Darstellung über die Erzeugung glaubwürdiger künstlicher Welten bis hin zur Verbesserung der künstlichen Intelligenz reichte. Die Anwendung solcher algorithmischer Prozesse und Denkweisen ermöglicht auch Landschaftsarchitekten den Computer nicht nur zum Zwecke der Produktion und Präsentation, sondern auch als mögliches Werkzeug für die Analyse und das Entwerfen zu nutzen. Auch wenn der holistische Ansatz der Landschaftsarchitektur nicht die gleiche Herangehensweise im Umgang mit komplexen Systemen erfordert wie die von Ingenieuren und Programmierern, so sollte sich die Profession doch mit der Einbeziehung rechnerischer Prozesse und Werkzeuge in den aktuellen Entwurfsdiskurs auseinandersetzen, um deren Potentiale für den Umgang mit den aktuellen zeitgenössischen Herausforderungen zu nutzen.

In diesem Kontext ordnet die vorliegende Arbeit die Rolle von Algorithmen in der Landschaftsgestaltung in drei grundlegende Kategorien ein: Erstens, die Bedeutung von Algorithmen beim Erzeugen von Formen in der Landschaft. Zweitens, wie Algorithmen Informationen formen, anreichern und zwischen komplexen Datensätzen vermitteln können. Und drittens, deren Performance in der zeitgenössischen Landschaftsarchitektur und wie mit Hilfe von Algorithmen Landschaft gestaltet werden kann die im Laufe der Zeit besser auf Veränderungen reagiert und die zugrunde liegenden Prozesse widerspiegeln.

Diese Kategorien algorithmischer Form, Information und Performance werden in dieser Arbeit aus drei Blickwinkeln betrachtet und in drei Teilen untersucht: Der erste Teil stellt Algorithmen und algorithmisches Design im landschaftsarchitektonischen Kontext vor. Im Rahmen einer historischen Aufbereitung wird beschrieben wie sich formale Systeme im Entwurfsdiskurs in verschiedenen Perioden der Menschheitsgeschichte entwickelt haben und wie sie durch neue Formen der Berechnung automatisiert wurden. Demnach sind formale Systeme nicht in einem Vakuum entstanden und nur insofern hilfreich als das sie zwischen den verschiedenen Informationsschichten natürlicher und kultureller Strukturen und Muster vermitteln können. Diese beobachteten Strukturen und Muster werden im zweiten Teil der Dissertation durch spezifische algorithmische Muster und Paradigmen näher untersucht. Im abschließenden dritten Teil werden die in den vorangegangenen Teilen herausgearbeiteten Konzepte und Muster vom Autor zu spezifischen Design-Fallstudien kombiniert.

Die historischen Grundlagen im ersten Teil, die rechnerischen Experimente im Zweiten sowie die in Teil drei vorgestellten Projekte tragen zu einem Gesamtbild bei, dass die Möglichkeiten und Schwierigkeiten bei der Anwendung algorithmischer Methoden zur Simulation, Modellierung und Gestaltung von Landschaften in komplexen zeitgenössischen Kontexten aufzeigt.

Keywords:

Algorithmisches Entwerfen, Digitale Landschaftsarchitektur, Form in der Landschaftsarchitektur

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End Matter

General Introduction

"The late 20th century may one day be known as the dawn of the age of the algorithm. If so, we wish to be the first to embrace the new rationality that sees space and matter as indistinguishable, as active mediums shaped by both embedded and remote events and the patterns they form." – Sanford Kwinter[1]

0.1. Background

Algorithms are everywhere, but only in the last few years has the concept exploded into everyday consciousness. As late as 1957, the word did not even appear in Webster's New World Dictionary and was only really known to dedicated mathematicians. Now talk of algorithms can appear in everyday conversation; we openly wonder why a Google search algorithm is returning a certain result, why a Facebook algorithm is suggesting we become friends with a certain person, or why we are suddenly being bombarded with certain advertisements to buy a particular product. Most have at least a passing awareness of how profoundly algorithms are changing our society. Algorithms are used to model political preferences, financial markets, taste in music, and may soon drive our cars. One prominent scientific writer calls the algorithm, after the Calculus, "the second great scientific idea of the West." He continues, "There is no third."[2]

One promise of algorithms is that they will change our world and society for the better—algorithmically controlled cars, for example, might save lives, genetic algorithms might optimize the aerodynamic forms of aircraft to a degree no human engineer could achieve before. Much as the industrial revolution promised to ease the burdens of physical labor, thinkers at least as far back as Leibniz foresaw the advent of calculating machines able to ease mental labor—"for it is unworthy of excellent men to lose hours like slaves in the labor of calculation which could safely be relegated to anyone else if the machine were used"[3] —and further speculated that such machines could even automate the processes of rational decision making.[4] For the design professions, algorithms might help us ascertain new forms, structures, patterns, and relationships, as asserted by the quote from Sanford Kwinter cited at the top of this page. These are only a few examples of what computation and the algorithm promises.

There is also a potential dark side. Self-driving cars would put millions of taxi, bus, and truck drivers out of work, and similar innovations in other industries—including the design professions—could lead to lost jobs.[5] Some argue, like Leibniz, that freeing the mind from tedious and rote tasks can unlock talent for better, more creative use in other areas, but others would argue that a menial job is better than no job. These arguments aside, there is a potentially darker, more sinister aspect to this. When algorithms make decisions on what song we should listen to next, what film we should watch tonight, what political content we should become exposed to, or even who we should fall in love with, our collective decision-making power and responsibility for our actions—our sense of free will—is at risk of being eroded. Even if the worst fears of dystopic science fiction writers are not realized, where hostile artificial intelligences seize control and enslave humanity, or even if the programmers of algorithms have all the best intentions, unwitting users of algorithmic procedures are at risk of being sucked into self-reinforcing, negative feedback loops created by imperfect human programmers. The threats of computer viruses are well-known, less well known are the threats of computer cancers—self-replicating patterns out of control.[6]

0.2. Goals and Research Questions

The object of this research, however, is not to directly answer the philosophical questions about whether algorithms and algorithmic design are on balance, more good or more bad. These are questions, however, which have always been churning in the background of this research, and of which the reader should be aware. It does, however, seek to explore in depth, how the **algorithmic manipulation of space has the potential to change the practice of landscape architectural design**, and then to reflect on what those potentials mean.

The aim of this thesis, then, is to address role of the algorithms, especially formal or spatial algorithms, in contemporary landscape architecture, to explore their unrealized potentials and how they can be effectively integrated into a design process, and finally to cast light on their deficiencies and limitations. Three broad questions addressed include:

> -How do algorithmic models relate to broader questions concerning the emergence and creation of form in natural and in human systems?
>
> -What are untapped potentials for integrating algorithmic tools and models from sister disciplines into the design and production of contemporary landscapes?
>
> -To what degree can landscape architects improve the performative aspects of landscapes and fulfill the ambitions of the systems thinking paradigm through algorithmic design?

A second theme, closely associated with the first, is to understand the role of planned or designed formal systems in light of concepts of emergence, self-organization, and indeterminacy, where algorithmic methods are used to bridge the classic divide between the categories of "formal" and "informal." The theorist Steve Johnson in *Emergence: The Connected Lives of Ants, Brains, Cities, and Software* described three phases of the dialogue surrounding self-organization. The first phase comprised a gradual awakening and paradigm shift where "inquiring minds struggled to understand the forces of self-organization without realizing what they were up against." The second phase involved interdisciplinary inquiry and comparison of findings and phenomena in one field to another. The third phase, which really only got started in the 1990s, is where people "stopped analyzing emergence and started creating it. We began building self-organizing systems into our software applications, our video games, our art, our music." [7] [8] This three part approach of 1) understanding, 2) engaging in interdisciplinary dialogue and inquiry, and finally 3)begin building forms the broad structure of this thesis.

0.3. Thesis Structure

In order to answer the three research questions and with a structure closely paralleling the three phases of understanding, dialogue and inquiry, and finally creating, as described by Johnson in the previous section, this research is also organized into three parts: 1)A theoretical framework to understand the forces at play, 2)a cross-disciplinary search for methods and models, and finally 3)an attempt to “stop analyzing” and to create, or in other words, to test the assumptions of the first two parts. A more detailed sketch of these three phases follows:

Part One: Theoretical Framework. This component consists of a theoretical exploration creating a framework of major themes and concepts related to algorithmic or generative design. It discusses the role of mathematics, technology, science, and art in the design of landscapes as well as positions widely discussed in recent landscape architectural discourse: ideas of emergence, self-organization, complexity, systems thinking, and non-linear systems, concepts which this research proposes algorithmic methods are particularly well-suited to address. It also draws heavily on concepts discussed by architectural theorists in relation to digital and algorithmic design starting in the mid-1980s, with particular attention paid to concepts that have been transported over into landscape texts and projects.

This survey is organized around six key figures, each representing a particular time period and philosophical worldview that has influenced the design of landscape space both historically and in the present. In each time period, an outstanding mathematician is placed in dialogue with another figure representing a contrasting point of view, a poet, a natural scientist, and an architect respectively, not so much to reinforce a stereotypical binary, but to break the binary down and show the fluidness of the categories. These include:

I. Classical worldview
    Euclid of Alexandria   Lucretius

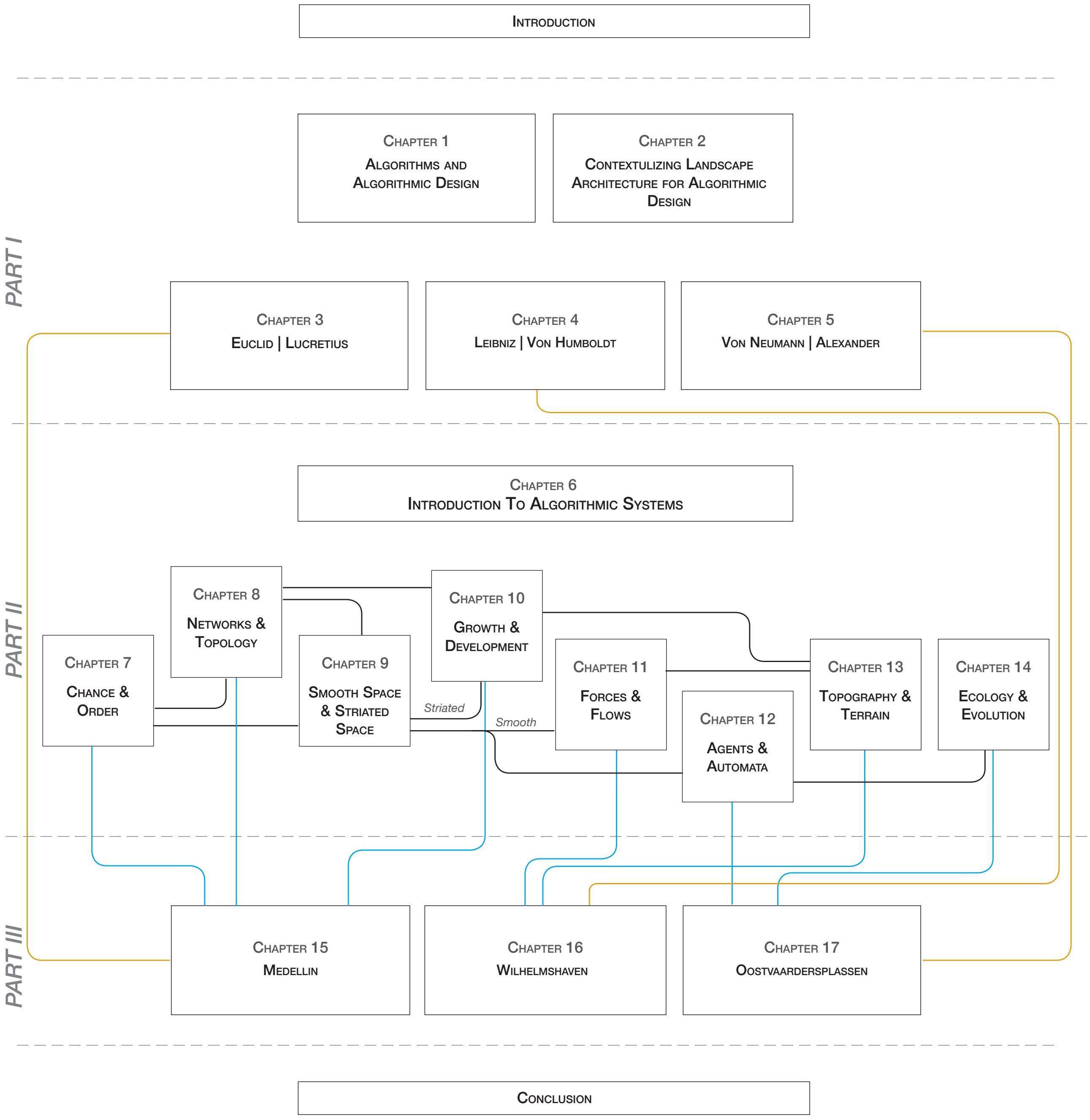
II. Early-modern worldview
    Gottfried von Leibniz   Alexander von Humboldt

III. Contemporary (Late-modern / Post-modern) worldview
    John von Neumann   Christopher Alexander

In addition to the individuals, other themes and individuals falling generally into these worldviews and perspectives are presented. Under each worldview, the themes of *Form*, *Performance*, and *Information* are treated to provide a comparative structure.

Part Two: Algorithmic Concepts and Categories. This section contains a survey of algorithms organized into topics of generally increasing complexity that have been commonly used in the visual and spatial design disciplines. It introduces important, recurring concepts germane to groupings of algorithms, a short explanation of the general logic of the algorithms presented, examples of applications in related disciplines, from art and architecture to science and engineering, and where applicable, examples of applications in landscape architectural projects and design. Apart from some explanatory examples in Chapter 6, the text itself will not get into the technical details of constructing such algorithms, which

Overall Thesis Structure



could be developed in any of a number of programming languages and environments; the reader will instead be referred to examples created by the author and archived on a public website should more technical information on constructing the algorithms be desired.

After an overall introduction of common themes and issues, the algorithms are discussed in the following categories and chapters. The categories seek to differentiate between deterministic vs. indeterministic algorithms and how uncertainty, randomness, and agency play a role while presenting opportunities and challenges for computation. The groupings are as follows:

I. Chance and Order
II. Networks and Topology
III. Striated and Smooth Space
IV. Growth and Development
V. Forces and Flows
VI. Agents and Automata
VII. Topography and Terrain
VIII. Ecology and Evolution

Figure 0.1: (opposite page) Diagram of the overall thesis structure, indicating major relational linkages between the chapters.

Part Three: Algorithmic Applications. The final section of the research concludes with several design "projects" which use algorithms developed by the author or algorithms contained within a number of software packages used by landscape design professionals. The purpose of these studies is to see how various algorithms can relate together, how they can be integrated into current workflows, and what are some potential directions for future research. The focus of each project corresponds to the four groupings introduced in Part Two of the thesis, although they may use other algorithms from the other groupings. The projects are as follows:

I. Medellín
   Tactical interventions in an informal settlement
II. Wilhelmshaven
   A design study for a coastal park near a tidal bay
III. Oostvaardersplassen
   A study for an ecological corridor in a "rewilded landscape."

This section will also reflect on the ease or difficulty in acquiring fluency in algorithmic design through the author's own experiences learning these programs as well as experiences teaching an elective course over the course of three years related to generative landscape design.

0.4. Research Methodology

This doctoral thesis is the product of an extensive literature review as well as numerous algorithmic tests and models. The character of the research in Part I can be generally categorized as "research about design", Part II as "research for design," and Part III as "research by design."[9] What follows is a synopsis of the major research tasks for each section.

Part I – Primary Research Methodology - Literature Review:
The first part of this research is informed by a literature review into historical and contemporary theories of form making in landscape design and how algorithmic thinking can enrich and extend the formal vocabulary and capabilities of designers. Drawing limits around this phase of the research has proved to be a difficult task, with an extensive corpus of writing which could potentially inform the topic, but with little to date directly

addressing computational approaches to landscape architectural design outside of the topics of digital representation, with a few notable exceptions noted below.

As such, Chapters 1 and 2 focused on a literature review relating to the key terms in the core hypothesis: The algorithmic manipulation of space has the potential to change the practice of landscape architectural design. The four key words and phrases here include 1) algorithm, 2) algorithmic design, 3) landscape architecture, and 4) manipulation of space. As such, the following major groupings of literature were reviewed in the composition of these chapters.

1. Writings from computer science and mathematics formally defining algorithms, explaining the origin of the term algorithm, and extending the definitions of algorithms beyond traditional notions.
2. Writings on generative and algorithmic methods in Art. (see especially §1.6-§1.9)
3. Writings on generative, algorithmic, and digital design coming out of architecture, notions of space syntax, as well as reflections on digital culture and practice. Especially notable are writings of Stan Allen, Antoine Picone, Mario Carpo, Sanford Kwinter, Bill Hillier, and Achim Menges. (see especially §1.12-1.13, §2.3-2.4, §2.10)
4. Writings on algorithmic methods in landscape architecture. As this research began in 2013, few comprehensive texts specifically addressing computational methods (as opposed to digital representational methods) in landscape architecture had been published. A notable exception could be said to be at the scale of large-scale landscape planning, where algorithmic methods or logics are used in combination with GIS data (see §1.11), but such methods have little to do with the *formal* or *performative* aspects of landscape architecture, that is at the scale of individual projects. Over the course of the research, several notable texts have been released moving in this direction. These include Jillian Walliss and Heike Rahmann's *Landscape Architecture and Digital Technologies* (2016, see §1.11, 1.2, 2.4) as well as Karen M'Closky and Keith Van Der Sys' *Dynamic Patterns: Visualizing Landscapes in a Digital Age* (2017, see §1.8). Released shortly after the completion of this thesis, and to which the author contributed a small chapter is Bradley Cantrell and Adam Mekies' *Codify: Parametric and Computational Design in Landscape Architecture* (2018, see §A12.2). A number of shorter essays also refer to algorithmic methods in landscape design, most of which have been released only in the past few years and which are referred to in the text.
5. Computational approaches in the fields of urban and environmental planning.
6. Writings dealing with formal systems and attitudes to form-making in landscape design, especially in the last 25 years. For this review, the abstracts for all the articles published in several major landscape architecture journals for the last 25 years were perused (*Landscape Journal*, *Topos*), and articles dealing with topics of form, process, complexity theory, emergence, self-organization and digital methods were further scrutinized. In addition, major anthologies published by landscape architectural theorists were reviewed for content related to the aforementioned keywords.

7. Writings on the structure and emergence of form in natural systems. A fundamental source for this was György Kepes *The New Landscape in Art and Science* (§1.8).
8. Writings on systems thinking. Key authors include Jack Burnham (§1.8, 1.9), Gregory Bateson, and Donella Meadows.

The second half of Part I, comprising Chapters 3, 4, and 5, presents a historical narrative structured around the concepts of form, information, and performance. This grows out of a construct first presented in §2.6—and seeks to introduce the evolution of formal systems, the core of algorithmic thinking, through three historical periods—antiquity, the Enlightenment, and the mid-twentieth century. The logic of formal systems is contrasted with the relational logic of a scientific and cultural understanding of the world characteristic of the philosophical construct of structuralism (see §1.8). To focus the historical exposition and to narrow the literature review, three figures become the focus of a "formalist narrative" in each of these three chapters: Euclid (Chapter 3), Leibniz (Chapter 4), and John von Neumann (Chapter 5). Euclid was chosen over Plato, who is also discussed in detail, as his geometric formal system forms the basis of the design language dominant for much of architecture's history (and to a lesser extent in landscape architecture). Leibniz was chosen as a bridge between antiquity and the modern world, who extended the geometric formal system from the Euclidean tradition, but who also laid the groundwork for modern computation. Finally, John von Neumann, a figure perhaps not as well known as the other two, but who contributed significantly to the development of modern computation and to 20th century mathematics, was chosen for representing the blind optimism of many from the period.

Finding a counterpoint to these three figures, representing a "structuralist/relational" strand of thought was a significant challenge and numerous individuals were considered to fill this role. In the end, the figures Lucretius, Alexander von Humboldt, and Christopher Alexander were chosen although the genealogy between these three is not as clear as for those in the "formalist narrative." Lucretius' was chosen as the most significant philosophical counterpoint in antiquity to the dominant Platonic school of thought to which Euclid subscribed. Alexander von Humboldt was chosen as figure who bridged Enlightenment thinking with Scientific Romanticism in the period in which landscape architecture began to emerge as a discipline distinct from architecture, while Christopher Alexander was chosen as a mathematician who renounced his early training to pursue a design philosophy based on the paramount importance of "feeling," (as opposed to von Neumann's cold rationalism), and for his significant contributions to the emergence of certain important software paradigms.

The thesis also proposed the need for a mediation between formalism and structuralism, and several characters emerged in the course of the research to inform this "performative" field between the two. These characters were not initially defined in the methodology and became a focus of research only as the writing of these chapters progressed. These include, among others, Julian of Ascalon in Chapter 3, Johnann von Goethe in Chapter 4, and Stephen Lansing in Chapter 5. In the end, a more careful study of these figures may prove most valuable in informing a meaningful, deep, responsive, and sensitive algorithmic approach to problems faced in cities and landscapes.

Part II – Research Methodology - Algorithmic modeling supplemented by a Literature Review

The second part of the research is informed by extensive research into codes and algorithms from a number of sources, and in most cases trying to replicate or reproduce the algorithms themselves. The focus was on exploring algorithms with spatial outputs, although it was necessary to explore other tasks with non-spatial outputs, such as data sorting, but these are not the focus of the research. Additionally, several different programming and scripting methodologies were tested, primarily in the environment of the 3D modeling program Rhino using either the Grasshopper interface or Python scripting. This methodology is described in more detail in Chapter 6, especially in §6.3, §6.10-§6.15.

This phase of the research began with a wide-ranging search through various sources into algorithms with spatial characteristics from numerous fields:

1. Texts and Artworks in the field of Generative Art. Important sources include Georg Nees' *Computer Graphik* (1969)*,* Gary Flake's *The Computational Beauty of Nature* (1998)*,* Hartmut Bohnacker et al. *Generative Gestaltung* (2009)*,* and Casey Reas' *Form + Code: In Design, Art, and Architecture.* Additionally algorithms were derived based on the the work of artists such as Sol Lewitt and Kenneth Martin, and architect Stan Allen.
2. Articles from Scientific Journals focused on algorithmic methods: Scientists from fields such as Botany, Geomorphology, and Ecology have active research programs into computational methods to understand how processes in nature.
3. Articles from architecture and urban design publications.
4. Computer science publications with interests from graphics to artificial intelligence to gaming have also published numerous algorithms potentially of interest to landscape designers, as replicating or simulating natural systems has been a key goal of programmers from computations earliest days.

Another component of this phase of research and to further explore how algorithmic thinking could inform landscape design, an additional goal was to analyze and deconstruct a number of natural and cultural landscapes, as well as landscape architectural projects, in strictly formal and algorithmic terms to see how and if they could be recreated using a generative approach.

Once a significant number of algorithms had been researched and tested (over 100 were developed in some detail) the next phase of the research attempted to categorize the algorithms into logical groupings. This categorization was informed by preparing both a theoretical lecture series as well as a weekly tutorial workshop for a course called "Generative Landscapes" which was offered three times between 2013-2015. In developing the course, the author also created a blog (generativelandscapes.wordpress.com) which also furthered the categorization process. Once categories were established, the author tried to push out the categories specifically searching for additional algorithms that might fall into each category. This necessitated in many cases a return to previous sources, an expansion of the source material, or developing algorithms as original creations.

Ultimately the eight categories structuring Part II were derived through this sorting process, an extension of the literature review began in Part I, and based on an understanding of "smooth" vs. "striated" spaces based on a reading of Delueze and Guattari's *A Thousand Plateaus* and Robert

Ulanowicz's *Growth and Development* (see Chapter 9). Natural systems derive their complexity through a combination of chance and entropy on the one hand (Chapter 7) and specific topological relationships between entities (Chapter 8). Where these topological relationships are clear, stable, and predictable, articulated spaces of development emerge (Chapter 10). In systems where topological relationships are unclear, indeterminate, or based on free agents, smooth and connected spaces tend to develop. (Chapter 11 and Chapter 12). Finally, these two types of spaces coexist to build larger structures, particularly of interest to landscape design are the questions of landform structures (Chapter 13), and ecological systems (Chapter 14). For each chapter, four algorithms were originally intended but this was reduced to three for reasons of space and the time investment. The algorithms chosen in each chapter were intended to show a diversity of approaches, but also be of a simple enough character to be explained with only a few paragraphs and graphic illustrations. Complex assemblages of various algorithmic processes were avoided and were to be explored in the next section.

Part III – Research Methodology - Algorithmic modeling

The final major phase of the research is based around the research method of modeling and consists of a number of "projects" to test the application of various algorithms learned in Part II to specific sites and problems, as well as to author new algorithms specific to each site. The goal was to see how numerous algorithms could work together to address various design tasks, with the formal constructs embedded in algorithms interacting with a field of landscape information to derive performative outcomes. The specific methodology is explained in more detail in the introduction to Part III.

0.5. Audience and Thematic Relevance

Much has been written about algorithmic, procedural, or generative design in an incredibly broad array of fields, each for a specific audience assuming certain prior knowledge and technical capabilities. This research is written in the context of landscape architectural design, where algorithmic approaches are still fairly new, and when used in projects, the role of the algorithm in the design process is often highly obscured, both for practical and professional reasons.

This research assumes the reader has a solid grounding in the field of landscape architecture and design, but not necessarily a thorough understanding of computational approaches. It is not meant as a "how to" manual for algorithmic design, but rather how to approach and evaluate the merits of a design which uses an algorithmic process, as well as how to determine when developing such a process may be a productive use of time in a design context. As more and more students enter design schools and later professional offices having been raised with games such as Minecraft (a procedural world and landscape generator) and not with Legos, it will become increasingly important to be able to engage this process critically,[10] and not to immediately accept such a design for its "wow" factor, or to summarily dismiss a design because it uses an approach not widely understood, or a formal vocabulary not easily produced using analog methods. At the same time, it is important for this research to strive for a degree of transparency in approach, and to not hide the process as is often done. As such, when certain algorithmic processes are first referred to in the text, their logic will be described in certain detail and those wishing further information will be referred to technical explanations provided on the author's website.

0.6. Personal Background and Motivation

Finally, while this work strives for a certain degree of objectivity free from personal opinions and biases, I believe it is important to briefly present important elements of my own personal background and biases. My experience and training stands on the generational shift between analog methods of design conception and production and an increasing reliance on digital methods in the profession. My early training in the disciplines of first architecture (MArch Georgia Tech 2003) and then landscape architecture (MLA Harvard 2009) relied at first on analog methods such as hand sketching, collaging, and traditional drafting, but quickly moved into almost exclusively digital platforms and techniques. At the same time, most of the instructors in my studies as well as the supervisors in my professional practice, having been trained and apprenticed almost exclusively in analog techniques, saw digital tools as a necessary evil to increase productivity, facilitate interdisciplinary collaboration, or to meet client expectations, but to *design* in the digital environment was anathema and to be avoided. As an instructor now myself of a younger generation that has lived their whole lives in a digital age, it is often easy to see the wisdom in this perspective, seeing students struggle with problems in a digital space which could easily be solved with a quick hand sketch or diagram.

Part of the solution to this pedagogical dilemma may well be to revisit and reinforce analog techniques, which may be a healthy direction to follow, but this is becoming increasingly impractical as prospective employers are demanding more, not less, software experience from new hires, and analog capabilities can be quickly lost in practice if they are not routinely reinforced. Analog techniques are also in many cases completely unsuitable for tasks that digital tools can do quite well, such as working with large data sets and systems modeling, tasks which the recent ambitions of landscape architectural discourse have favored. An early hypothesis upon beginning this research was that while digital tools have become pervasive over the course of the last decades in both academia and in practice, digital thinking, or more rather systems thinking, has not been adequately integrated into current pedagogy or practice.

To design in the computer may very well require better training in understanding how the computer operates—its internal logics—which in turn may allow for a more productive use of its capabilities. This requires at a fundamental understanding of concepts germane to computer science and the development of computer algorithms. Again, I stand in the middle of a generational shift, having some early exposure to computer coding as a young child when my father enrolled us in a basic programming course with the software Logo on a TRS 80 computer. I again tried to pick up software programming at various points of my life as computer technologies evolved for various personal and professional aims, but I had no sustained experience with software coding before beginning this research. Learning how to structure, code, and create algorithms has been the most difficult but also most rewarding part of this research.

Finally, this research and text falls back on my initial liberal arts training in historical research and writing (BA History, Brigham Young University, 2000). A major challenge of this research is that it is within a fast developing field of knowledge and new publications of relevance are being published on a constant basis. What seemed promising or innovative in 2012 when I began these studies can now sometimes be seen as passé. The historical research has helped frame this work and lend it some perspective, for while the “Digital Revolution” is rather recent, the issues and questions at stake are often longstanding and timeless.

Endnotes

1 Sanford Kwinter, "The Cruelty of Numbers," in *Far from Equilibrium: Essays on Technology and Design Culture*, ed. Cynthia Davidson (Barcelona: Actar, 2008), 97.

2 David Berlinski, *The Advent of the Algorithm: The 300-Year Journey from an Idea to the Computer* (London: Harcourt, 2000), xv-xvi.

3 Martin Davis, *Engines of Logic: Mathematicians and the Origin of the Computer* (London: W.W. Norton & Co., 2000), 8.

4 *Ibid.*

5 Martin Ford, *The Rise of the Robots: Technology and the Threat of Mass Unemployment* (London: Oneworld Publications, 2015).

6 See Gilles Deleuze and Felix Guattari, *A Thousand Plateaus: Capitalism and Schizophrenia.* Translated by Brian Massumi (London: The Athlone Press, 1993), 163-165.

7 Steve Johnson, *Emergence: The Connected Lives of Ants, Brains, Cities, and Software* (New York: Scribner, 2001), 20-21.

8 Tom Verebes, *Masterplanning the Adaptive City: Computational Urbanism in the Twenty-First Century.* (New York: Routledge, 2014), 104.

9 For a brief synopsis of the categories in this "trinity of design research," see Martin Prominski, "Research and design in *JoLA*." *Journal of Landscape Architecture* 11:2 (2016), 26-29.

10 See Daniel Short, "Teaching Scientific Concepts using a Virtual World – Minecraft," *Teaching Science* 58:3 (September, 2012), 55-57.

Part I

Theoretical Context for Algorithmic Design in Landscape Architecture

Chapter 01 – Algorithms and Algorithmic Design

“A striking parallel exists between the ‘new’ car of the automobile stylist and the syndrome of formalist invention in art, where ‘discoveries’ are made through visual manipulation. Increasingly ‘products’ –either in art or life—become irrelevant and a different set of needs arise: these revolve around such concerns as maintaining the biological livability of the Earth, producing more accurate models of social interaction, understanding the growing symbiosis in man-machine relationships, establishing priorities for the usage and conservation of natural resources, and defining alternate patterns of education, productivity, and leisure…We are now in transition from an object-oriented to a systems-oriented culture. Here change emanates, not from things, but from the way things are done.” – Jack Burnham[1]

Figure 1.0: (*page opposite*) Peter Eisenmann‘s *Memorial to the Murdered Jews of Europe.* The repetitive variation of thousands of similar but ultimately unique forms is a hallmark of many *parametric* landscapes.

1.1. Introduction

The introduction to this thesis introduced the concept of the algorithm as a ubiquitous underpinning of much of contemporary society. An ancient but little used word repurposed for the computer age, the word algorithm has come to define much of our global culture, especially in the course of the last two decades. Those in wealthy Western countries, in the developing global South, and in the ancient but rapidly changing societies of the East all are living lives increasingly mediated by technology, with algorithms fueling the core logic of much of the emergent technology reshaping the world. Recent events underscore the fact that it is no longer advisable to be passive consumers of algorithmic flows and manipulations of information, but to critically engage how they work. Also, as design practice relies increasingly on digital and computational methodologies and automated processes, it is important for designers to understand how computers can be used to explore and manipulate form. A deeper critical understanding of these methods, both in society in general and in design practices specifically is needed to move beyond the all-too quick acceptance of the wow-factor of computer graphics, or the all-too quick rejection of digital methods due to lack of an understanding of the forces at play.

The general introduction also introduced a general goal of this thesis to explore in depth, how the *algorithmic manipulation of space* has the potential to change the practice of *landscape architectural design*, and then to reflect on what those potentials mean. Before setting off, however, it is important to present a brief sketch or definition of the critical concepts contained in this goal. Specifically, the following two chapters aim to define first, what is an algorithm? Second, what is algorithmic design? Third, what is understood as the scope of landscape architecture? Fourth and finally, what is understood by “manipulation of space” in this context? The first two questions are the subject of this chapter, while the third and fourth questions will be addressed in Chapter 2.

1.2. Definition of an Algorithm

In order to address the role of algorithms in the context of landscape architectural design, the term algorithm must first be adequately defined. A good starting point for a definition is closely, but not quite captured by terms such as "*recipe, process, method, technique, procedure, routine, rigamarole.*"[2] The term algorithm is now usually associated with methods or procedures executed by a computer, but this is not a requirement in most definitions. Before the development of the modern computer and up to the 1950s, for example, the term was usually associated with the so-called Euclidean algorithm, a method developed by Euclid more than 2000 years ago for finding the greatest common divisor of two natural numbers. (Fig. 1.1) Berlinski defines an algorithm more precisely, while avoiding some of the technical language associated with other definitions, as "a finite procedure, written in a fixed symbolic vocabulary, governed by precise instructions, moving in discrete steps, 1, 2, 3, …, whose execution requires no insight, cleverness, intuition, intelligence, or perspicuity, and that sooner or later comes to an end."[3]

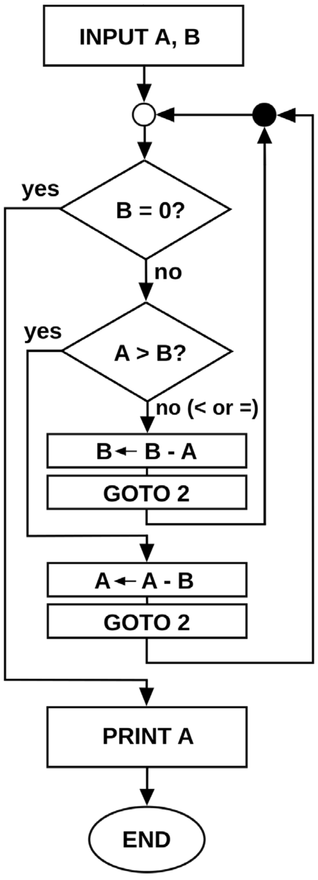


Figure 1.1: Diagram of Euclid's Algorithm for determining the greatest common divisor of two real integers.

1.3. Effectiveness, Definiteness, Finiteness

More formal definitions of algorithms, of which there are many, almost always contain three key words: effective, definite, and finite. A concise example of such a definition given by Harold Stone defines "an algorithm to be a set of rules that precisely defines a sequence of operations such that each rule is *effective* and *definite* and such that the sequence terminates in a *finite* time." (emphasis added)[4] The three terms were similarly used by Donald Knuth who defined the three terms as follows:

> "1. Finiteness. An algorithm must always terminate after a finite number of steps."
> "2. Definiteness. Each step of an algorithm must be precisely defined."
> "3. Effectiveness. An algorithm is also generally expected to be *effective* in the sense that its operations must all be sufficiently basic that they can be done exactly and in a finite length of time by someone using pencil and paper."[5]

A quick reading of Knuth's definition, however, points to the fact that the notion of effectiveness already implies definiteness ("operations must all be sufficiently basic that they can be done exactly") as well as finiteness ("and in a finite length of time"). The notion of effectiveness, a term which Berlinski avoids using directly, but which is implied, seems to be key to defining an algorithm, and for some authors, the term algorithm and *effective procedure* are synonymous.[6] [7] This term, in addition to the criteria listed by Knuth, also implies the notion that the operations can be done without requiring any "insight or ingenuity or invention."[8] In his definition of an algorithm, the evolutionary philosopher Daniel Dennett words this notion a bit differently using the term "underlying mindlessness" describing a task "simple enough for a dutiful idiot to perform—or for a straightforward mechanical device to perform."[9] Regardless of whether it is done by a mechanical device or a dutiful human, a definite, finite, and effective procedure should yield infallible results.

1.4. Historical Development of the Modern Definition of an Algorithm

The notion of effectiveness can be understood more deeply with an historical understanding of how the word algorithm became defined in the modern sense. The word is itself a corruption of the older English word *algorism,* which in turn was derived from a crude Latinization of the name of the Persian mathematician Al-Kwarizmi, the author of a famous textbook whose Latin translation, *Algoritmi de numero Indorum,*[10] introduced the decimal numeral system along with its associated operational methods to the West. The decimal system, the operations of the *algorists*, along with the new mathematics of *algebra* (also formalized by Al-Kwarizmi) were to eventually revolutionize nearly every aspect of western mathematics, economics, and science, and paved the way for the innovations of Descartes, Newton, and Leibniz, but the algoristic counting methods only gradually replaced the methods of those who used the old Roman system, which required the use of an abacus for more complex operations. Those skilled in the use of algorism, on the other hand, could perform operations with no specialized devices and could instead perform all of their basic arithmetic operations (addition, subtraction, multiplication, division) with only a simple writing instrument and paper. (Fig. 1.2) The association of the term algorithm with these four basic mathematical operations was still present in the 1741 German mathematical dictionary *Vollständiges mathematisches Lexicon.*[11] These basic operations of algorism gradually began to be defined by number theorists, along with other functions, as *primitive recursive* or *general recursive* functions.[12]

Figure 1.2: Calculating-Table by Gregor Reisch: *Margarita Philosophica*, 1508. This woodcut shows the two contemporary methods of computation, on the left by algorism, and on the right by abacus.

A second historical thread essential to understanding the modern definition of an algorithm and the notion of effectiveness begins with Gottfried Leibniz, who after devising a mechanical device which could perform the basic operations of addition, subtraction, multiplication, and division, dreamed of developing a device capable of solving problems of *reason.* (Fig. 1.3) The goal of realizing such a device was the impulse which guided Leibniz to his new formalizations in number theory and logic, including his description for the first time of a binary numeral system and a system of conditional (i.e. Boolean) logic, two innovations which only centuries later would be recognized as the building blocks of modern computer science.[13]

Leibniz' purpose of creating a decision making machine was taken up centuries later by the mathematician David Hilbert, who in his 1928 text *Grundzüge der theoretischen Logik* proposed what has become known in computer science as the *Entscheidungsproblem.* The problem asked if it was possible to find a general process whereby a machine could prove by giving a 'yes' or 'no' answer any given mathematical formalization within a well-developed and complete formal system.[14] [15] Hilbert believed it *was* possible to formulate a mathematical system where every statement could be proved through mechanistic means. Within a few years of being proposed, however, Hilbert's optimistic proposition was disproved. The first hints of this came through the mathematician Kurt Gödel, who in 1931 delivered a formal proof that in *any* formal system, there are problems which "do not allow themselves to be decided from the system's axioms." Furthermore "this circumstance does not lie in the special nature of the examples presented [in this paper], but is valid for a very broad class of formal systems…" which he goes onto describe as any *consistent* formal system.[16] In other words any formal system could not be *consistent* and *complete* at the same time. The mathematician Alonzo Church confirmed Gödel's proof in 1936 and delivered a negative answer to the *Entscheidungsproblem* where he demonstrated that only recursive functions are *effectively* computable.[17] A few months later Church's proof was further validated by the mathematician Alan Turing, who demonstrated that a function which is "effectively calculable if and only if it is computable by a specific mechanistic process—a universal machine—which Turing goes on to describe and which has since come to be known as a Turing machine."[18] The theoretical musings and rigorous debate between Turing, Church, Gödel, and Hilbert could have remained confined to the ivory towers of the academy were it not for Turing's description of the machine which has come to define what an algorithm is. (Fig. 1.4) Within a few years, the mathematician John von Neumann in America and the technician Konrad Zuse in Germany would take Turing's template for a device for universal computation and construct the world's first computers. (Fig. 1.5, §5.3)

In summary, in light of the work of Church-Turing and Gödel, it is possible to make the following generalizations about algorithms: 1) An algorithm is any formalization capable of being solved definitively by a robot, 2) The formalizations required for effective computability are very basic and any computable problem can be solved using a very limited set of operations, which can be exclusively formulated as primitive recursive functions, or self-referential looping statements. At times the results of these loops can be somewhat expected and banal, but they can often be unpredictable and surprising, what Hofstadter terms "strange loops"—the existence of which he believes to be the key to understanding how consciousness *emerges* from inanimate matter, and how meaningless symbols acquire meaning.[19] A final point, hinted at by Gödel, is that with the current paradigm of computation, some problems cannot be adequately formulated or solved—in other words there are limits to what computation can achieve, unless the paradigm is expanded in some way.

1.5. Expanded Notions of Algorithms

The very simple but powerful propositions of what has come to be known as the Church-Turing thesis have proven to be incredibly robust, but while numerous experiments have strengthened their thesis, it is still open to extension and new interpretations. Many challenges to the current definition of computability are proposed in current attempts to precisely define what algorithms are in the post-Turing age. Blass and Gurevich offer a number examples, opening with a quote from Gödel's private notes, who after accepting Turing's general analysis writes about:

> "a philosophical error in Turing's work. Turing … gives an argument which is supposed to show that mental procedures cannot go beyond mechanical procedures. However, this argument is inconclusive. What Turing disregards completely is the fact that mind, in its use, is not static, but constantly developing, i.e. that we understand abstract terms more and more precisely as we go on using them, and that more and more abstract terms enter the sphere of our understanding."[20]

Gödel understood that minds *learn*, and that this learning can influence future decisions or behavior. Was Gödel speaking only of biological minds, or did he believe that an algorithm could "learn from its own experience, becoming more sophisticated and thus compute a real number that is not computable by a Turing machine?"[21] The answer to this question starts to move into the developing realm of machine learning, an active new field of research.

A second category of algorithms not addressed by Turing, according to Blass and Gurevich, include algorithms which interact with their environment, and which are open to non-deterministic inputs. While a classical Turing algorithm is completely deterministic in nature and cannot generate truly random results (§7.6), if the computer "reads" random information from the environment, such as the state of a quantum particle,

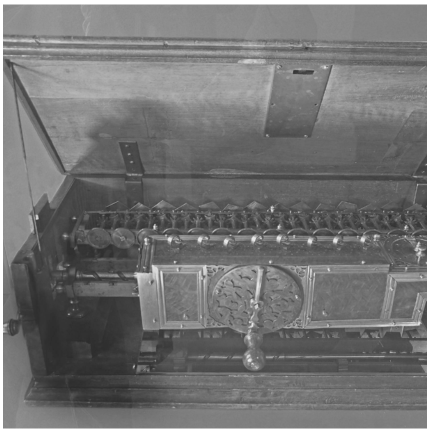


Figure 1.3 (*Top*): One of Leibniz's calculating machines, the first which could perform the four basic arithmetic operations.

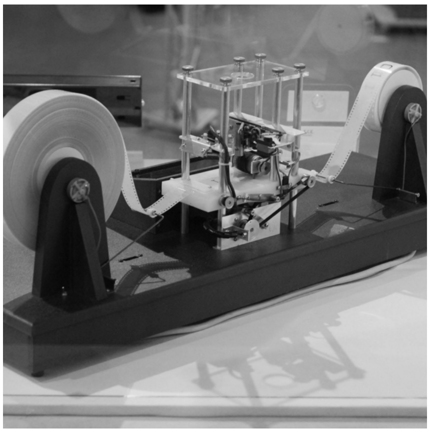


Figure 1.4 (*Middle*): A prototype built based on Turing's description of a machine for Universal Computing. Turing himself never built such a machine.

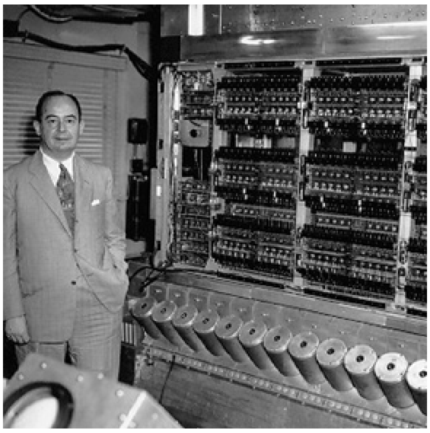


Figure 1.5. (*Bottom*): John von Neumann next to the ENIAC (§5.3). His computer architecture is still used to this day.

or the whims of a user, the algorithm *is* capable of computing non-recursive functions.[22] Turing also does not deal with *non-discrete* computations, such as "classical, geometrical ruler-and-compass algorithms,"[23] but also any problem dealing with continuous curves or surfaces, in other words analog vs. digitalized reality.

In another direction, some see the concept of algorithms as extensible to other realms of learning outside of computer science—especially biology—which has come to be seen increasingly in computational terms. Daniel Dennett argues in his book *Darwin's Dangerous Idea: Evolution and the Meanings of Life* that natural selection is fundamentally an algorithmic process, since it meets the requirements of algorithms (to an extent) as defined by Turing, Gödel, and Church,[24] and rephrases Darwin's fundamental idea as "life on earth has been generated over billions of years in a single branching tree—the Tree of Life—by one algorithmic process or another."[25] Perhaps anticipating criticism of his stretch, but also pointing to the promise of using algorithmic tools to understand any process, Dennett continues:

> "Are there any limits at all on what may be considered an algorithmic process? I guess the answer is No: if you want to, you could treat any process at the abstract level as an algorithmic process. So what? ...the algorithmic level *is* the level that best accounts for the speed of the antelope, the wing of the eagle, the shape of the orchid, the diversity of species, and all the other occasions for wonder in the world of nature."[26]

Dennett is not the only one who has made this connection and algorithmic simulations are now a primary tool to study complex natural and social phenomena and systems. Melanie Mitchell argues in *Complexity: A Guided Tour* that the three building blocks of modern complexity science are information, computation, and evolution, further asserting that not only can "life and evolution…be mimicked in computers" but "the notion of *computation* itself is being imported to explain the behavior of natural systems."[27] The connection between the two is not hard to grasp with an understanding of the fundamental recursive nature (i.e. self-referential, step-by-step incremental change, see §6.6, §6.7) of natural and human systems, and while complexity theory and science encompasses much more than what can be reduced to an algorithm, Turing's machine with its incremental recursive logic for the first time gave us "honest step counting and became eventually the foundation of complexity theory."[28] The reconciliation of the algorithm, a key component of Mitchell's second building block of complexity, with Mitchell's first building block—information—and her third building block, the evolution of information and computational structures—is the dilemma hinted at by Gödel in his reflections on Turing's work.

1.6. Algorithms in Art and Design - Generative Art

Not only have algorithms and algorithmic thinking had an impact on how natural scientists and philosophers perceive reality, since at least the mid-1960s they have had an impact on the thinking and work of artists and designers. The age of computer graphics as well as computer art began with the work of three independent researchers: Georg Nees, Frieder Nake, and Michael Noll. All three began working as early as 1963 on algorithmically generated graphics with the help of Konrad Zuse's recently invented plotter, the Zuse-Graphomat. Nees was the first of the three to exhibit his work, in a small exhibition in Stuttgart in early 1965,[29] and submitted what may be the first doctoral dissertation on computer graphics in 1968.[30] At first, Nees had no specific agenda for his drawings, remarking in relation to the newly acquired Zuse-Graphomat: "There it was, the great temptation for me, for once not to represent something technical with this machine but rather something 'useless' – geometrical patterns."[31] Gradually, and under the guidance of his mentor and doctoral advisor, the information theorist Max Bense, he realized he was on to something much more:

> "*Dabei ist die generative Graphik in der glücklichen Lage, in der sich die Astronomie erst nach der Erfindung des Teleskops befand. Sie kann nämlich die Programme, die sie erstellt, von den als Computern oder Datenverarbeitungsanlagen bezeichneten Maschinen auswerten lassen. Man hat den Computer als Komplexitätsfernrohr bezeichnet, weil er vorher unzugängliche Komplexität überhaupt erst auflösbar, dann allerdings sogar manipulierbar macht.*"[32]

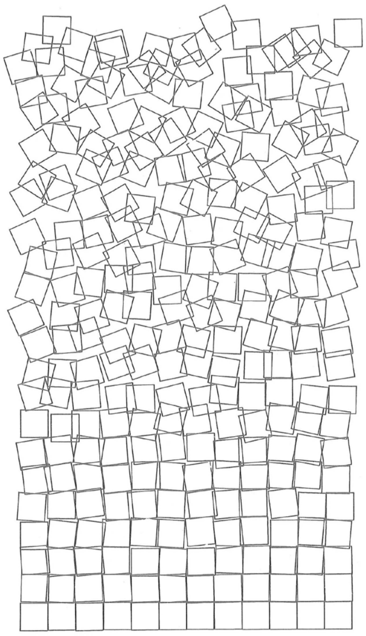


Figure 1.6: Georg Nees, *Schotter*, 1968-70. (first iteration 1965) ©Victoria and Albert Museum, London

At this time, of course, complexity was not yet defined in the terms often used today; for Nees it is often synonymous with randomness and his drawings relied very heavily on the outputs of a pseudo-random number generator. But the first hints of the tenuous relationship between order, chaos, and complexity, and the ability to manipulate such, were evident in many of the pieces such as in Nees' *Schotter* (1965). (Fig. 1.6) Commenting on the piece in 1974, the architect Robert Krawczyk said: "What intrigues me with this 'ancient' piece was the use of exact mathematical computations to model a chaotic image and the progression from the ordered to the disordered."[33] The pieces were also, despite their pure formalism, beginning to take on semantic meaning despite themselves. Relationships to real world phenomena or images were beginning to be recognized—even the name *Schotter* references the image of gravel stones—a decided tactile object from our everyday experience. The wider implications for the design arts were also beginning to be recognized—to make complexity open to manipulation. Krawczyk continues: "This piece has greater meaning to me today since many of the recent efforts in developing perfect forms and curved surfaces are of great interest in product design, sculpture, and architecture."[34]

The first experiments in algorithmically generated art parallel two related, but distinct larger trends. The first of these, the development of the very broad systems thinking paradigm, will be further explored in the next section. Specific to the art world, generative art emerged concurrently with the development of the minimalist aesthetic. The principles of geometric abstraction and pure formalism inherent in minimalism in turn grew out of the general trend towards abstraction evident in the work of artists such as Paul Klee, referenced in Frieder Nake's 1965 *Hommage à Klee Nr. 2,*[35] (Fig. 1.7.) or Piet Mondrian, whose 1917 *Komposition mit Linien* was the object of study for Michael Noll's 1964 *Computer Composition with Lines.*[36] (Fig. 1.8) One of the main objectives of the minimalists was to remove subjectivity from art, which they believed was only possible in the context of a pure formalism divorced from semantic meaning. Algorithmically generated art took this thinking to the next logical step, as computer programming forces the required precision and logic to remove subjectivity. A typical attitude was expressed by artist Manfred Mohr in 1971, who asserts:

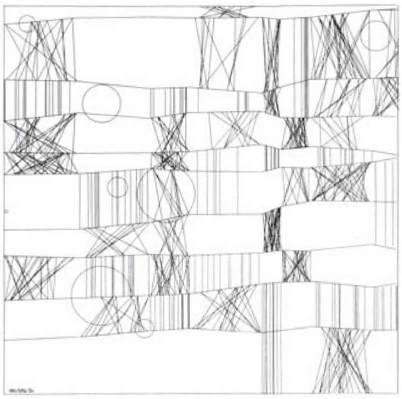


Figure 1.7: Frieder Nake, *13/9/65 Nr. 2*, also known as *„Homage à Paul Klee"*. Computer graphic, India Ink on Paper, 40x40 cm, 1965. In the possession of Kunsthalle Bremen. © Frieder Nake

> "Within this context it is possible to ignore the former 'good' and 'bad', and aesthetical decisions can be based on WERTFREIE procedures…. The fundamental consequence of this attitude is, that after a period of tests, modifications of the logic, and parameter exchanges, all possible results of a program have to be rigorously accepted as final answers… The concentration which is necessary to

> establish a logic (writing a program – that means to give a definition of all instructions that have to be done in the machine) will reflect itself in the result as a clear construction which could be understood by everybody and there will be less and less mystical barriers behind which the artist can hide himself."[37]

This did not mean, however, that the artist could not or did not inject his or her own (arguably subjective) vision into the work. Mohr himself was already an established artist before he began his experimental pieces with computer programming, and a definite aesthetic vision or intentionality can be seen in his pieces in contrast to some of the early work from Nees, Nake, and Noll.[38] Nake, who has taken a more reflective and critical take towards generative art as a writer, after his early, enthusiastic output of images, concludes somewhat more cautiously: "*In diesem Buch soll zu keiner Zeit der Eindruck entstehen, die Maschine tue etwas aus sich heraus, ohne von uns kontrolliert zu sein. Selbst wenn wir von der modellhaften Simulation menschlicher Tätigkeiten in formalen Begriffen reden, so reden wir doch nur von deren Simulation. Der Computer ist ein Produktionsinstrument, kein Gehirn*."[39] The validity of this statement will be a recurring question in this thesis, as will questions of authorship, "*wertfreie*" procedures, as well as the role of randomness in design. This will be again addressed specifically in Chapter 7.

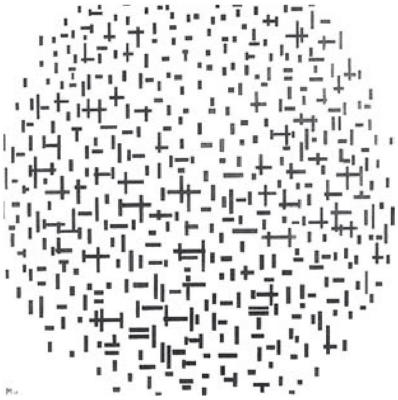


Figure 1.8*: (above)* Piet Mondrian, *Komposition mit Linien*, 1917 *(below)* Michael Noll, *Computer Composition with Lines*, 1964. ©Victoria and Albert Museum, London

1.7. Instructional Art

It is worth mentioning here, that while Nees, Nake, and Noll were specifically interested in exploring the potentials of computation—Nake finding it hard to separate "generative art" from the instrument—Nake's other thesis that the intelligence or artwork lay not in the machine, but in the intelligence of the programmer seems to contradict this. Returning to the definition of an algorithm from the previous section, it should be *effectively* solvable either by hand or machine. In this light, other artists of the period whose work emphasized the processes and procedures over the final image can also be seen as embodying the spirit of algorithmic art. This emphasis is particularly evident in the work of artists such as Kenneth Martin (Fig 1.9) or especially the post-minimalist artist Sol LeWitt. While LeWitt did produce his own artworks, what is of interest here are his "instructional art" pieces, where the product a client would buy was not a finished painting or sculpture, but a piece of paper containing a straightforward series of commands, along with a license to use this "software." An example might be this instruction for Plate 6 from his 1971 *Work from Instructions*:

> "Using a black, hard crayon draw a twenty inch square. Divide this square into one-inch squares. Within each one inch square, draw nothing, or draw a diagonal straight line from corner to corner, or two crossing straight lines diagonally from corner to corner."[40]

The steps continue to contain a level of ambiguity, and are open to different levels of interpretation by the "mindless machines" (the hired draftsmen) who would execute the work, but they are approaching a recipe or set of instructions which could be executed by the mindless machine of the computer when only a few additional variables or constraints are fixed (Fig. 1.10). What is important in LeWitt's work and in the thinking of the instructional artists, however, is the notion that the artwork is not in the matter, nor in the physical labor to produce the matter, but in the idea. The intellectual pedigree used to justify this position itself has a long history, with clear references to Plato's concept of the world of Forms (see §3.5) but perhaps even more closely linked with the working method which emerged in the profession of architecture in the

Renaissance, where the act of designing and the act of building are seen as separate and distinct. (§1.13)

1.8. Emergence of Systems Thinking

A second broad trend corresponding with the emergence of algorithmic art and design was the development of systems thinking in the scientific disciplines, considered by many to have begun following Ludwig von Bertalanffy's 1950 essay "An Outline of General System Theory"[41] and a corresponding development of a *systems aesthetic* in the art world. It also can be seen as part of a broader intellectual shift in the 1960s that can be characterized as a shift from formalism to structuralism. To review, formalism in linguistics, literature, and art, as hinted at in the previous section, was focused on the internal logics of objects being studied or of artworks being produced. A formalist piece of literature, for example, would focus largely on the grammatical structure of phrases, the rhythm and tonality of language, while the story or content might only be considered of secondary concern. Minimalism and early generative art was also largely formalist in nature, that is it sought to free itself from semantic associations, with a focus on form, color, technique, but not on content or meaning. Structuralists, on the other hand argued that a thing cannot be considered outside of its context. In other words, exterior relations are of critical importance, not interior logics. As an example, the word "red" has no inherent meaning in and of itself—the letters and sound are meaningless unless associated with concepts learned through experience. The word "red" for an English speaker is a color, for a Spanish speaker it is a thing—specifically a "net." The form has not changed from one language to the other; meaning is derived through the word's "structural" associations with other words and experience. Structuralism existed as a linguistic paradigm for many years, but began to influence other fields after Claude Levi-Strauss's work of structural anthropology, *La Penseé Sauvage* published in 1962.[42] It then spread to other disciplines, and can be seen to inform, as argued here, notions of systems thinking as well.

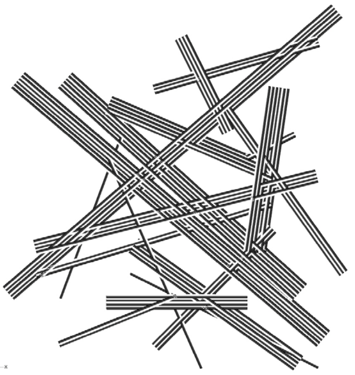


Figure 1.9: An iteration of an algorithm based on Kenneth Martin's *Chance and Order* series. (1971-72). Algorithm by Joseph Claghorn, 2015.

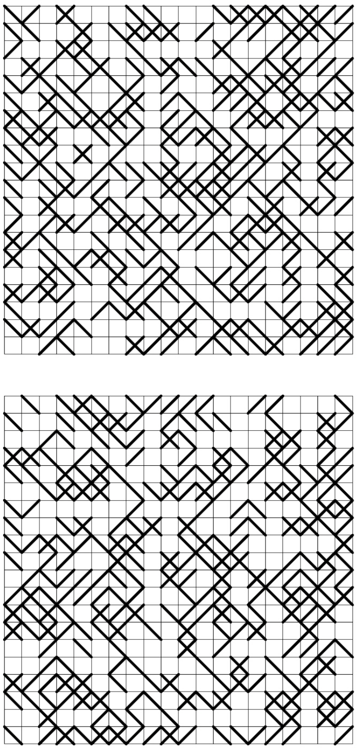


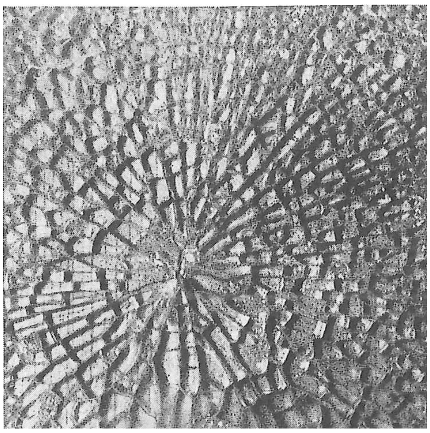
Figure 1.10: Two iterations of an algorithm based on Sol LeWitt, *Work from Instructions, plate 6* (1971). Algorithm by Joseph Claghorn, 2017.

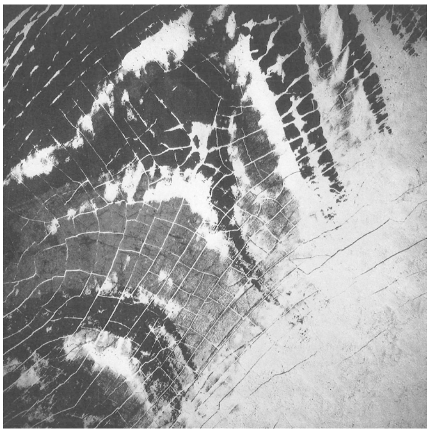
Figure 1.11-1.14 *(Opposite Page: Top to bottom)*: 1.11: *Glass Fracture, 1.12: Stagnant Lake at Edge of Columbia Glacier beside Ruff and Tuff Island, 1.13: Vascular System of Yolk Sac of Shark Embryo, 1.14: Mud Flats at Low Tide.*

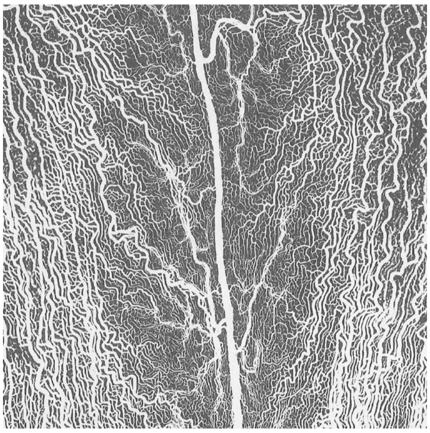
Relational and structuralist thinking has had a profound impact on the design professions and in particularly on landscape architecture, with systems thinking in particular having taken on an increasingly important place in landscape architectural discourse in recent years; Adriaan Geuze recently asserted it has become the dominant paradigm in the discipline.[43] A good introduction to systems thinking in the context of landscape architecture is offered by M'Closkey and VanDerSys in their book *Dynamic Patterns: Visualizing Landscapes in a Digital Age.*[44] The authors cite two key figures in the emergence of this paradigm, the ecologist Gregory Bateson and artist György Kepes. Both saw in spatial patterns the concrete expression of dynamic processes. Kepes claims: "Patterns are the meeting-points of actions. Noun and verb must be seen as one: process in pattern, *pattern* in *process*."[45] (emphasis in original) Bateson likewise saw the goal of the various threads in his seminal work *Steps to an Ecology of Mind* as an attempt to "build a bridge between the facts of life and behavior" and to identify the "nature of pattern and order."[46] For him, patterns are things that connect, and "ecological consciousness and patterns are inseparable."[47]

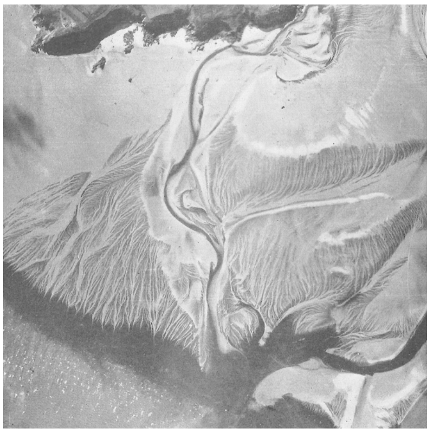
One of Kepes' early works which tested his thesis that patterns were an expression of processes was a book based around a photographic collection of images only made possible with then new methods of seeing, such as aerial photography, electron microscopic images, and instruments for digitizing phenomena such as light and sound. In this book, *The New Landscape in art and science,* Kepes argues that technical and scientific advances have fundamentally changed our relationship and our perception of nature, and that we need new forms of art to comprehend and ultimately give meaning to the modern world: "Like the forest and mountains of medieval times, our new environment harbors strange menacing beasts: invisible viruses, atoms, mesons, protons, cosmic rays, supersonic waves."[48] Kepes looks for patterns in these images to reveal their fundamental *idea*[49] eschewing the depiction of the objects themselves, but zooming in or zooming out to frame the transformational processes evident in the images. He state that when "looking at the pictures, we find no clear-cut beginnings and ends, no *things*; we see movements in nature."[50] Kepes also recognized years before Mandelbrot's pivotal text *The Fractal Geometry of Nature* (see §6.11) the principle of "self-similarity" at work in nature. He observed that:

> "Seen together, aerial maps of river estuaries and road systems, feathers, and the tree-like patterns of electrical discharge-figures are connected, although they are vastly different in place, origin and scale. *Their similarity of form is by no means accidental. As patterns of energy-gathering and energy-distribution, they are similar graphs generated by similar processes.*"[51] (emphasis in original)









In Kepes' text, he lays an image of fractured glass next to a dried lake bed, an image of blood vessels next to dendritic mudflats at low tide, and a cross section through fallopian tubes next to a volcanic crater to show this, at the time, surprisingly new view of the unity of nature.[52] The images also suggest deep connections, but also fundamental differences, between natural and artificial processes. (Figs. 1.11-1.14) He included some of the first images of the patterns created by computation, but at this early stage it was impossible to delve much deeper into the subject. But what was original in Kepes was the notion that the logics governing systems in nature, systems in art, and systems in design, were all connected.

By the mid-1960s systems thinking was beginning to have a deep impact on the art world and not only in the computational art previously described. A pivotal piece came in 1968, when a young art critic (and soon to be fellow at Kepes' Center for Advanced Visual Studies at MIT) Jack Burnham published a piece in *Artforum* entitled "System Esthetics" (sic), where he observed that: "We are now in transition from an object-oriented to a systems-oriented culture. Here change emanates, not from things, but from the way things are done."[53] As an example of the systems-oriented approach to art, Burnham points to another nascent art movement at the time—the land art movement. In land art, Burnham sees a model for the new approach to art where the artist develops a series of instructions or processes to reshape the environment, maintaining authorship but not total control. In land art, the idea of *process* takes precedence over end results.[54]

While LeWitt and others may have been interested in the pure formalism of systems and selling a "product", this was not the case with Burnham. As described in the quote cited at the beginning of the chapter, Burnham believed art had a responsibility to move beyond mere aesthetic concerns or the development of a commodified product and to address concerns such as "maintaining the biological livability of the Earth, producing more accurate models of social interaction," and ultimately redefining how society, technology, the environment interact with each other, especially in terms of "education, productivity, and leisure."[55] Laid out in full, Burnham's program proposes that:

> "The scope of a systems esthetic presumes that problems cannot be solved by a single technical solution, but must be attacked on a multileveled, interdisciplinary basis. Consequently, some of the more

> aware sculptors no longer think like sculptors, but they assume a span of problems more natural to architects, urban planners, civil engineers, electronic technicians, and cultural anthropologists. This is not as pretentious as some critics insisted. It is a legitimate extension of McLuhan's remark about Pop art when he said that it was an announcement that *the entire environment was ready to become a work of art*."[56] (emphasis added)

Burnham's philosophy should undoubtedly resonate very strongly with the current generation of landscape architects. Nearly fifty years after Burnham's manifesto, returning to Geuze: "The systems approach seems to be winning. The landscape architect has to become an engineer again, making cautious interventions on the basis of knowledge of the systems and cycles of nature."[57] In some ways, parts of the world are in a much better state since Burnham's exhortation to make the environment a work of art. In the West at least, air quality has improved, rivers are cleaner, but in some ways these problems have simply been outsourced to the developing world. In addition, problems unforeseen in Burnham's day such as global warming and depopulation of the world's oceans underline the urgency to again make the environment a work of art, but perhaps on a scale not possible in 1968.

1.9. Computation and Mind – Burnham's Software Exhibition

At the same time, as noted by Geuze, too much a focus on the "systems approach" in landscape architecture risks clouding an equally important mission of both art and landscape design—"the idea that the landscape is always an expression of collective memory" operating "on the basis of a tradition in which meaning, memory, and our mythic desires are fostered."[58] This dualism or binary has been cast in many different constructs—machine vs. nature, machine vs. mind, Rationalism vs. Romanticism—but Geuze argues this does not need to be the case, citing the case of Dutch culture where the engineered landscape and the national myth are deeply intertwined. Burnham, likewise, rejected this binary, and sought to find a sort of resolution between systems thinking and the human experience in of all places, computation.

Soon after publishing his *Artforum* manifesto, Burnham, then a resident at György Kepes' Center for Advanced Visual Studies at MIT,[59] was invited to host a major exhibition at the Jewish Museum in New York, which would explore the concept of the "cybernetic," a concept which was unfamiliar to most of the art world at the time but which was already becoming passé and too undefined among computer scientists.[60] The result was a groundbreaking, highly experimental exhibition entitled *Software*.[61] Here, Burnham maintains his interest in the "conceptual and process relationships"[62] of art, but in contrast to his *Artforum* piece, in *Software* his focus was not on questions of detached authorship or leveraging systems to remake the "entire environment," nor on the aesthetics of computer generated imagery, but more on the implications of the potentially intimate relationship between human beings and computational machines. Here a few years before the advent of the personal computer, Burnham speaks of how computers reflect the inner workings of their users, and can "carry on brilliant dialogues with articulate human beings and very uninspired conversations with dull people."[63] Burnham quotes the mathematician Marvin Minsky, who asserts that machines on one level deal with "*mechanical, geometrical,* and *physical* matters" while on another deal "with things like *goals, meanings,* and *social interactions*."[64] Computer programming can be either "the most varied and creative activity one can do on salary, allowing the most initiative and variety of personal means of expression" or can be one of "the most boring and regimented experiences possible."[65] Burnham recognizes the computer as a tool which does not create new ideas, but allows its users to "telescope and edit experiences."[66]

Herein is the crux of Burnham's proposition: computer programs are value neutral, but the users of computer programs are not. While at times lauding the potentials of software, Burnham is also aware of risks. As an example, he foresaw the current ethical questions surrounding big data and digital privacy, presciently asserting that "computerized data files on individuals…[are] an extremely serious threat to human rights, and one against which there are few real protections." Burnham asks if "future generations of information systems will be used with any more sensitivity than radio and television have been up to now."[67] In the end, Burnham sees the computer in a paradoxical light: it is one of the only practical tools to address the expanding magnitude of humanity's problems—such as resource management problems in ecology, in other words to apply "system esthetics" to the project of repairing the environment, but it (along with "system esthetics") is also riddled with "ethical, political, and biological implications that are overwhelming but nevertheless critical."[68] The paradox is encapsulated here: "It appears that we cannot survive without technologies potentially just as dangerous as the dilemmas they are designed to solve."[69]

It should be noted, in closing, that Burnham's *Software* exhibition was an enormous flop. One retrospective describes how:

> "[The computer] that controlled many of the works did not function for the first month of the exhibition due to problems with, ironically enough, the software. The gerbils [in another artwork] attacked each other, a film was destroyed by its editors, and several aspects of the exhibition - including the catalog - were censored by the Board of Trustees of the museum."[70] (Fig. 1.15)

Figure 1.15: Gerbils shift blocks in the computer controlled environment of Nicholas Negroponte's *Seek,* an installation in Burnham's *Software* exhibition. In this exhibit, a computer slowly builds an idealized structure with blocks but must contend with the unpredictable rearrangements of the blocks as gerbils move through the space. The exhibit was popular, but the gerbils did not like it, and ended up attacking each other.

Courtesy The Jewish Museum, New York.

Burnham himself never hosted another exhibition, and released no major publications after the early 1970s, his later writings expressing disillusionment and taking a mystical turn into topics such as Kabbalah.[71] Perhaps a nadir was reached in 1974 when he expressed that "systems theory may be another attempt by science to resist the emotional pain and ambiguity that remain an unavoidable aspect of life."[72] Despite his apparent retreat from the developing discourse around systems thinking, computation, and cybernetics, his ideas are again coming to the forefront of discourse in many disciplines as many of the technical limitations which made his *Software* exhibition a failure in the first place have largely disappeared, and as other parts of his prophetic vision are being uncannily fulfilled. In a retrospective of Burnham's work, Shanken asserts in closing that "the problem now confronting artists and curators involved with technology is not so much getting the machines and software to work, but living up to the conceptual richness of the house that [Burnham] built."[73]

1.10. Systems Thinking – Promise and Peril

The narratives associated with György Kepes and Jack Burnham are instructive for those interested in computational approaches to landscape architecture. Kepes early recognition of the correspondences of patterns across scales, and between human and natural processes, to the patterns observed in landscapes, especially when observed from above, seems to point to a natural fit between landscape and computation. Kepes expects the viewer, however, to make the connections between the two sets of images intuitively, and does not delve much deeper than that. Kepes' lack of rigor in decoding the patterns can be forgiven in 1956, but unfortunately, more than

60 years later, bombarding the reader with seductive imagery and hoping a light bulb will go off still seems to be a common approach in many texts in the discipline. Burnham's story also points in a similar direction. His embrace of systems theory as a model for making the environment the subject of a redemptive art project, his links to process based art and the emerging land art movement, along with his initial enthusiasm for cybernetic hybrids reflects much of the most optimistic aspects of contemporary landscape architectural discourse. Burnham dove deep into the nuts and bolts of computation, and walked away from the experiment disillusioned, not just with systems theory, but with the whole rationalist-positivist approach to design. This pattern of initial optimism and stages of defeat is common to all advances into new territory, especially in the world of computation. There are however, stories of success of adapting a systems approach and computation to design problems.

1.11. Initial Successes of Computational Approaches in Landscape Architecture: Geodesign

A recent text on digital techniques in landscape architecture by Jillian Walliss and Heike Rahmann begins with a well-known story to many in the discipline. At the same time Burnham was working on his *Software* exhibition at MIT, a Master of Landscape Architecture student at Harvard GSD was also working with systems thinking at the school's laboratory for Computer Graphics and Spatial Analysis. After finishing his MLA degree, Jack Dangermond who was a student assistant in the lab took some of the ideas which were developed at Harvard to found the company Environmental Systems Research Institute, the world's largest developer of GIS (Geographic Information Systems) software, a company whose annual revenue today exceeds $1.1 Billion. The development of his systemic, computational approach to evaluating the landscape and making land-use decisions has earned him a net worth estimated to exceed $4 Billion,[74] making him undoubtedly the wealthiest landscape architecture graduate of all time.

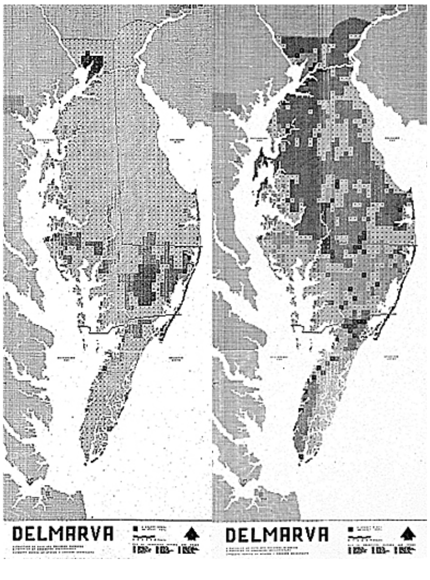
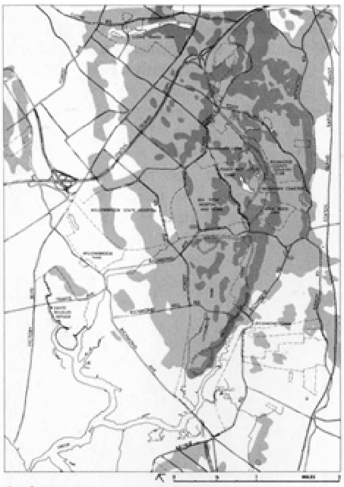


Figure 1.16: Land Use studies from the first studio project at Harvard GSD using computational methods. The methodology devised in this studio went on to form the core logic of much of GIS analysis. Courtesy Carl Steinitz.

The story of the development of GIS began around the same time that Nees began his first experiments with generative art in Stuttgart. In 1963 Chicago architect Howard Fischer applied for a grant from the Ford Foundation to develop a computer program to draw maps on a line printer.[75] The grant was awarded and work began in 1965 at Harvard University in a newly founded Laboratory for Computer Graphics and Spatial Analysis. The focus of the team quickly turned to questions of environmental planning, and in 1967 the leader of Fischer's research team, Carl Steinitz, organized in collaboration with the department of landscape architecture an early studio to map the Delmarva peninsula to create a map of land-use suitability. (Fig. 1.16) They were supported in their endeavor by soil scientist Agnus Hill and two landscape architects, Philip Lewis from the University of Wisconsin and Ian McHarg from the University of Pennsylvania. [76] McHarg was already developing a methodology for environmental assessment using transparent overlays at the time, the results of which are a core theme of his cornerstone text *Design with Nature* which was written in that same year.[77] (Fig. 1.17) In this particular case, the transparent overlays from McHarg's technique were converted into various vector and gridded data layers where they were then combined by the mapping program. From the data in these layers, suitability was then determined by a sum of weighted factors attached to each layer.[78] The computational method developed by the team at the Harvard lab in 1967 informed the core logic of GIS, commercialized by Steinitz's student Dangermond. This informed the emergence of a new discipline at the intersection between urban, environmental, and regional planning as well as landscape architecture, later described by Steinitz as "Geodesign."[79] It is here that a clear alignment is seen between systems thinking, McHarg's task of designing with nature, and computational approaches. One might also say Fischer and Steinitz' project also points towards Burnham's ambition to make the whole environment a "work of art." This is where the narrative gets a little cloudy, however—with the term art—and perhaps lies at the root of why integrating computation and systems thinking into the discipline, despite successes, meets with sustained resistance.

Ultimately, the GIS-based approach to design uses algorithms and computation primarily as a heuristic, decision-making device, but says little about form or design expression. Few would doubt here that the methodology proposed by McHarg in *Design with Nature* or in Steinitz' writings is "design;" Steinitz himself offers the definition proposed by Herbert Simon: "Everyone designs who devises courses of action aimed at changing existing situations into preferred ones."[80] GIS is certainly a valuable tool in helping make decisions about the future of the landscape. The success of GIS in changing working methods in a broad spectrum of disciplines outside or on the periphery of landscape architecture is also well-known. Despite the early and clear success of GIS and widespread adoption in universities and practices in the 1980s and 1990s, however, the profession seems to have distanced itself from the tool in recent years,[81] and the recent rebranding of the approach by ESRI and Steinitz as a new discipline—Geodesign, not landscape architecture—suggests a deeper schism. Walliss and Rahmann suggest this has to do with the overemphasis with the tool on "scientific positivist methodologies"[82] where a rational analysis in computational space is supposed to point to a best approach. This hearkens back to Mohr's assertion that the "*wertfreie* procedures" of algorithmic design would yield results that "have to be rigorously accepted as final answers." Steinitz would reject this characterization, emphasizing in the end the importance of (subjective) decision makers and professional judgement at each step of the way.[83] But the emphasis of design in Steinitz' paradigm—the intelligence—is on creating the method, establishing and weighing the parameters, identifying the strategies, but once established, effectively (mindlessly) executing the rules. This, to take Steinitz slightly out of context: "works best when there is a substantial component of anonymity and a low personal involvement" in the design expressions, which shouldn't be seen as "a test of the [designer's] skill or intelligence."[84] This reduction of what many traditionally have seen as the most important and rewarding part of the design process to a task which can be mindlessly executed flies in the face of a profession which sees design as "requiring 'human creativity' and 'human spontaneity.'"[85] Another reason for the schism may be more related to the scale at which projects are conceived and designed and as GIS works mostly with large datasets at low resolutions, GIS often cannot be used to apply an algorithmic approach to site level landscape architecture, "for whom productive dynamic modeling needs to make use of finer scales and simple, entirely local rules."[86]



SLOPE

SURFACE DRAINAGE

SOIL DRANAGE

Figure 1.17: Slope, Surface Drainage, and Soil Drainage Analyses from Ian McHarg's *Design with Nature.*

1.12. Can the algorithmic approach to landscape architecture do more?

The question of the relationship between computation and creativity lies at the heart of contemporary practice and of this research. In general, very few practices have completely resisted the incorporation of digital methods into their practices, but it is still seen by many as either a necessary evil or "simply a tool" to improve workflow. This attitude was conveyed by George Hargreaves, an early adopter of digital tools in the 1990s, who in his forward to Nadia Amoroso's 2012 *Digital Landscape Architecture Now* describes the computer's potential almost solely in terms of a 1:1 transfer of analog

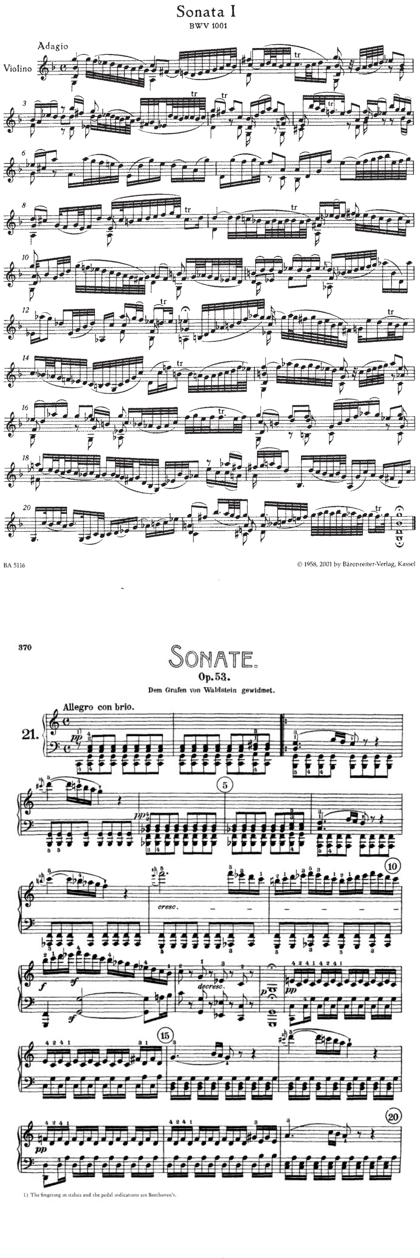


Figure 1.19: Bach‘s Sonata I for violin and Beethoven‘s Waldstein Sonata for piano. An analogy can be made between analog and digital techniques when considering the potentials of the two instruments (§1.12)

methods to a digital environment, especially focusing on topics such as computer visualization, concluding "that digital tools will never ultimately do the designing for us."[87] Others in the profession fear that digital tools are eroding creativity, a key thesis of Marc Treib's *Drawing/Thinking: Confronting an Electronic Age,* who at his most generous offers that the computer at least gives the "untutored and underrepresented … access to graphic capabilities never before achievable."[88] His premise should not be dismissed too quickly, even by boosters of digital methods. There is a considerable amount of evidence that in certain contexts, computer drawing versus hand drawing *does* hamper creativity. Bryan Lawson explored this notion in a 2002 essay "CAD and Creativity," citing numerous examples of student work with a high level of mastery of computer graphic techniques, but poor design expression, and concludes that "CAD is by no means a neutral tool. Like all tools, it suggests being used in a certain way. This threatens to set an agenda for architecture that is unhealthy and irrelevant."[89]

The purpose of this research is not to settle this debate, but to offer the proposition that it is not the tool itself that impedes creativity, but how it is being used. When analog methods are translated 1:1 into a digital environment solely to increase productivity, this danger is especially acute. Instead, the instrument needs to be looked at in a new way to unlock its potentials. Consider a parallel analogy in the field of music and two instruments, the violin and the piano. The violin is an analog instrument and can conceivably play an infinite number of notes, but only one note at a time. Producing sound with the bow and the string in a pleasing way takes years of practice. The piano, by contrast, is a digital machine. In contrast to the violin, the piano can only produce 88 notes. Anyone untutored in piano playing can hit a key and can produce a note with consistent sound quality. With a few days of practice, a piano player can play the same notes in a piece written for violin that the violinist was only able to play after years of toil. Most people, however, would prefer to hear the violin version of this piece, and rightly so. The full range of expression of the piece is only possible with the violin, where it can subtly play notes slightly higher or lower than those written in the score, and can fluidly move up and down the scale. The piano version of the piece (which is playable) is only a crude abstraction of the violin version. The piano, however, allows something that the violin does not: it allows the musician to play multiple notes at a time, in theory up to ten with the fingers while hundreds more can be sounding simultaneously with the sustain pedal, producing rich musical layers and harmonies. In a classical orchestra score, the single musician at the piano is often on par with the rest of the orchestra combined. But to achieve this level of proficiency with the piano, a virtuoso level, takes just as much effort as that invested by a dedicated violinist, and neither can be accused of being more or less creative or talented than the other. (Fig. 1.19) Returning to the argument of analog vs. digital design methods, what is all too common in current practice is that we are still, so to speak, trying to play violin scores on the piano, and as a result the conversation risks being, to borrow Burnham's phraseology, one of "the most boring and regimented experiences possible" rather than a creative activity "allowing the most initiative and variety of personal means of expression." If the creative potential of the computer hinted at by Burnham and others is achieved, it will have enormous implications for the practice of design of the landscapes of the future.

1.13. Authorship and Instrumentality

As referenced earlier in the discussion on instructional art, the working method which currently dominates architectural and landscape architectural practice in much of the developed world, and which makes a clear distinction between the act of designing and the act of building, is neither universal nor especially ancient. Mario Carpo explores this theme in *The Alphabet and the Algorithm* before speculating on the implications of the change of instrumentality on notions of authorship in design. In contrast to architectural production in antiquity through the middle ages, where the architect was intimately involved in the process of building, and where skilled craftsman tended to follow established patterns and practices passed on from generation to generation, since the time of Leon Battisti Alberti, the object of architectural design has switched from designing and constructing the building to designing the set of drawings and models which would then be used by others to construct the building. (Fig. 1.19) This shift occurred for several reasons—one was to elevate the architect above the "toilsome business" of construction and hence elevate his social standing —but more practically this was an innovation only allowed by the spread of a new technology, the production of inexpensive paper.[90] This change in the instrumentality, however, changes the way the designer thinks about design and the way it is constructed. Alberti advocates that the builders must execute the instructions conceived by the architect without any variation or hesitation, and that the architect should even avoid visiting the site.[91] Ironically, however, this detachment from the actual process of building is what allows the architect, at least in Alberti's eyes, to claim "authorship" of the building—up until then unprecedented.[92] The building is the product of the architect's sole intellectual genius, not the mindless laborers toiling on the work of construction, in contrast to earlier buildings, which were the product of collective effort and intellect, and whose author or architect remains nameless in history books.

Carpo foresees another shift in methods of practice and notions of authorship with the adoption of digital and more specifically algorithmic methods in practice. Specifically, he claims that two forms of authorship seem to be emerging; the first is the designer of what Carpo calls the *objectile*, a term borrowed from Deleuze, which in Carpo's definition is "the program or series of generative notation" while the second level of authorship is of the end product itself.[93] Carpo compares the first type of authorship to the programmer of a video game, and the second type of authorship to the player of that game, who creates a unique narrative, but always within the rules that the first author has set. Authors (designers) who focus on the design of objects, then, are little better than video game players, playing in a sandbox designed by someone else.[94] Carpo concludes that:

> "Soon designers will have to choose. They may design objects, and then be digital interactors. Or they may design *objectiles*, and then be digital authors. The latter choice is more arduous by far, but its rewards are greater."[95]

Carpo's statement is both provocative and interesting, but needs to be read with a note of caution, especially in the specific context of landscape architectural design. The focus on the design of generic instructions without accounting for the *matter* and *substance* of the design problem is troubling, as complex layers of instructions or codes are often latent in the problem itself and the generic system needs to be wholly rewritten or recoded when the context is changed. But Carpo also recognizes that such an approach may ultimately allow for more democratic authorship and design practice, where "open-endedness, variability, interactivity, and participation" are all allowed into the process.[96] All of this can only happen when designers confront the computer, not as Marc Treib would advocate, by severely limiting its scope

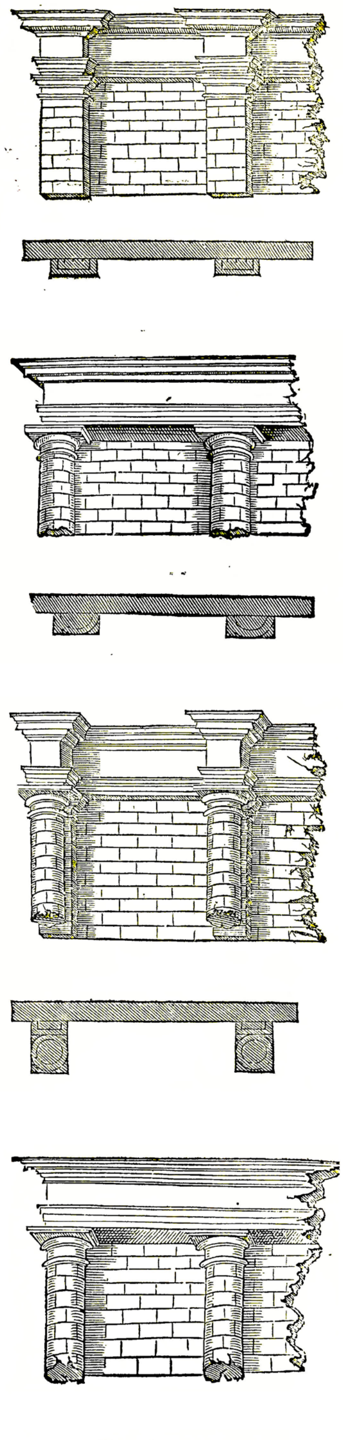


Figure 1.19: Drawings from F. Franceschi‘s 1565 Italian translation of Leon Battista Alberti‘s *De re aedificatoria.* Contemporary readings of Alberti‘s work see the precursors of algorithmic architecture and architectural shape grammars in his instructions.

to production tasks and keeping it out of design, but by learning to play the new instrument on its own terms and in its own language—*algorithmically*.

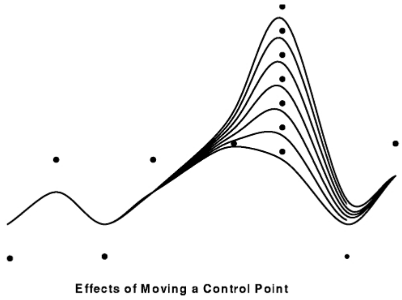


Figure 1.20: Effects of moving a control point on a NURBS curve. Here all points are fixed except for point 6 of 8, which is moved slowly up in the Y direction.

1.14. Algorithmic Design and related terms

This research discusses computational approaches to landscape architectural design favoring the term *algorithmic design* over several other terms which might be regarded as synonymous or generally equivalent in design literature and practice. A few of the most common include *computational design, parametric design, generative design, procedural design*, *relational design*, alongside algorithmic design. Also frequently encountered in the discourse are the verbs *coding, scripting*, and less frequently in the design disciplines *programming*. To some degree many of these terms can be considered interchangeable, but algorithmic design is favored in this text for several reasons.

Of the previously listed terms, one of the most widely used has been parametric design and it is still frequently used in the context of computational design approaches. This term was favored, for example, in Walliss and Rahman's text. Among many who work with computational approaches, however, the term is being seen as increasingly problematic. This may be partly because of negative associations with some of the worst expressions of computational design, with the belief that changing a single parameter creates something new and interesting. Quoting Kwinter: "Deadheads, cooing 'wow' as the 395th glorious variant of the same digital meatball renders out in four splendid dimensions."[97] The term parametric design has also since 2008 has become increasingly associated with a particular style of design, partly in response to Patrick Schumacher's controversial piece "Parametricism as Style - Parametricist Manifesto." The piece makes the controversial argument that "Parametricism is the great new style after modernism. Postmodernism and Deconstructivism have been transitional episodes that ushered in this new, long wave of research and innovation."[98] The essay makes several salient points, and will be referred to again later in this text, but it also moves very quickly into defining "strictures" or dogmatic rules without adequately defining a why:

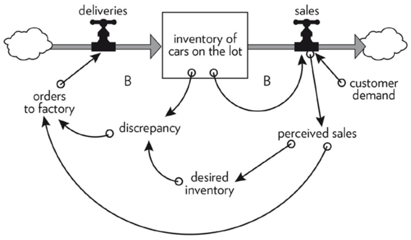


Figure 1.21: Systems diagram from Donella Meadows' *Thinking in Systems.* Courtesy Academy for Change, Chelsea Green Publishing.

> "Negative heuristics: avoid familiar typologies, avoid platonic/hermetic objects, avoid clear-cut zones/territories, avoid repetition, avoid straight lines, avoid right angles, avoid corners, …, and most importantly: do not add or subtract without elaborate interarticulations.
> Positive heuristics: interarticulate, hybridize, morph, deterritorialize, deform, iterate, use splines, NURBS, generative components, script rather than model, …"[99]

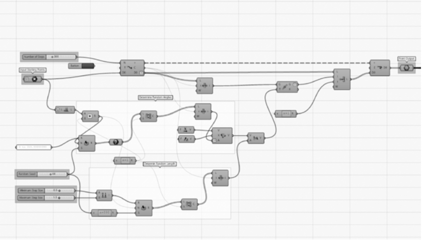
Of course, this was intended to be a brief manifesto, and Schumacher's other writings deal more fully into the why, but a focus on the heuristics, pursuing a NURBS form (Fig. 1.20) for the mere sake of pursuing a NURBS form, is problematic at best.

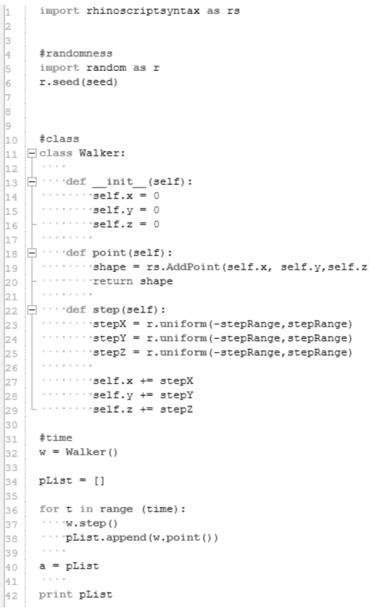
Style and taste aside, perhaps the most important reason why this thesis avoids the term parametric design is that it places the focus of the computational approach on perhaps the least consequential part of the overall system, where, according to the systems theorist Donella Meadows, changing the values of the parameters of a system is often the least effective method of intervention, and that if meaningful or effective change is wanted, the focus should be on modifying other aspects of a system, such as its goals, rules, constraints, feedback loops, types of inputs, or flows.[100] In some cases, modifying the values of parameters may yield interesting or surprising results, but this is still just one part of many aspects which need to be considered in the design of systems. (Fig. 1.21)

Another term frequently encountered is *generative design* and this term was incorporated into the title for the author's Internet catalog of studies of simple algorithmic patterns, *Generative Landscapes*. In contrast to parametric design, where the focus is put on the manipulation of the input parameters, in generative design the focus is on the internal mechanisms of computation, with the goal being to "program the computer so that it produces 'aesthetic objects' without any additional input from the [user]."[101] The first use of "generative" in the context of computation can be traced back to the earliest experiments with computer graphics, and was promoted by Max Bense, the mentor of George Nees, as a subset of his larger "information aesthetic".[102] As generative art corresponded very closely to the pure formalisms of minimalist art, freed from subjective bias, the term seems to be used more in relation to art than to design. Regardless, the term is also avoided later in this text since it seems to suffer from a similar problem to "parametric," placing the focus on the internal machinations of computation while minimizing the potential of algorithms to relate to external inputs from users or the environment.

The term computational design avoids to some degree the biases associated with parametric or generative design, and was the term favored by Menges' and Ahlquist's 2011 compilation *Computational Design Thinking*. In many ways, this is an umbrella term which can encompass many computational approaches, but it appears too broad, especially for non-experts. A casual reader might assume that using Photoshop, AutoCAD, or a 3D modelling program, since they are on a computer, are examples of computational design. One can effectively use these programs, however, without any regard to computational design *thinking*, which is a more specific approach. Among others who have made a similar observation, Kostas in his introduction to *Algorithmic Architecture* is careful to make the distinction between what he terms "computation" and "computerization," computation being "the procedure of calculating, i.e. determining something by mathematical or logical methods, computerization is the act of entering, processing, or storing information in a computer."[103] Furthermore, it is also increasingly possible, through the use of tools such as Bentley's Generative Components, McNeel's Grasshopper, Autodesk's Dynamo, or Vectorworks' Mariotte, to engage in computational design without getting into the nuts and bolts of computer coding or scripting. (Fig. 1.22) While designers can accomplish a lot through the use of these visual algorithm editors—use of Grasshopper, for example, is essential to much of the work presented in later chapters of this research—eventually users of these tools will probably hit a wall which can only be overcome by making a jump to a more traditional scripting or coding language. (Fig. 1.23) In the interest of narrowing the scope of the research, but also to focus on the importance of scripting or coding, algorithmic design is generally favored in this text instead.

Is algorithmic design not simply computer programming? In some senses, yes, as a computer program is essentially an elaborate algorithm. The word "programming," however, is used judiciously in this text for two reasons. First, in the context of the design disciplines, the term programming already has a specialized meaning, referring to the allocation of various types of uses in space. The second reason is that in computation, programming is an involved task requiring specialized training, with a much broader set of tasks than might be needed in the context of the spatial design disciplines. Questions of user interfaces, conservation of limited computational resources, interoperability, etc. have to be considered, and even when these issues are addressed, an extensive phase of debugging must be undertaken to





```
import rhinoscriptsyntax as rs


#randomness
import random as r
r.seed(seed)




#class
class Walker:
    
    def __init__(self):
        self.x = 0
        self.y = 0
        self.z = 0
        
    def point(self):
        shape = rs.AddPoint(self.x, self.y,self.z)
        return shape
        
    def step(self):
        stepX = r.uniform(-stepRange,stepRange)
        stepY = r.uniform(-stepRange,stepRange)
        stepZ = r.uniform(-stepRange,stepRange)
        
        self.x += stepX
        self.y += stepY
        self.z += stepZ

#time
w = Walker()

pList = []

for t in range (time):
    w.step()
    pList.append(w.point())
    
a = pList
    
print pList
```

Figure 1.22 and 1.23: A simple algorithmic process for a random walk, see chapter 7)

Figure 1.22 *(top)* shows a version developed with Grasshopper, a visual algorithm editior,.

Figure 1.23 *(bottom)* shows the same algorithm coded with Python scripting, a high-level programming language Both algorithms produce similar results.

The relations between functions are often more easily understood by beginners using a visual algorithm editor, but algorithms written in more traditional programming languages are both more flexible and computationally more efficient.

ensure the program works with every conceivable user scenario. As proposed by Burnham earlier in this chapter, the focus of the designer should be on tapping the creative potential of the computer while avoiding the danger of getting trapped in the rote aspects of coding. This creativity, however, must be critically engaged. Kwinter cautions that "no computer on earth can match the processing power of even the simplest natural system" and that the real challenge of computational design is the difficult and challenging task of "learning how to make a simple organization (the computer) model what is intrinsic about a more complex, infinitely entailed organization."[104] The rewards for this endeavor, however, can be extremely great, and "offers the possibility of apprehending developmental patterns of extraordinary and unprecedented depth and abstraction, offering tantalizing glimpses of the very free-form structure of time itself (chaos, complexity, self-organization)."[105]

1.15. Summary Conclusion

This chapter has introduced algorithms as deterministic recipes, procedures, or programs usually executed for reasons of efficiency by the computer. Although the tasks they complete can seem highly complex and can generate surprising results, at a fundamental level they are very simple and follow only a few basic operations, which will be further described in Chapter 6. Despite this simplicity, however, algorithms are useful for describing the structure, processes, and patterns of many natural and artificial complex systems, partly because nature also operates based on simple, "mindless" rules of interaction between the fundamental particles which make up all of reality. As such, both scientists and artists are increasingly adopting algorithms as tools to understand nature and complex human systems, and increasingly to intervene in these systems.

Algorithmic design has become established in many disciplines, and is increasingly having an impact on landscape architectural design. Early algorithmic approaches were integrated into the discipline of landscape architecture at large, planning scales with the advent of GIS, but algorithmic methods have been much more slowly adopted the scale of individual design projects. Issues surrounding a perceived erosion of creativity and loss of individual authorship need to be addressed before gaining widespread acceptance. A productive way forward is to view algorithmic methods as not a replacement for analog methods, but as an extension of the repertoire of tools available to the designer, and which fills gaps not well addressed by traditional methods. To paraphrase Jack Burnham, algorithmic design can be a mundane and repetitive task in certain hands, but can also be one of the most creative tasks one can do on a salary. To explore the avenues for the creative manipulation of space in landscape architecture at smaller and intermediate scales, however, it is important to more precisely define these terms. This is the task of the following chapter.

Endnotes

1 Jack Burnham, “System Esthetics,” *Artforum* (September, 1968), 31.

2 Donald Knuth, *The Art of Computer Programming, Vol 1: Fundamental Algorithms,* 3rd ed. (Bonn: Addison Wesley Longman, 1997), 4.

3 David Berlinski, *The Advent of the Algorithm: The 300-Year Journey from an Idea to the Computer* (London: Harcourt, 2000), xviii.

4 Harold Stone, *Introduction to Computer Organization and Data Structures* (New York: McGraw-Hill, 1975), 5.

5 Knuth, 5-6.

6 Stephen Cole Kleene, *Mathematical Logic* (Mineoloa, New York: Dover Publications, 1967), 231.

7 Marvin Minsky, *Computation: Finite and Infinite Machines* (Englewood Cliffs, NJ: Prentice Hall, 1967).

8 Kleene, 223.

9 Daniel Dennett, *Darwin’s Dangerous Idea: Evolution and the Meanings of Life* (London: Penguin, 1995), 51.

10 Loosely translates as “Al-Kwarizmi’s text on the Indian number system.”

11 Knuth, 1-2.

12 Recursion, as it is such a powerful concept in computation, is discussed in more detail in §6.6 and §6.7. Generally, it involves performing a series of repetitive operations in sequence and in the exact same manner, but with the initial quantity being varied at each step and with successive steps, the operation being performed on the successor and not the initial values. These repetitive operations on successor values are familiar to grade school students performing operations such as long division.

13 Martin Davis, *The Universal Computer: The Road from Leibniz to Turing* (London: CRC Press, 2012), 3-20.

14 David Hilbert and W. Ackermann, *Grundzüge der theoretischen Logik, 2. Auflage* (Springer: Berlin, 1938), 90-99.

15 Alan Turing, “On Computable Numbers, with an Application to the Entscheidungsproblem.” *Proceedings of the London Mathematical Society* 42, no. 2 (1937): 259.

16 Kurt Gödel, “Über formal unentscheidbare Sätze der ‘Principia Mathematica‘ und verwandter Systeme I,” *Monatshefte für Mathematik und Physik* 38 (1931): 173 – 174. Author’s translation.

17 Andreas Blass and Yuri Gurevich, “Algorithms: A Quest for Absolute Definitions,” *Bulletin of European Association for Theoretical Computer Science* 81 (2003): 5.

18 *Ibid.*

19 Douglas Hofstadter, *Gödel, Escher, Bach: An Eternal Golden Braid.* (New York: Basic Books, 1999), 49-51.

20 as quoted in Blass and Gurevich, 6.

21 Blass and Gurevich, 7.

22 *Ibid*, 8.

23 *Ibid.*

24 Dennett, 48, 50.

25 *Ibid*, 51.

26 *Ibid*, 59.

27 Melanie Mitchell, *Complexity: A Guided Tour* (New York: Oxford University Press, 2009), xiii.

28 Blass and Gurevich, 6.

29 Christoph Klütsch, *Computer Grafik: Ästhetische Experimente zwischen zwei Kulturen, Die Anfänge der Computerkunst in den 1960er Jahren* (Vienna: Springer, 2007), 19.

30 *Ibid*, 116.

31 Bernhard Serexhe, curator, “Georg Nees: The Great Tempattion – Early Generative Computer Graphics,” Exhibition ZKM 19.08.2006 – 15.10.2006., http://zkm.de/en/event/2006/08/georg-nees-the-great-temptation, (accessed 14 Jul 2017).

32 Georg Nees, *Generative Computergraphik* (Berlin: Siemens Aktiengesllschaft, 1969), 25.

33 As quoted in Klütsch, 124.

34 *Ibid.*

35 image from Klütsch, 145.

36 *Ibid*, 165-166. The same Mondrian image is also referenced at the beginning of Stan Allen’s text “From Object to Field.”

37 As quoted in Klütsch, 190-191.

38 Klütsch, 107.

39 Frieder Nake, *Ästhetik als Informationsverarbeitung* (Vienna: Springer, 1974), 5.

40 Sol Lewitt, *Work from Instructions.* 1971, Nova Scotia College of Art and Design, https://www.sollewittprints.org/lewitt-raisonne-1971-18. (accessed 29 Mar 2018)

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42 Simon Blackburn, *Oxford Dictionary of Philosophy*, second edition revised. (Oxford: Oxford University Press, 2008).

43 Adriaan Gueze, “Landscape as Construct, Engineering as Memory,” in *Thinking the Contemporary Landscape.* Christophe Girot and Dora Imhof, eds. (New York: Princeton Architectural Press, 2017), 260.

44 Karen M’Closkey and Keith VanDerSys, *Dynamic Patterns: Visualizing Landscapes in a Digital Age* (London: Routledge, 2017).

45 György Kepes, *The New Landscape of art and science* (Chicago: Paul Theobald and Co., 1956), 205.

46 Gregory Bateson. *Steps to an Ecology of Mind*, paperback ed. (New York, Ballantine Books, 1972), xxxii.

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48 Kepes, 19.

49 Kepes, 23. Here Kepes cites W. Jaeger’s Paideia XX, who claims

Greek philosophy was fundamentally concerned with seeing "the *idea* in everything namely visible pattern."

50 *Ibid*, 226.

51 *Ibid*, 260.

52 *Ibid*, 262, 263, 267, 269, 270.

53 Jack Burnham, "System Esthetics," *Artforum* (September, 1968), 31.

54 *Ibid*, 32.

55 Burnham, "System Esthetics," 31.

56 *Ibid*, 34.

57 Adriann Gueze, "Landscape as a Construct, Engineering as a Memory," trans. Michael O'Loughlin in *Thinking the Contemporary Landscape,* ed. Christophe Girot and Dora Imhof (New York: Princeton Architectural Press, 2017), 261.

58 *Ibid.*

59 *Ibid*, xvii

60 Jack Burnham, *Software: Information technology: its new meaning for art,* exhibition catalogue (New York: The Jewish Museum, 1970), 11.

61 Hans Haacke points out in the retrospective of Burnham's writings the fact that the word "Software" was not in common use outside of computation, and was never encountered in an art context. Foreword, *Dissolve into Comprehension: Writings and Interviews 1964-2004 by Jack Burnham,* ed. Melissa Ragain. (Cambridge, MA: The MIT Press, 2015), x.

62 Burnham, *Software*, 12.

63 *Ibid*, 12.

64 *Ibid*, 11.

65 *Ibid*, 14.

66 *Ibid*, 14.

67 *Ibid.*

68 *Ibid.*

69 *Ibid.*

70 Edward A. Shanken, "The House that Jack Built: Jack Burnham's Concept of Software as a Metaphor for Art", *Leonardo Electronic Almanac* 6:10 (Nov 1998) www.artexetra.com/House.pdf, (accessed 7 Jul 2017).

71 Melissa Ragain, Introduction, *Dissolve into Comprehension: Writings and Interviews 1964-2004 by Jack Burnham,* ed. Melissa Ragain. (Cambridge, MA: The MIT Press, 2015), x.
xxi-xxvii

72 as quoted in Ragain, xxvii.

73 Shanken, 3.

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80 As quoted in Steinitz, 3.

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82 *Ibid.*

83 Steinitz, 148.

84 *Ibid*, 116.

85 ASLA 2013 survey, referenced in Walliss and Rahmann, xix.

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91 *Ibid*, 21.

92 *Ibid*, 22.

93 *Ibid,* 126.

94 *Ibid.*

95 *Ibid.*

96 *Ibid.*

97 Sanford Kwinter, "Playboys of the Western World," in *Far from Equilibrium: Essays on Technology and Design Culture*, ed. Cynthia Davidson (Barcelona: Actar, 2008), 30.

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99 *Ibid.*

100 Donella Meadows, *Thinking in Systems* (London: Sustainability Institute, 2008), 194.

101 Klütsch, 17.

102 Nees, 23.

103 Kostas Terzidis, *Algorithmic Architecture* (Amsterdam: Elsevier, 2006), xii.

104 Sanford Kwinter, "The Cruelty of Numbers." in *Far from Equilibrium: Essays on Technology and Design Culture*, ed. Cynthia Davidson (Barcelona: Actar, 2008), *97.*

105 *Ibid.*

Chapter 02 – Contextualizing Landscape Architecture for Algorithmic Design

"Landscape appears as production more evidently than it has in the past. Whereas the pictorial gaze, which has long dominated the cultural understanding of landscape, suggested ideas of stability and permanence, digital tools accentuated the dynamic and instable fields and forces that shape the earth and constrain human interventions on its geography." – Antoine Picon[1]

2.1. Introduction

Nees' dissertation *Generative Computergraphik* begins with a question posed by Nake: "'*Kann ein Computer Kunst erzeugen?' Und er fährt fort: 'Immer noch wird oft übersehen, daß diese Frage überhaupt erst gestellt werden kann, wenn eine Definition von 'Kunst' vorliegt. Es scheint nun keine Schwierigkeit zu sein, 'Kunst' einmal so zu definieren, daß die Frage mit ‚ja' beantwortet wird, ein anderes Mal mit ‚nein*'."[2] A similar question could be posed: Can a computer create landscape architecture? This can only be answered once an adequate definition of landscape architecture is provided. As hinted at by Nees and Nake, the definition itself reveals a certain bias towards a certain answer, and in this case, it *is* important to create a definition that fits with the larger structure of this thesis. The temptation to define landscape architecture in terms that will provide a preferred 'yes' or 'no' answer, however, will be avoided.

Figure 2.0: (*page opposite*) Foreign Office Architects' *S-E Coastal Park* represents an early computationally designed landscape. Despite early praise, the project has fallen into a state of disrepair and neglect. Here formal exploration is prioriitzed over integrating the project into the relational context of Barcelona's urban metabolism.

There are about as many varying definitions of the scope of landscape architecture as there are texts about landscape architecture. This section does not pretend to provide a definitive definition of the scope of the discipline, nor to circumscribe the profession with hard or fixed boundaries. Part of the challenge of the profession, but a source of attraction for many, is that what constitutes a landscape architectural work *can* be so broadly defined, and the scope of the discipline may be determined by things such as a designer's personal philosophy, background, and talents, or even by his or her cultural context. In developing a definition, this text assumes a very close affinity to architecture itself. This may reflect the bias of the author's own personal professional development, but it should be noted that in many cultural contexts, almost no distinction is drawn between the two professions, and even in cultures with a strong tradition of landscape architecture, architects are often the designers of projects which fall under the core competency of landscape architects (e.g. Tschumi, Park de la Vilette, Eisenmann, *Denkmal für die ermordeten Juden Europas,* Koolhaas/Mau, Downsview Park). As such, at times in this research arguments which apply equally to architecture as well as landscape architecture may become conflated, but eventually distinctions will be drawn between the two disciplines, mainly to elucidate the special opportunities and challenges which exist in applying algorithmic approaches to the design of landscapes vs. the design of buildings. The definition will also deal with three words—*form*, *information*, and *performance*. The readings of these three words will be developed over the course of the next few paragraphs and later over the course of the theoretical chapters, but as starting point, form will be associated with the concept of formal systems and generative rules, information with the notions of semantic context and meaning, while performance will be cursorily defined as the congruence between form and information. These three words will also contribute over the course of Part I of this thesis to forming a conceptual framework for the algorithmic manipulation of space.

2.2. Landscape Architecture—Constructions, Projects, Terrains

In the context of this research, a starting point for defining what is a work of landscape architecture is offered by the architecture critic David Leatherbarrow, who identifies landscape architecture with *constructed projects*. Furthermore the constructed project needs to be built *somewhere*—somewhere being a site which exists outside of the project, with *dynamic forces* and *interactions*, which Leatherbarrow identifies as the *terrain.*[3] All of these terms—constructed, project, terrain—are open to interpretation and nuances of meaning which could expand or contract the ultimate definition of the scope of landscape architecture. For example, with the term “constructed” the first image to come to mind might be of bulldozers and workers with hardhats. But landscapes can also be “constructed” by grandmothers weeding their gardens, by non-human agents such as animals or plants, or even, or especially by non-living geological forces. The term project implies intentionality and planning. A strict definition of a project would require a client with a program and budgets, but this definition might unfairly exclude theoretical explorations of “paper architecture”, or rightly exclude the intentionality and planning of a spider building her webs, or a beaver building his dam. Lastly, *somewhere* could be interpreted as being anywhere on the oft-used philosophical construct of “any possible world” or it could be, as suggested by the word “terrain” be limited to earth. To avoid getting into the realm of the absurd, the three concepts of *constructed*, *project*, and *terrain* are here taken to be concepts which are open to logical scrutiny, description, or analysis—a distinction which will be clarified shortly.

Defining landscape architecture in light of the terms *constructed*, *project*, and *terrain*—here in a reasonable, though not necessarily limiting way—what then would such a definition exclude? First, landscapes which exist purely in the digital realm, specifically procedurally generated landscapes[4] lacking a deep semantic context, would be excluded. (Fig. 2.1) These landscapes, while containing numerous ingenious rules for landscape construction, generally lack the specific setting—the somewhere of the terrain, with its dynamic forces and interactions—to qualify as works of landscape architecture. This is not to say that the rules of construction for procedural landscapes cannot be applied to landscape architecture in the “real” world—that is in fact, to put it succinctly, the key idea of this thesis—that algorithmic (procedural) rules of formation *can* be productively applied to landscape architectural projects. In many cases, the procedural algorithms used to create representations of natural landscapes can create images nearly indistinguishable from photographs of pristine natural landscapes in the real world, partly because of the algorithmic, rule based *nature* of much of reality. (Fig. 2.1, *middle*) Not only the natural world, but much of human endeavor also lends itself to description with procedural generation techniques. An engine for generating procedural cities complete with procedural buildings, for example, was developed as part of a doctoral thesis at ETH-Zurich and later integrated commercially into ESRIs “City Engine” in order to test future scenarios for urban environments.[5] (Fig. 2.1, *bottom*) As powerful as the *formal* rules in such virtual environments can be, however, they lack the rich palimpsest of history, the non-linear series of chance interactions and feedback loops which accumulate new forms of *information* over time to create the semantic context which give the rules of formation their inherent *meaning*. In a procedural engine, a user can simply change one random number, and a completely different reality appears while the old disappears. This is not the case with real landscapes, where the designer must confront the accumulated accretions of history. Also, artworks lacking a specific context or place would also be excluded from this definition. Most artwork *does* respond to a complex socio-cultural semantic context, but the physical space of the artwork does not usually inhabit this space. Here we will assume that landscape architecture must have a specific physical as well as abstract context.

On the other hand, projects which purely analyze the characteristics or qualities of a place, the work of landscape scientists and historians, geographers and anthropologists, are also generally excluded in the context of this research as being works of landscape architecture. This is not to say this gathering of *information* about the dynamics of terrain is not valuable or necessary. Girot identifies the primacy of the site, the existence *a priori* of a landscape before the existence of a landscape architect, as a key distinction between this discipline and architecture.[6] The availability of information and the technologies which make the gathering of information possible, such as mapping and surveying, can have tremendous impacts on how landscapes are altered, as demonstrated by David Blackbourn in his case study on how advances in surveying and engineering, specifically is in the way in which information is collected and made available, made possible the complete alteration of Germany's hydraulic landscape.[7] But a project which remains purely in the realm of *information* and data without a proposal for clarifying, reinforcing, challenging, or somehow altering the rules of *formation* fails Leatherbarrow's "construction" test.

Up to now this argument has identified the word "constructed" with the *formal* rules or rules of *formation* in projects, while identifying the word *information* with the specific context, or terrain, in which the project exists, reading the word project in its noun form. If the word project is read as a verb, however, the meaning changes quite a bit. A construction is *projected* onto a terrain. This does not, however, nor should it be a linear relationship. A terrain can also be *projected* onto a construction. The landscape architectural project, then, is contained in this non-linear dialogue between a system for giving form, and the information embedded in the site. The degree to which this two-way projection is successful; to which the system of forms is informed by the system of information and in turns re-forms this situation, determines whether the project *performs* well. In the mathematical formal systems, the degree to which a formal system corresponds to other mathematical objects, or to reality, reflects its *isomorphism*. A formal system which is isomorphic in turn acquires *meaning*.[8]

Figure 2.1: *Top* - Minecraft jungle biome, part of a procedurally generated block world. *Middle* - Similar rules are used to generate this scene in Terragen using procedural Xfrog trees. *Below:* Procedural rules can also generated superficially plausible cities, such as in ESRI's CityEngine.

2.3. What does Landscape Architecture add to Landscape? Hillier's Space is the machine

The previous discussion begins to move in the direction of providing a working definition of the task of landscape architecture but fails to draw a distinction between the actions of the landscape architect and that of other actors who shape the landscape, also with projects or aims that can be scrutinized. Farmers building fields, foresters chopping down rainforests, miners scooping up lignite, engineers building dikes, grandmothers planting flowers—arguably these groups collectively have a much more significant effect on the constructed form of the landscape than the work of most landscape architects. The key to understanding the added value of landscape architecture, then, must again rest in the definition of the word "project."

Landscape architects are not the only professionals who have experienced sleepless nights wrestling with their professional self-worth. Architects as well have constantly asked two similar questions in the context of their profession 1) what is the difference between architecture and building, and 2) what does architecture add to building? A productive answer to this question was proposed by Bill Hillier in his book *Space is the machine*. Hillier rejects the common notion that the added value of architecture is contained in its aesthetic or artistic value, noting that many 'buildings' are more loved than a lot of 'architecture.'[9] Hillier first identifies building with what he calls the *non-discursive* vernacular tradition associated with humanity's intuitive or instinctual need to organize space. Hillier asserts that humans are naturally configurational thinkers who intuitively sense and manipulate patterns and relations. (Fig. 2.2) As evidence of this, Hillier points to the fact that humanity has been successfully organizing settlements and constructing buildings based on cultural traditions, rules, and codes—largely unwritten or unspoken—at least for the last 300,000 years. (Fig. 2.3) Furthermore, these buildings are not only "practical and functional objects" but "prior to architecture…are already complex instances of the transmission of culture through artefacts."[10] Building, in other words, represents an emergent phenomena that fulfills biological and deeply ingrained cultural needs, and aesthetic expression is among those needs. Architecture only begins, Hillier argues, when the processes and codes associated with building are taken out of the realm of instinctual, non-discursivity, and become subject to analytical scrutiny (formalizations) and can be talked about in an appropriate language.[11] Once the relations and configurations of building are identified, the architect can then begin to manipulate these relations to establish new connections and new configurations, which in turn change the "code" which produces building. Hillier's key thesis can be summarized as: "The bringing of the non-discursive, configuration dimension of built form from cultural reproduction to reflective awareness" means that "all possibilities are open rather than simply the permutations and phenotypical innovations that are sanctioned by the vernacular."[12] Additionally, if the architect's new relations are successful and become replicated by the culture, the architectural work may be in turned subsumed back into the culture as a new series of codes and relationships.[13]

A similar relationship could be said to exist between landscape and landscape architecture. Landscape, as an analogy to building, could be defined as the set of emergent processes and codes which shape the physical world and which result in distinct configurations and patterns. Natural landscapes as well as cultural landscapes have rules of production and formation, interacting relationships and complex dynamics. Both natural and cultural landscapes can produce forms and atmospheres of great beauty without the intervention or planning of a landscape architect, but do so on a non-discursive level. The task of the landscape architect, then, is to identify and understand these configurational relationships, subject them to analysis and discursive scrutiny, and to then find new or unseen connections and potentials after which a proposal to reconfigure parts of the system can be made. Hillier exerts a note of caution in his analysis here: innovation can be productive or destructive, and architectural theories can be disastrously wrong.[14] Emergent natural or vernacular landscapes, to rephrase Hillier in the context of landscape architecture, have safeguards built into their coding—in other words they are the "fittest" survivors of a process of evolution. The work of an outside actor manipulating the code can fundamentally change the genotype of landscapes, and as can be seen in nature with large evolutionary jumps, hybrids, mutants, and monsters can either redefine the species in a positive way, or can be the first to succumb

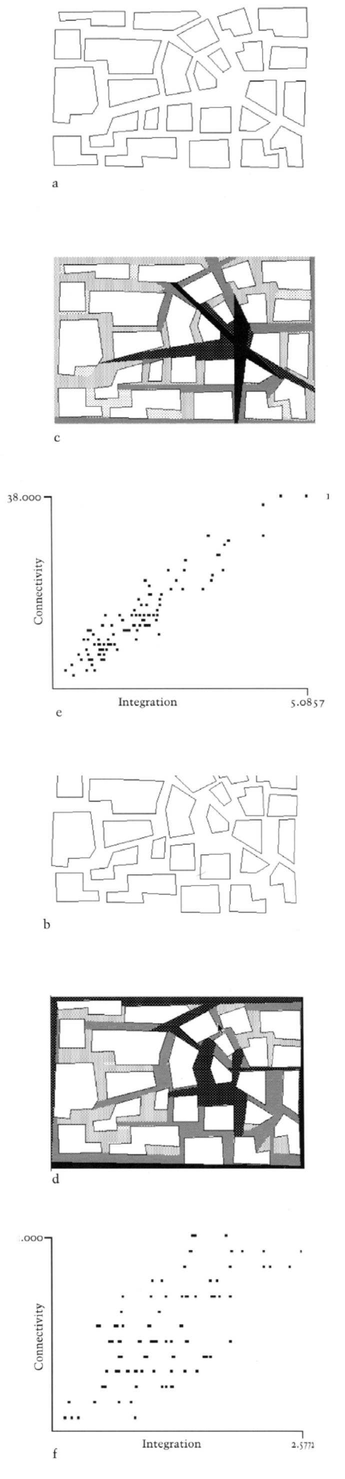


Figure 2.2: Determining the connections between spaces, i.e. their configurations, is an important part of the design task. For complex spatial configurations, computer analysis can help judge the merits of a design. With the two design configurations show above, the analysis points to to top design being more "intelligible."
From Hillier (1996) ,126.

to the pressures of nature selection, or in the worst cases, can become destructive and out of control. This is the dilemma hinted at by Deleuze and Guattari when discussing the process of destratification, a process akin to Hillier's extraction of codes. They remark that: "Every undertaking of destratification (for example, going beyond the organism, plunging into a becoming) must therefore observe concrete rules of extreme caution: a too-sudden destratification may be suicidal, or turn cancerous. In other words, it will sometimes end in chaos, the void and destruction."[15] In many cases, however, we have no choice but to intervene in the codes, to destratify and deterritorialize, and to reconfigure. In contemporary society, change often happens faster than evolutionary strategies can be evolved through natural means to adapt to these changes. This was a dilemma at the core of the thinking of John von Neumann and Christopher Alexander, and will be returned to in Chapter 5.

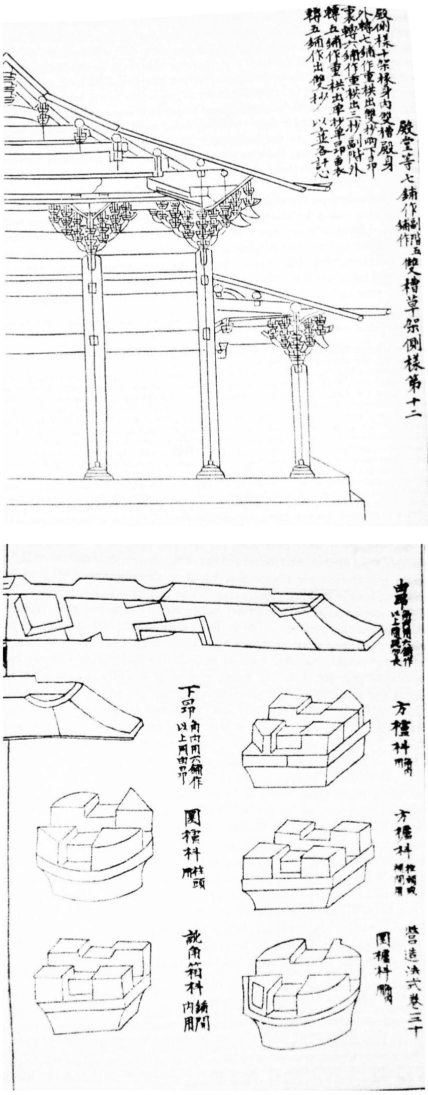


Figure 2.3: Pages from the Yingzhao Fashi 營造法式 (1103 CE), an early treatise systemitizing Chinese vernacular building practices.

Studying vernacular practices and patterns is an important source of decoding strategies humans have evolved to deal with societal challenges and cultural issues.

2.4. Form, Information, Performance

So far this definition of landscape architecture has been moving towards a seductive oversimplification which has emerged numerous times over the course of Western thought, but which serves as a useful abstraction to clarify the argument before it becomes messy again. It will also serve as a simple skeleton on which to flesh out other ideas of this thesis, especially in the next three chapters. At its core, this simplification posits a binary between two positions—are mind and matter separate or are they intrinsically connected? This notion is present in the binaries of Plato's "world of Forms" vs. the sensual philosophy of the Epicureans, in the Kantian distinction between the rationalists Descartes, Spinoza, and Leibniz or the empiricists Locke, Berkeley, and Hume, or in the 20th century linguistic and philosophical schools of Formalism vs. Structuralism. Often these binaries are resolved into a third category, such as Platonism vs. Epicureanism to Aristotelianism, Rationalism vs. Empiricism to Pragmatism, Formalism vs. Structuralism to Functionalism. In all case, however, fundamental questions of how we perceive reality, whether what is essential lies in matter, or whether it inhabits some higher conceptual plane, and so on are being addressed. (Fig. 2.4)

A good starting point in this dialectic is with perceived reality; a mixture of matter, substance, structure, and space. For Lucretius, this is *natura*,[16] for von Humboldt, the *Kosmos*,[17] for Kepes it is *landscape.*[18] Increasingly, in the modern world, the notion of nature/cosmos/landscape is being further redefined and understood as a repository of information. Antoine Picon in his essay *Substance and Structure* observes that "it now seems that landscape is made with the information that pertains to it. In other words, it has become more and more difficult to distinguish between landscape and datascape."[19] The word information can be read in several different ways. A first, conventional reading implies a rather static quantity—the bytes and bits that are stored on a computer hard drive, for example. The etymological roots of the word, however, imply something much more dynamic and active, deriving from the Latin verb *informare* "to shape, give form to, delineate."[20] Information, then, is literally a quantity that has been shaped, been given form to, or which has been delineated. This redefinition of landscape in terms of information serves several useful purposes; according to Picon it allows us to move beyond the association of landscape with the pictorial gaze, with unspoilt nature, and to see landscape both as a production and as a part of "emergent reality," where "dynamic systems ranging from geological forces to economic trends" can be considered as part of the same reality.[21] It also allows for landscape to recover its "memorial roots," where landscape is seen "as a by-product of the capacity of information to constitute archives."[22]

Figure 2.4: Theories on the origins of forms as well as concepts on how forms should be judged permeate philosophy and art. Two influential theories of form in the Western tradition include Plato‘s concept of ideal froms derived from the “World of Forms“ (*top*) and Lucretius concept of “seeds.“ (*bottom*) In contemporary parlance, Plato‘s concept of the ideal form is a largely top-down theory of form, while Lucretius‘ seeds are a bottom-up view on the emergence of form.

Picon’s *information* may in turn be associated with Deleuze and Guattari’s notion of *substances*, which they describe in “The Geology of Morals” as “nothing other than formed matters” or “molar compounds” comprised of “functional, compact, stable structures (forms).” They further explain that “forms imply a code, modes of coding and decoding.”[23] This is where the dialectic emerges—are the modes of coding and decoding (and recoding) part of the same nature as the substances, or do they exist in a separate reality? For Plato, the answer would be, the Forms (abstract templates) are eternal, unchanging, and in a separate reality, and that the flow of information is a one-way street from the world of Forms to perceived reality. For Lucretius they inhabit the same space, where “different forms [substances] come together into one mass and things are made with mingled seeds [formal templates].”[24] Lucretius also implies that his seeds [formal templates] are open to evolutionary change, and that many seeds have been added to the earth since the beginning.[25] These are not simply abstract philosophical questions, however, and they have profound consequences for how designers or societies act in the world. LeWitt’s instructional art or Carpo’s notion of the generic objectile have echoes of the Platonic worldview; Hillier’s notion of decoding and bringing the non-discursive into the realm of the discursive—the process of developing a formal language, or a system of generative rules, which in turn could be manipulated and put back into the system where it is then open to further evolution, contains hints of the latter.

Finally, as introduced earlier, the interplay between formal systems and systems of information resolves into a third category, also with the word “form” at its root—*performance*. The topic of performance has become rather trendy in contemporary landscape architectural discourse, and is closely related to the goals of systems thinking and Burnham’s project to make the whole environment a work of art. Again Picon’s essay delves into this topic in light of the digital where, “landscape is expected to produce certain effects, in other words to perform.” He goes on to explain that “digital culture tends to promote an approach to design focused on practical objectives rather than centered on the production of a harmonious composition following predetermined principles.”[26] Wallis and Rahmann also use the term “performance” to define an era in the development of the digital which began roughly with the Ecological Urbanism Conference at Harvard in 2009, and which closed out their earlier era of “parametricism.”[27] This reflects a shift from using the computer as primarily an information processing tool (GIS) to a tool for pure formal exploration (parametricism) to the current desire to use the computer to facilitate social or ecological outcomes. This shift also parallels the introduction of scripting engines to major software packages and the trend towards incorporating algorithmic methods into design.

2.5. Performance and Deep Form

There may be a danger in making performance the sole goal of design, or rather in defining performance too narrowly to imply that only certain ‘pragmatic’ outcomes are valid. Students wishing to make a performative roof garden, for example, might feel that a proposal to put a treatment wetland on the roof would make this landscape “perform” when in effect, a treatment wetland in this context may be one of the least performative options. Previously, performance was defined as inhabiting the space between rules of formation and the molar compounds of formed matter or information. Performance in this reading is specifically related to the *isomorphism* or congruency between the formal system and the reservoir of information which comprises reality—or more specifically the reading of the reservoir of information pertinent to a particular project. This isomorphism, according to Hofstadter, creates meaning. Kepes uses the term *analogue* to describe this isomorphic relationship, asserting that "the link between pattern and pattern, between pattern and process, between pattern and beholder, is the *analogue*, the factor of invariance, of similarity in the midst of difference."[28]

The notion of analogue and isomorphism (as well as Lucretius' evolving formal templates or seeds) is reflected in John Tillman Lyles essay "Can Floating Seeds Make Deep Forms?" where he proposes that:

> "Form and process are inseparable. For landscape design to be truly meaningful, it should also give visible expression to the processes that shape the earth, thus making a connection between nature and human culture. Landscapes that accomplish this can be described as having deep forms."[29] (Fig. 2.5)

Figure 2.5: Lawrence Halprin's *Ira Keller Fountain* in Portland, Oregon, would be considered by Lyle an example of "Deep Form" as the forms are abstracted variations of locally significant natural forms.

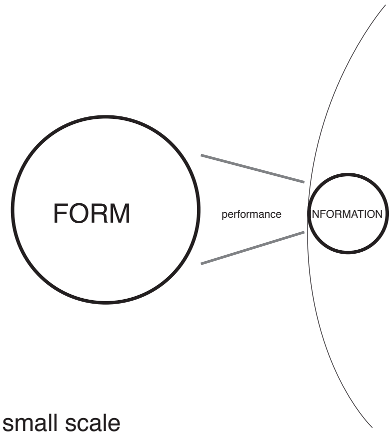
A quick reading of this may imply that deep form is only possible when it reflects natural processes that shape the earth, but in light of Picon's thesis, and after a closer reading of Lyle's text, both natural *and* cultural processes can be viewed as earth shaping processes. In many ways, Picon and Lyle have the same goal. Lyle seeks to "fill the chasm that the 19th century dug between nature and humanity"[30] and to escape the notion of the pictorial gaze of landscape, and "the limitations involved in considering the surface expression of all this wonderful complexity [of nature] as mere picture."[31] Picon sees a redefinition of landscape in terms of information as solving Lyle's first problem as "information ignores the distinction between the natural and the artificial."[32] Likewise the second problem is solved in light of the digital, where the pictoral gaze is supplanted to "accentuate the dynamic and instable fields and forces that shape the earth and constrain human interventions on its geography."[33] Picon is not as clear as Lyle, however, in drawing the line back to formal design expressions through the performative/process filter.

Returning to the case of the performative roof garden and the notions of *isomorphism*, *analogue*, and *congruence* informing the definition of performance, one might look at Ken Smith's proposal for the Museum of Modern Art rooftop garden, where he composes a series of plastic rocks and plastic trees into a camouflage pattern. Although it serves no ecological goals, by a broader definition of performance it would be considered more performative than a hypothetical rooftop stormwater treatment wetland, as not only does it work better with the practical constraints of the project—the budget, the structural capacity of the building—but as an *analogue*, drawing associations between the rather dominant formalism of the proposed pattern, and informational associations in the viewer, such as to pop-art and minimalism. It also makes a nod to a typical cliché in landscape architectural design where the landscape architect is engaged in a project at the the end to "camouflage" or disguise the mistakes of others, a rather witty response to a design brief which called for "hiding" the roof from the residents of a nearby high-rise.[34] In other words, such a project should not be expected to perform ecological functions in its unique informational context since that context itself is largely "artificial." Neither should it be read as "shallow" form, since it actually responds quite well to its socio-cultural context. Now this same formal composition, placed in another informational context, something more "natural" might be a wholly inappropriate response and could indeed be seen as shallow.

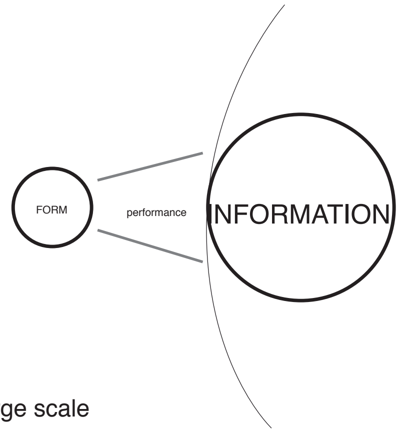
2.6. Form, Performance, and Information in Relation to Scale

One last aspect to consider in this form/performance/information schematic framework before moving on for the time being is the question of scale in relation to where the emphasis of a project might lie. Formal systems are generally scale-free, but information and scale are intimately connected. Naturally, as a project size increases, so does the reservoir of information to which a project might respond. This implies that the *isomorphism* with the formal system or the performative relationship must also change. At smaller scales, where the size of the information reservoir can be more limited, formal experimentation can be the focus of the design, and the formal rules can take priority. This is not to say that the performative and informational aspects should be neglected, they simply take on a much more circumscribed role. In minimalist art, which in some ways can be seen as pure formalism, there is still context, such as the medium or the space in which the artwork is placed. Even the minimalist programme, which sought to rigorously eliminate semantic association, is in its own way a notion within a larger informational context. At the larger scale, the opposite is true; here the informational aspects of the project are so complex, that the focus needs to be on the understanding, categorizing, and the prioritizing of this vast reservoir of information, and the importance of an external formal system is minimized. At the medium scale, however, a rich complex of information might be at play, and likewise the formal system might attain a similar level of richness. Here the focus of design intentionality needs to be on ensuring that the formal system and the informational system have a rich set of *isomorphisms*, *analogues*, and *congruencies*. Here at the middle scale the focus is on performance. (Fig. 2.6)

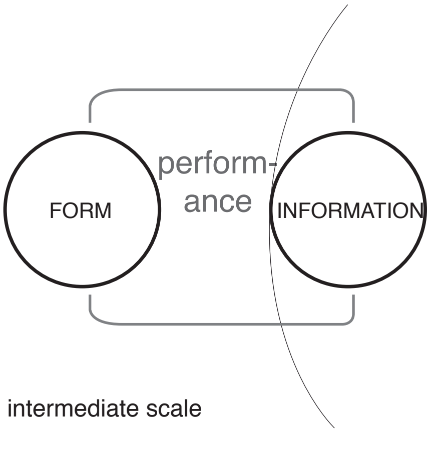
This framework corresponds quite well with a similar argument Steinitz makes in his writings where he observes that “at large scale, you are dealing with strategy; at middle scale, you are dealing with tactics; and at small scale, you are really dealing with details.”[35] Strategy, “a careful plan or method” or “the art of devising”[36] such plans, refers to answering the question “what are we trying to do?” and is or should be the product of a careful analysis of complex sets of information. The term tactic, “a device for accomplishing an end,”[37] refers to the how things are done, in other words the performative implementation of a set of instructions. Steinitz and others associated with Geodesign tend to operate at the middle-large to large scale, in other words their emphasis is naturally on strategy and tactics, information and performance. In contrast, this thesis will tend to deal with the small-middle to middle scale, where the emphasis will be on details and tactics, form and performance.



small scale



large scale



intermediate scale

Figure 2.6: Relative weight of three categories of form, information, and performance at various scales.

2.7. Differentiating Landscape Architecture from Architecture

In developing a definition of landscape architecture, the previous paragraphs sought to develop a dialogue between formal, informational, and performative aspects of projects in order to define the scope of landscape architectural work. No clear distinction, however, was yet drawn between the two disciplines or architecture and landscape architecture. This is partly because the two disciplines have a great deal in common, sharing a common historical lineage, representational and working methods, as well as a similar discursive vocabulary. This text was also hesitant to use the negative binary set to ultimately define the scope of landscape architecture, avoiding the trap identified by Elizabeth Meyer of defining landscape as the passive contrast to architecture: or that landscape is “what is *not architecture*.”[38] There *are* however several fundamental differences between architectural and landscape approaches to design, and these differences will have significant consequences for developing an algorithmic approach. The first notion that will be considered is the significance of the site in landscape architecture, and its role, according to Meyer, in "differentiating landscape architecture from other disciplines."[39] Then the text will introduce some of the key distinctions between *landscape space* and *architectural space* through Meyer's notion of *figured ground,* Allen and Corner's writings on *fields*, Girot's concept of *topology*, and the Deleuzian spaces of folds, rhizomes, and stratifications. Finally this Chapter will close with a few initial speculations on what this implies for the algorithmic manipulation of landscape space.

2.8. The Site

Previously this text referenced an observation by Girot that "the landscape as such precedes the landscape architect, while, in comparison, a piece of architecture under no circumstances precedes the architect"[40] to reflect the relative primacy of the site—the informational context—in landscape architecture as opposed to in architecture, where the formal or generative rules might take priority. A similar sentiment is echoed by Picon, continuing a theme introduced in the last sections where he observes that:

> "Our contemporary digitally structured landscape could very well be defined as a by-product of the capacity of information to constitute archives. The contrast with architecture could not be greater in this respect. Whereas digital culture seems to have cut architecture from its memorial roots, it may very well do the reverse for landscape."[41]

Here again, the relative bias in landscape architecture is seen as towards the information pole of the form-information continuum. Indeed, landscape architecture especially in the 19th century tended to privilege the practitioner's ability to read and interpret sites[42] and the overall concern was not with geometrical systems but with amplifying the site's latent characteristics.[43]

This does not mean, however, that ideas, concepts, and structures outside of the site do not play a role. Olmsted, for example, relied heavily on compositional structures and rules derived from European ideals, especially the English landscape garden, and applied them to American landscapes[44] but gradually these gave way to a new set of rules emphasizing concepts from geology and ecology where the rules placed an emphasis on relationships, not parts.[45] Meyer also proposes an early emphasis in landscape architecture on tactics—armatures, frameworks, articulated fields[46]—a notion associated with the middle, performative scale. The question of scale, in landscape, indeed may explain many of these key differences between architecture and landscape design, as most buildings inhabit the small scale, where formal rules have relatively more priority, and architecture only begins to approach the medium scale at the scale of the city. Is the distinction, then, simply a question of scale? Is a small scale landscape architectural project the same as a small architectural project with the same area? To answer this question with "no" there must be other layers of difference between the space of landscape architecture and architectural space.

2.9. Ground as Figure and *Figured Ground*

Meyer notes in "Site Citations" that landscape architecture's focus on sites may be one of the reasons the discipline was relegated to an inferior role vis-à-vis architecture during Modernism's heyday in the early to mid 20th century, as its focus on the specifics and idiosyncrasies of place seemed out of step with the emphasis in modern art and design on "abstraction, objecthood, … and universality."[47] As a result, the space of the ground took a subordinate

Figure 2.7: Fall of Icarus, Pieter Bruegel the Elder. Here Landscape is subject, and the title character of the painting is reduced to two small legs beneath a massive ship.

role to the architectural figure. This parallels the emphasis in much of art, especially Western art, upon the figure or "positive space" in contrast to the ground, which is often synonymous with notions of "background" or "negative space."[48] Indeed, even among landscape architects, the significance of ground is often reduced in favor of object—this is especially notable in the German term *Objektplanung* which is often used in the discipline by practitioners who focus on smaller scales.

The ground, however, occasionally comes into focus in art. This is evident in the work of artists such as M.C. Escher who plays with what might be called "Figure-Figure" relationships, which Hofstadter describes as a *recursive* figure "where ground can be seen as a figure in its own right."[49] Islamic art has also developed the ground in art to a high level of refinement, in part due to the Islamic prohibition on depictions of figures. While the focus often tends to be on the superficial aspects of Islamic geometric patterning, and the abstract, paradisiacal and fantastical qualities of their gardens,[50] the formal system of geometric patterning in the Islamic world was also intimately connected with everyday life at multiple scales and even used to organize landscapes, garden cities, and garden territories on a very broad scale.[51] In Western art, the most notable instances of the ground escaping its inferior position as background and becoming subject is perhaps evident in landscape painting. Geuze sees the emergence of the ground as subject in Dutch landscape painting as an outgrowth of the Age of Discovery, where Dutch society was exposed to ever more cosmopolitan influences and concepts of exotic and unknown landscapes. At first the landscape paintings reflected this exhilaration of unknown landscapes, where "puny figures were set in a lyrical fantasy of hills, bays, coasts, and hamlets."[52] (Fig. 2.7) Eventually, however, there was a reorientation of the subject of the landscape ground to celebrate the "euphoria" of the everyday Dutch landscape. Gueze sees in this both an escape from the closed paradigms of the medieval world, and a recognition and celebration of a new category—not the God-given gift of nature, but the human-shaped, hard-earned artifact of landscape.[53]

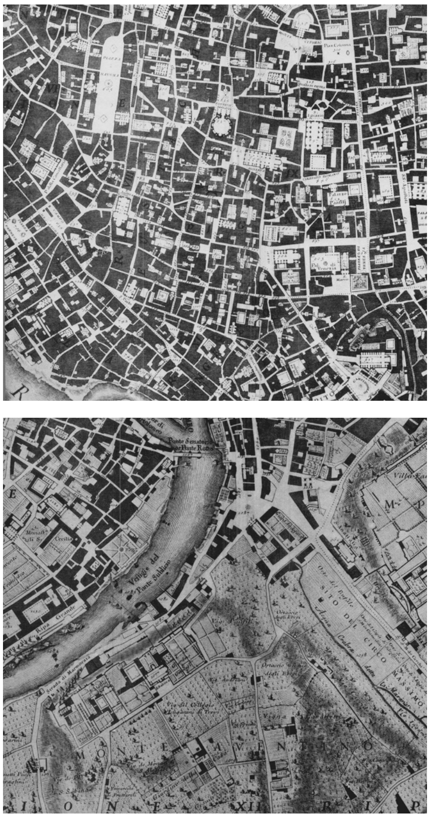


Figure 2.8: Nolli's famous map is an oft-cited precedent for figure/ground studies. Less talked about are other parts of the Nolli map, where the ambiguities of landscape are depicted with various strategies, such as the topography of the hills, the flow of the river, the the planting of the fields.

This recognition of the ground not as a passive gift or neutral field, but of an active field shaping and being shaped by humanity, with both positive and negative consequences for our societies, has taken on new urgency in the wake of the failures of Modernism, and spurred a new interest in the ground. Meyer cautions, however, against falling into the binary trap of simply reversing the binary where ground dominates figure, or where open space becomes the new figure, such as in Nolli's famous map of Rome. (Fig. 2.8) Instead she suggests new "languages, codes, and principles" for approaching landscape design by first suggesting why the binary category is flawed in the context of landscape space, and then proposing an alternative way of approaching the problem and developing landscape space. As an example, she introduces her concept of articulated space with the observation that vegetal masses such as bosques and forests are neither solid nor void, figure nor ground.[54] Instead they are complex gradients of densities that created "layered gray zones" which are "neither open nor enclosed."[55] They also have spatiality which is variable and seasonal, enclosing spaces in summer and connecting, yet screening them in winter.[56] (Fig. 2.9) Similarly, the ground also defies this binary, with both the subtle and abrupt changes in topography, "the earth's undulating corporealness" defying categorization as figure or ground, Meyer proposes that allowing the "passive" ground to speak, by figuring, or thickening the ground, is one of the great potentials in landscape design. [57] As an aside, this ambiguity of landscape identified by Meyer, in contrast to much of architecture, creates particular problems in computational design which operates on a system of Boolean or binary logic (see §6.5), which will be reflected upon more carefully in this thesis's conclusions.

2.10. Objects to Fields

At the same time Meyer was conducting research into the ambiguities inherent in the binary between the architectural object and the landscape field, two other practitioners, James Corner and Stan Allen, made a similar set of observations and connections. Corner explored the uneasy relationship of the layering of two sets of fields, the underlying landscape morphology of the American heartland and the Jeffersonian grid, an abstract ordering device with multiple self-similar levels of subdivision, devised to expedite the orderly colonization of the American West. With the aid of photographs from aerial photographer Alex Maclean and atmospheric collages intended to reveal some of the underlying measures and geological forces present in the photographs. In the photographs, the relentless grid is nearly always evident, but it is constantly subverted, morphed, and distorted by the logic of the underlying land.

Corner's observations in *Taking Measures Across the American Landscape* along with his close associations with Ian McHarg's "layer-cake" methodology led him to favor a methodology for intervening in landscapes where various landscape structures or systems are devised as isolated, "thin" layers, from which a "thick" landscape emerges through the interaction between the layers.[58] This strategy for achieving a high degree of complexity through the layering of relatively simple and comprehensible layers was also advocated by Giancarlo de Carlo, who expresses the belief: "that it is possible to start from Euclidean geometry and overlap, intertwine, layer, its rules and figures so as to obtain a tool that describes and represents a complexity similar to that of our contemporary society."[59]

The ideas contained in the discourse on fields, layerings, and the geometries of overlapping geometries (moirés) were also explored by Corner's associate and co-founder of Field Operations, architect Stan Allen. (Fig. 2.10) Allen was not the first to apply the concept of the field to architecture, Kwinter frequently referenced this in the 1980s and early 1990s, and as previously discussed, Meyer and Corner had used the concept to explore notions of landscape space; but Allen crystallized several strands of thought through his two essay, "From Object to Field" and "Field Conditions" in the late 1990s which a major influence in shaping the agenda of architecture, urban design, and landscape architecture in the early 2000s.[60] Allen describes a field condition as:

> "any formal or spatial matrix capable of unifying diverse elements while respecting the identity of each. Field configurations are loosely bounded aggregates characterized by porosity and local interconnectivity. The internal regulations of the parts are decisive; overall shape and extent are highly fluid. Field conditions are bottom-up phenomena: defined not by overarching geometrical schemas but by intricate local connections. *Form matters, but not so much the forms of things as the forms between things*."[61] (emphasis added)

Allen connected the concept of the field to architecture through two examples, describing the mosque in Cordoba as essentially an architectural field, and citing an unbuilt project of Le Corbusier, the Venice hospital, but the concept has difficulty at the scale of most architecture, often useful only for creating superficial pattern, and only reaching its full spatial potential in the complex layerings of urban and landscape space.[62] Allen also connected

Figure 2.9: Herrenhäuser Alleé in Hannover. In winter, the trees define space as a screen, with the central space open to the surrounding landscape. In summer and fall, the central space has an enclosed feeling.

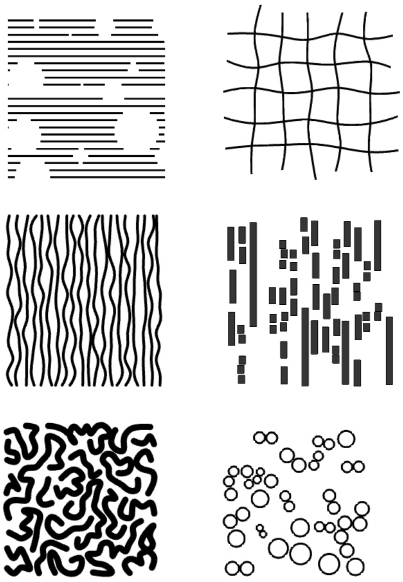


Figure 2.10: Six field algorithms based on Stan Allen's field diagrams. Joseph Claghorn, 2017, after Allen, 1998. See also §A9.1.

the concept of the field explicitly to digital space, seeing in algorithmic methods the potential to express visually and compositionally the invisible vectors which structure the natural world, such as in flocks, crowds, and swarms.[63]

The field is not a static or neutral skin or superficial compositional device, and is in many ways a microcosm of Lucretius' *natura*, Humboldt's *Kosmos*, and Kepes *landscape*; Kwinter proposes that: "The field describes a space of propagation, of effects. It contains *no matter or material points*, rather functions, vectors and speeds. It describes local relations of difference within fields of celerity, transmission or of careening points, in a word, what Minkowski called the *world*."[64] In addition to the larger world, fields in the thinking of Allen and Kwinter are also intimately connected with *systems*, networks, and *infrastructural grids,* which Kwinter sees as the truly fertile terrain of digital design rather than gratuitous form finding.[65] When read in this light, Allen's recognition of the trend from "object to field" in design is an outgrowth of Burnham's observation in the late 1960s that "we are moving from object-oriented to a systems-oriented culture." The thinking of Corner and Allen and the concept of the field is explored in more detail in Chapter 9.

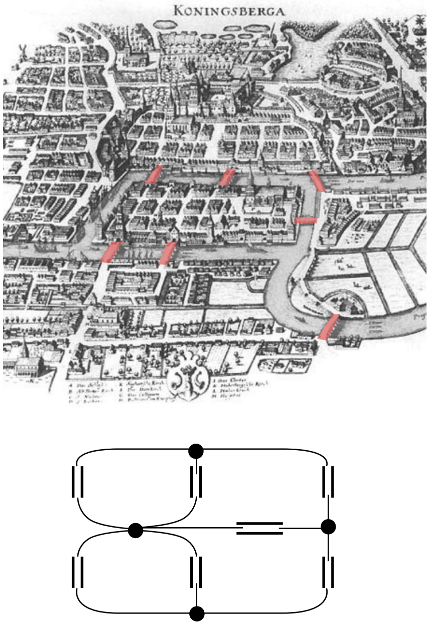


Figure 2.11: The classic „Seven Bridges of Königsberg" problem. Euler solved a long-standing local dilemma and proved it was impossible to cross all seven bridges without crossing one or more of the bridges multiple times. By abstracting the problem into the essential nodes and paths, the complex urban topological structure is greatly simplified, but only to solve a particular problem. This simplified urban topology would be inadequate to address a number of other questions about the city.

2.11. Two Definitions of Topology

The field as described by Allen, Kwinter, Alexander, and others focuses on *relations*, "the forms between things," and *configuration*. The study of the relational networks between objects is facilitated by the mathematical discipline of topology, which is "concerned with those properties of geometric configurations which are unaltered by elastic deformations"[66] and with the "organized spatial relationships and proximities within surface structures."[67] The discipline has its roots in the writings of Leibniz—his *geometria situs* and his *analysis situs*—and Leonhard Euler, who was able to solve the famous "Seven Bridges of Königsberg" problem by abstracting the urban space of the Prussian town down to its seven nodes—the bridges—to prove that it was impossible to cross all seven bridges without crossing a bridge more than once.[68] (Fig. 2.11) Despite these early advances, the mathematical discipline of topology really only came into its own with the writings of Henri Poincaré at the end of the 19th century. Mathematical topology will be explored in more depth in Chapter 8, but for now it is sufficient to say that it is a critical component of understanding network theory and the behavior of systems, and provides a clear link between formal conceptions of space, systems thinking, and computation.

The topological structure of architectural space, urban space, and landscape space, however, all differ in significant ways and this can present important challenges to landscape architects, or rather, this requires landscape architects to think about topology in a different way. Architectural typology or configuration tends to be fairly rigid. Hillier gives numerous examples of this by abstracting building plans, where nodes are rooms and the topological connections between them are doors or passageways.[69] A window might complicate this reading, providing a visual connection, but not necessarily free passage. Of course, doors can be locked, or with intensive effort, sealed off or removed, but the topological connections tend to be clear and manageable. On the urban scale, this becomes slightly more complex, but on some levels, urban space's typology is also very straightforward, as seen in road or transit networks, or in the seven bridges problem of Königsberg.

Landscape, on the other hand, can have high levels of topological ambiguity. Even where paths in a park are fixed, for example, these do not tend to constrain movement through the park in other ways, as evidenced by the emergence of "desire paths." Some landscapes experience regular typological reconfigurations, such as islands in a tidal flat, where figures merge and coastal barrier islands become part of the mainland every six hours. (Fig. 2.12) Other times the topological reconfigurations are much less frequent or unexpected, such as after a flood, but these changes all have an impact on how animals and humans move through them. In the designed landscape, landscape "rooms" are also ambiguous, where doors and windows open and close with the seasonal growth of vegetation, as described by Meyer, or with the ambiguity of rooms shaped by terrains. Plazas and square can also exhibit this changing and ambiguous topology. A further complicating factor is that elements in the landscape can inhibit movement in some cases or enable it in others. A river, lake, or sea can be an obstacle or it can be a highway. Mountains may block passage to some, but not for birds, goats, or airplanes. Architecture can be described in terms of walls and roofs, landscapes in terms of membranes, screens, filters, and canopies.

Figure 2.12: The coast of East Frisia at high tide is the familiar image, with a distinct coastline (controlled by a dike) with offshore barrier islands. *(image, top)*. But these islands become peninsulas for around 12 hours a day and can be reached by foot from the mainland. *(image, bottom)* Which represents the "True" topology of East Frisia's coast?

What does this mean for an understanding of topology in the context of landscape architecture and how does this relate to algorithmic and digital methods in the field? First, it implies a fundamental distinction between approaching architecture or landscape architecture as Hillier's configurational science. It also implies a fundamental difference in algorithmic approaches to the two disciplines as will be explored in Part II of this thesis, as traditional algorithms require an internal topological structure—the decision tree—which is free from ambiguity, and the algorithms also tend to express themselves with predictable external topological outputs. This is an important distinction to recognize in the context of landscape design, although the realization is not entirely novel. Girot and Freytag seize on the ambiguity of mathematical topology in the context of the space of place inherent in landscape architecture to redefine the word, or rather to link the word back to its original meaning, where topology is defined as the "topographic study of a particular place; specifically: the history of a region as indicated by its topography."[70] This theoretical position encompasses the wide range of positions discussed so far which distinguish landscape space from architectural space, emphasizing "ground, water, climate, and plants" as well as survey and measure, while retaining an emphasis on surfaces, networks, linkages, and the ordering of space "into meaningful, livable structures."[71] Girot and Freytag also see this conceptual framework as a counter position to the layering methodology of McHarg and Corner, which in Girot's estimation tends to "flatten" space and place.[72] Girot and Freytag's topology makes use of digital methods, but in ways very different from the mappings of McHarg or Corner or their GIS parallels, and represents a different way to introduce computational methods into sites.

2.12. Emergent and Evolved Landscapes

Two final essential characteristics of landscape space which fundamentally distinguishes it from architectural space is that landscapes are *emergent* and *evolutionary*. The concept of emergence has been of considerable theoretical interest in architecture in recent years, but as Picon notes, the concept "applies in a more obvious way to landscape than to architecture."[73] Building codes, as noted by Hillier and Weinstock *do* evolve through time, but generally in architecture the concept of emergence has been used largely as a morphogenetic form-finding strategy to produce life-like forms (i.e. biomimicry), but the individual designed work is still a building, not a living organism. Unlike in landscape, in classic architecture the concepts of emergence and evolution are unlikely to achieve their full conceptual potential. Landscapes, in contrast, must confront growth and change through time, or as Prominski notes, the issues of "determinacy versus indeterminacy, the integration of time in design and systemic openness for changes in the design environment."[74]

The most conceptually rich landscapes use the issues of growth, emergence, and evolution as a design opportunity, again moving landscape away from the static image of the picturesque, to the "system esthetic" of Burnham.[75] Systems, however, can often behave in unexpected ways, and future states are very hard to predict. This is especially true in *nonlinear systems*, which most landscapes and all evolutionary and emergent systems tend to be. As described by Barnett in *Emergence in Landscape Architecture:*

> "A nonlinear system is characterized by continual inputs of matter-energy that flush through it providing it with the energetic resources required for its existence. An important feature of nonlinear systems is that they require disturbance in order to grow and evolve. Perturbations in the system, or turbulence from its farthest reaches, cause the system to assimilate the disturbance and as a result achieve sometimes greater and sometimes simply different conditions of complexity and vigor. Nonlinear systems are open, and emergent."[76]

By understanding the characteristics of emergent systems and reading landscapes in this light, according to Barnett and Prominski, landscape architects will make better decisions in their design process and will contribute to a relevant contemporary cultural discourse. This research will return later to Barnett's and Prominski's recommendations, but it should be noted that the discourse surrounding emergent and evolutionary aspects is not limited merely to the ecological aspects of landscapes, but can apply to social, cultural, urban, and other aspects as well; "biota" according to Barnett, are not "the only self-organized material of interest in landscape design."[77]

A possible danger in the discourse surrounding evolutionary, emergent, or bottom up approaches to landscape is a real danger that the designer can get lazy and abdicate design responsibility to the ability of time to fix his or her mistakes in the long-term, or to hesitate to intervene at all, since the "emergent" present condition of a landscape is, to borrow a phrasing from Leibniz, "the best possible world." (see §14.5) Another temptation is to use the rhetoric surrounding complexity, nonlinear systems, and emergence—notions which are deeply rooted in scientific experiment—to justify decisions taken in a non-sequential or non-logical way. As mentioned earlier, scientists who study complex systems have come to rely considerably upon the power of computation to identify and track patterns, and to create models for future scenarios. Likewise, in architecture and landscape architecture, computation allows us "both to produce environments of high degrees of intricacy and to quickly evaluate their effects."[78] Different sets of initial conditions can be tested to make an informed proposal that will direct the system more rapidly to a desired future state. As early as the 1960s, Fumihiko Maki observed in the context of the city, that most people admire cities which have been built by "generations of men working over decades and centuries of time," and that the poverty of much of contemporary urban design, where designers must build in a significantly "abbreviated time," is a direct consequence of the lack of this emergent quality in cities.[79] Thom Mayne asks if computation can facilitate a resolution to Maki's dilemma, posing the question: "is it possible to collapse the time required for urban evolution, to achieve in one year what once took a hundred?"[80] Landscape architecture has been described by JB Jackson and others as fundamentally an art concerned with the manipulation of time, whether speeding it up or freezing it in a certain moment.[81] Can computation, in the spirit of Mayne's *Combinatory Urbanism*, likewise facilitate an acceleration of the emergent and evolutionary qualities of landscape?

2.13. Approaching Landscape Space Algorithmically

Generally within the framework described in the previous paragraphs, algorithmic approaches may prove productive in the context of landscape design in three broad areas; in allowing for a deeper reading of the various layers of *information* embedded in the landscape, in understanding and manipulating the *formal structures* which shape landscape, and in establishing a dialogue between formal structures and information to achieve *performative* outcomes. To delve equally into these three areas would prove impossible in the context of this dissertation, but understanding some of the key issues in each of these areas is important.

A significant area of research in contemporary landscape architectural practice revolves around experimentation with new tools for the collection of various types of information embedded in landscapes. Methods for collecting information and for measuring the landscape have always shaped the nature and scope of potential interventions. In contrast to past ages, however, many of the tools used to measure and read landscapes in the present "rely on large three-dimensional data sets that are unwieldy to decipher and meaningful workable formats."[82] Meaningful information can only be extracted from the datasets with the use of algorithms, and different algorithms will present a different picture of what the dataset means. While it is often outside of the scope of most landscape architect's ability to create these post-processing algorithms—which require considerable specialized knowledge—in light of the ever expanding amounts of "big data" available for use in projects, the skill to be able to look at datasets critically will become more and more crucial. Key to understanding a dataset is how the data was gathered, what algorithms were used to process the data into a usable form, and what the inherent biases are in both the instrument used to gather the data and in the post-processing algorithms.

There is a seemingly endless array of technologies that fall into this category, and new tools and methods are popping up all the time. At broader scales, remote sensing data gathered from satellites and aerial flyovers has been used to compile GIS datasets at least since the 1960s. While useful for larger scale mappings, such datasets tend to prove of limited use at the site scale. Tools have been developed in recent years for collecting data at ever finer scales, however, and big data may soon revolutionize site design as it has landscape planning. Aerial UAV's (drones) have been used by Rekittke, Paar, and others while laser scanners by Girot's team at ETH-Zürich have revealed the subtle elevational contours in sites conceived of as "flat", such as a polder landscape in the Netherlands, to reveal important patterns where a height change of as little as 10 cm can have a significant impact on plant ecology, hydrological conditions, and suitability for development.[83] In all cases, however, the processed datasets need to be tested against the realities of the site. Another line of research looks at datasets, which are in a constant state of flux or change, and developing design responses to these indeterminate fluxes and flows in the landscape. Bradley Cantrell describes in *Responsive Landscapes* a cybernetic landscape future, where "the process of feedback, sensing the environment, processing the sensed data, and visualizing the response is the core design focus."[84] This is made possible with "swarms" of low-cost data-collection devices that provide real-time feedback on current landscape conditions, which can then be processed by algorithms to alter systemic inputs and flows to achieve desired outcomes.

In contrast to the research to reveal the interacting layers of information at the site scale—the intelligence of the site—a second line of algorithmic research seeks to understand the series of generative codes that create landscape structure. Since the Hellenistic period, Euclidean geometry has dominated as a formal language in Western art, philosophy, and design. Euclidean geometry, specifically, and formal systems in general, however, should not be read as dialectically opposed to the emergent logics of sites and cultures. Formal systems acquire their power, and associated meanings only insofar as they are useful and correlate to patterns and structures observed in reality. In many ways, geometric systems can be read as an emergent phenomenon themselves, developed in many cultures around the world without any kind of recognized intellectual exchange, or at least as a cultural practice whose use spread rhizomically from one culture to another. There have been significant advances, however, in the mathematical and scientific understanding of geometry and other formal structures since the time of Euclid. Cartesian algebra allowed for geometry to be described by algebraic equations rather than the instruments of ropes, compasses, and straight edges. Leibniz and Newton's Calculus allowed for not only the mathematical description of complex or irregular curves in a way not possible with Euclidean or Cartesian methods, but of the dynamics of changing quantities or values. Whole new branches of mathematics, from topology, to fluid dynamics, to fractal geometry, allow for a description of the natural world in ways not possible with Euclidean geometry. Computation allows all of these systems to be revisited in a design context. As an example, the design experimentations of the 1990s, which are often couched in the philosophical concept of the "fold" as described by Leibniz and reintroduced by Deleuze[85] can equally be seen as a product of the development of algorithms to describe Bezier and NURBS curves in CAD programs.[86] Algorithms open up countless other mathematical formal systems to study and experimentation in a context where designers may be unfamiliar with the underlying mathematics. Most importantly, perhaps, are the potentials inherent in the studies of the patterns which emerge from open, non-linear systems, which no linear equation can describe, but which can only be revealed either in nature, or in the second nature of the computer. These patterns are of the most interest in this research.

2.14. Summary Conclusion and Sketch of Next Chapters

This chapter has introduced a framework centered on the concepts of form, information, and performance in the context of design problems at various scales, where landscape architecture is defined as the construction of specific projects on defined territories or sites. Performance is seen as the *isomorphism, analogue,* or *congruence* between a formal system, or a construction on the one hand, and an informational context, or a site on the other. As the scale of a project increases, the importance of the informational context increases if performative outcomes are to be obtained. The chapter has also introduced the notion that design is the act of bringing the codes, procedures, or recipes of the non-discursive realm into a discursive realm where new combinations, hybrids, and evolved strategies can be tested. It is imperative, however, to use caution in this process, and to find methods to test possible outcomes. Algorithmic design provides one possible means of decoding landscapes and creating, evolving, and testing new hybrid conditions. When projects are approached algorithmically, the special ambiguities of landscape space which resists many of the traditional binaries associated with design, such as figure-ground, as well as the topological ambiguity inherent in landscape structures needs to be considered.

The next three chapters will go into greater detail to describe the development of formal systems or logical calculi on the one hand, and the cultural reading of the landscape of information—nature—on the other. This will be done by presenting two figures who serve as a proxy for a milieu of ideas developed first in the Hellenistic period (Euclid | Lucretius), and later emerging in the European Enlightenment (Leibniz | Von Humboldt). These are two periods where, according to Glacken in *Traces on the Rhodian Shore*, the modern conception of nature was formed, whose role as "subject" was only made possible in a cosmopolitan society in contact with multiple modes of living in a diverse range of environments.[87] In both cases, the binary relationship between the two modes of thought will be presented not as an either-or relationship, but as intimately intertwined. Chapter 5 will jump to the 20th century, and will examine the emergence of computation along with the development of a new paradigm for understanding culture, nature, and space (Von Neumann | Alexander).

Endnotes

1 Antoine Picon. "Substance and Structure II: The Digital Culture of Landscape Architecture." *Harvard Design Magazine,* 36. (2013), 125.

2 Georg Nees, *Generative Computergraphik.* (Berlin: Siemens Aktiengesllschaft, 1969), 5.

3 David Leatherbarrow, "Not anywhere, not only here." in *Thinking the Contemporary Landscape.* Christophe Girot and Dora Imhof, eds. (New York: Princeton Architectural Press, 2017), 199.

4 A procedurally generated landscape is a landscape created, usually for applications in film or in computer gaming, to simulate either natural landscapes in the real world, or to speculate as to what could be a landscape on an imaginable world. A typical procedural landscape generator in a gaming context uses a series of algorithms which operate in sequence, beginning with terrain generation, first at the scale of continents and then at a more local scale, after which climate and hydrology are simulated, which in turn establishes biomes, which then are populated with animal and plant agents appropriate to the biome. One of the best known implementations of procedural world generation is found in the hit game Minecraft, but many other titles exist using similar or more refined procedural techniques.

5 see Yoav I.H. Parish and Pascal Müller, "Procedural Modeling of Cities." in *SIGGRAPH 2001 Proceedings of the 28th annual conference on Computer graphics and interactive techniques* (New York: ACM, 2001), 301-308.

6 Christophe Girot. "Towards a general theory of landscape." in *About Landscape: Essays on design, style, time and space* (Berlin: Birkhäuser, 2003), 83.

7 David Blackbourn, David. *The Conquest of Nature: Water, Landscape, and the Making of Modern Germany* (London: W.W. Norton & Co., 2006), 43-44.

8 Douglas Hofstadter, *Gödel, Escher, Bach: An Eternal Golden Braid.* (New York: Basic Books, 1999), 9, 49-50.

9 Bill Hillier, *Space is the machine,* electronic edition (London: Space Syntax, 2007), 10-11.

10 *Ibid*, 31.

11 *Ibid*, 32-36.

12 *Ibid*, 35.

13 *Ibid*, 34.

14 *Ibid*, 39-40.

15 Gilles Deleuze and Felix Guattari. *A Thousand Plateaus: Capitalism and Schizophrenia,* trans. Brian Massumi (London: Bloomsbury, 2004), 585.

16 Titus Lucretius Carus, *On the Nature of Things,* (original title *De rerum* naturum) trans. Cyril Bailey (Oxford: Clarendon Press, 1911). The ancient concept of nature is very different than our modern concept and is often translated as "reality" instead of nature in some texts.

17 Alexander von Humboldt, *Kosmos: Entwurf einer physischen Weltbescreibung.* (Frankfurt am Main: Eichborn, 2004). Humboldt resurrected the ancient Greek term κόσμος as a corollary to the Latin *natura*. Today cosmos tends to evoke images of outer space, although this meaning has also changed through time.

18 Kepes' *The New Landscape* takes an incredibly broad definition of landscape probably more so than what most landscape architects would be comfortable with. It approximates very closely the ancient *natura* or Humboldt's *kosmos.*

19 Picon, 126.

20 Definition of inform (v.) from *Online Etymology Dictionary*. etymonline.com/index.php?term=inform. (accessed 1 Aug 2017).

21 Picon, 126-127.

22 *Ibid*, 127.

23 Deleuze and Guattari, 47.

24 Lucretius, 88.

25 *Ibid*, 103.

26 Picon, 127.

27 Jillian Walliss and Heike Rahmann, *Landscape Architecture and Digital Technologies: Re-conceptualising design and making* (London: Routledge, 2016), xxv. The previous era of "Parametricism," according to the authors ended upon the publication of Schumacher's essay declaring "Parametricism" as the new Modernism.

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30 *Ibid*, 46.

31 *Ibid,* 39.

32 Picon, 129.

33 *Ibid*, 126.

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39 Elizabeth Meyer, "Site Citations: The Grounds of Modern Landscape Architecture.", in *Site Matters: Design Concepts, Histories, and Strategies.* Carol

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41 Picon, 127.

42 Meyer, "Site Citations," 95.

43 *Ibid*, 97.

44 *Ibid,* 101.

45 *Ibid,* 99.

46 *Ibid,* 103.

47 *Ibid,* 94.

48 Hofstadter, 67.

49 *Ibid.*

50 Attilio Petruccioli, "Rethinking the Islamic Garden." *Yale Forestry and Environmental Studies Bulletin,* 103 (1998), 350.

51 *Ibid*, 357-363.

52 Gueze, 260.

53 *Ibid,* 260-261.

54 Meyer, "The Expanded Field of Landscape Architecture.", 57.

55 *Ibid,* 58.

56 *Ibid,* 59.

57 *Ibid,* 53-54.

58 James Corner, "The Thick and the Thin of It," in *Thinking the Contemporary Landscape*, Christophe Girot and Dora Imhof, eds. (New York: Princeton Architectural Press, 2017), 117-135.

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60 Allen's writings also heralded the interest in Infrastructure, dedicating a section of his Point + Lines to the new concept of "Infrastructural Urbanism."

61 Stan Allen, "From Object to Field." *AD Architectural Design Magazine: Architecture after Geometry.* (Feb 1998), 24.

62 Barnett cites a colleague who upon reading Allen's essay exclaimed "Those Bastards! They did it again," to express his dismay at the architects "robbing" a concept that landscape architecture should own.
Rod Barnett, *Emergence in Landscape Architecture* (London: Routledge, 2013).

63 Allen, 28-29.

64 Sanford Kwinter, as quoted in Stan Allen, "Field Conditions." *Points + Lines.* 1999,

65 Kwinter, "Playboys of the Western World," in *Far from Equilibrium: Essays on Technology and Design Culture*, ed. Cynthia Davidson (Barcelona: Actar, 2008), 27-29.

66 Merriam Webster, Topology, definition 2.

67 Christophe Girot, *Topologie / Topology*, pamphlet 15 (Zürich: gta Verlag, 2013), 7.

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69 Hillier, 21, 24, 26.

70 Merriam webster, Topology, definition 1.

71 Girot, *Topologie / Topology*, 34.

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76 Barnett, 21.

77 *Ibid,* 38.

78 Thom Mayne, *Combinatory Urbanism: The Complex Behavior of Collective Form* (Culver City: Stray Dog Café, 2011), 33.

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85 Martin Prominski and Spyridon Koutroufinis, "Folded Landscapes: Deleuze's Concept of the Fold and Its Potential for Contemporary Landscape Architecture." *Landscape Journal,* 28 (2009), 154.

86 Les Piegl, "On NURBS: A Survey," *IEEE Computer Graphics and Applications* 11, 1, (Jan. 1991): 55-71.

87 Clarence J. Glacken, *Traces on the Rhodian Shore: Nature and Culture in Western Thought from Ancient Times to the End of the Eighteenth Century* (Berkeley: University of California Press, 1967), 24-25.

Chapter 03 - EUCLID | LUCRETIUS

"For this reason Egypt was intersected. This king also (they said) divided the country among all the Egyptians by giving each an equal parcel of land, and made this his source of revenue, assessing the payment of a yearly tax. And any man who was robbed by the river of part of his land could come to Sesostris and declare what had happened; then the king would send men to look into it and calculate the part by which the land was diminished, so that thereafter it should pay in proportion to the tax originally imposed. From this, in my opinion, the Greeks learned the art of measuring land." - Herodotus[1]

3.1. Introduction

While algorithmic design is a relatively recent development, the intellectual roots of the methodology can be said to go back much further. Several important aspects are presented in this chapter. The chapter first introduces the notion that algorithmic logic is inseparable from logics associated with formal systems, which in the Western tradition trace their genealogy back to the Greek mathematician Euclid. In many respects, the structure of his propositions differ little from the logical structuring of modern computer algorithms. Euclid's formal system was itself the result of a fertile period of intellectual inquiry in ancient Greece between the 6th and 3rd centuries BCE that would set the agenda not only for mathematics, but also for a wide range of philosophical and intellectual inquiry crossing many disciplines. Even the nature of reality itself was often explained in terms of Euclid's mathematics—most notably by those associated with Plato's school of thought which posited that reality was in a fixed, immutable state of *being* and that perceived change and even movement was a mere illusion of the senses. The design disciplines which also made use of Euclid's geometric system as a consequence inherited many of the philosophical ideals associated with this system, linking designed and engineered form to the philosophical world of ideal forms and stable archetypes—the stable world of being.

As a counterpoint to this philosophical position, however, other thinkers developed a parallel understanding which saw reality in a constant state of *becoming*, characterized by dynamic change and seeming randomness with new forms continually emerging and disappearing from the world. The Latin writer Lucretius provides a clear and powerful description of this alternate intellectual tradition and challenges the notions of permanence and stability and the relevance of ideal forms in the Euclidean-Platonic tradition. The focus of Lucretius and his successors was not on geometric ideals, but on collecting and relating vast bodies of information to paint an accurate picture of a world in flux with emergent and evolutionary properties. With the juxtaposition of these two alternate worldviews and with their focus on the notions of *being* and *becoming* respectively, the holistic view of an all-encompassing nature of which man was an intrinsic part was gradually eroded and categories such as formal vs. informal or artificial vs. natural began to emerge.

Figure 3.0: (*page opposite*) Walls of ancient Roman ruins in southern Spain. Building practices can be seen as the evolved evolution of building practices in a dialogue between the internal logic of construction and the external relations of culture.

Figure 3.1. Egyptian surveyors using rods and ropes to survey fields. From Menna's Tomb in Luxor. His official title was "Scribe of the Fields of the Lord of the Two Lands of Upper and Lower Egypt."

This chapter seeks to explore in more detail the intellectual roots of the Formalist and Structuralist traditions introduced in the previous chapter (§2.4) through the characters of Euclid and Lucretius. It recognizes the bias of both algorithmic logic and of design thinking towards the former of these two positions, but also makes a plea for incorporating aspects of the later. It argues that many aspects of dynamic and emergent forms can increasingly be described using geometric and algorithmic logics. It also argues that when formal systems respond to or interact with evolving contextual fields of information, well-adapted and performative outcomes can be achieved. This is evident in the vernacular traditions of urban or cultural landscapes with the methodology of Julian of Ascalon being presented as a model in this regard.

3.2. Origins of Geometry

It is 1400 BC. The annual floods of the Nile have receded, and the landscape has been made anew, the land covered in dark and fertile soil as far as the eye could see. The farmers were ready, having been informed by the priests, based on their observations of the heavens, that the day of planting would soon be upon them. But first, they needed to be told where to find their plots of land, somewhere in the now unfamiliar landscape, but allocated to them and their ancestors since time immemorial by the god-king Pharaoh. Soon, the king's servant arrived, Menna, "Scribe of the Fields and Lord of the Two Lands." (Fig. 3.1) Those accompanying him were carrying ropes and rods. From an old monument, they began walking on the newly created earth, placing rods in the ground, stretching their ropes, at times tracing great arcs, at times walking great distances to the goddess Nile. Slowly, the marks made on the land became recognizable, and gradually the exact pattern of fields that had marked the landscape in previous years emerged. (Fig 3.2) In a matter of days, the farmers were back in their fields, just as they had been before the floods, and after they had planted the amount of grain recommended by the priests, they found they had just enough to fill the field and no more.

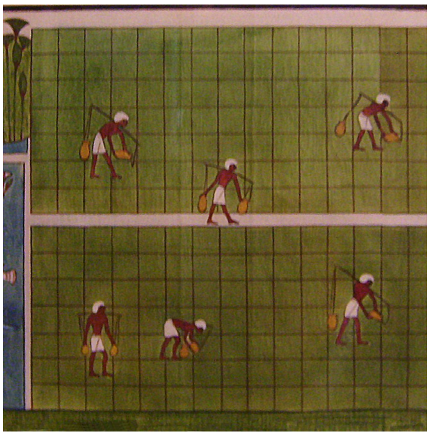


Figure 3.2: Workers in a gridded field. Gardens of Amun at the Temple of Karnak, early 14th century. From the tomb of Nakh, the chief gardener.

To the farmer in this context, this must have all seemed like magic, from the prediction of the cycles of the river, to the re-creation of the world as it was before through coordinated movements, to the precise estimation of the quantity of grain needed to plant a field. The priests and officials who guarded this knowledge may have wanted to encourage such thinking, since the stability of the state and their social order relied on a fair taxation of grain based on the quantity of land allocated to each farmer, but they themselves may have wondered at the beauty of this system that had been handed down to them as well, from generation to generation.[2]

Around 300 BCE, a Greek mathematician living in Alexandria, the new Hellenistic capital of Egypt, compiled a treatise comprised of thirteen books related to the topic of geometry, literally "earth measure," with its conceptual and procedural roots in the Egyptian system of dividing, measuring, and controlling landscape space, but which was refined and systematized in the schools of Greek philosophers. In their practice, the taut ropes and arcs were replaced with a compass and straightedge, and the flat, fertile flood plain of the Nile with a blank paper, but the concepts for deriving and manipulating form in this *tabula rasa* environment remained the same. This treatise, *The Elements*[3]*,* was to become the foundational text for the discipline of geometry for the next two thousand years, and was to have profound implications not only for the design disciplines, but also for philosophy, religion, science, aesthetics, ethics, and logic as well. (Fig. 3.3)

3.3. The Euclidean Formal System

The Elements[4] is widely regarded as the oldest extant comprehensive formal system in western thought. A formal system can be seen as a sort of game or "language composed of primitive symbols acted on by certain rules of formation (statements concerning the symbols, functions, and sentences allowable in the system) and developed by inference from a set of *axioms*. The system thus consists of any number of formulas built up through finite combinations of the primitive symbols—combinations that are formed from the axioms in accordance with the stated rules."[5] The "game" operates independently from outside meaning or semantic content, although it is often used as a logical decision making apparatus in other contexts, such as in philosophy. A formal system is often, although not necessarily, mathematical in nature. The formal system devised by the Indian linguist Panini, predating *The Elements* by about 100 years, for example, was based not on geometry and mathematics, but on the logical construction of language.[6] This was to have consequences outside of the formal system; whereas much of western philosophy has a mathematical basis for its arguments and proofs, Indian philosophy can be seen as largely linguistic in nature.[7]

The rules of formation for the game that Euclid devised consisted of ten axioms—five of which were called postulates (e.g. two points can be connected with a line, a circle can be drawn with a center and a radius), and five called "common notions" (e.g. things equal to the same thing are also equal to one another).[8] Implicit in these rules were the tools he would be using to conduct his operations, which were restricted to a compass and a straight edge[9] corresponding with the surveying ropes and rods of the Egyptians. Also described was the kind of space in which he was operating—a completely flat and infinite plane, reminiscent perhaps of the Nile flood plain, but in reality not corresponding to any actual space on the surface of the earth.

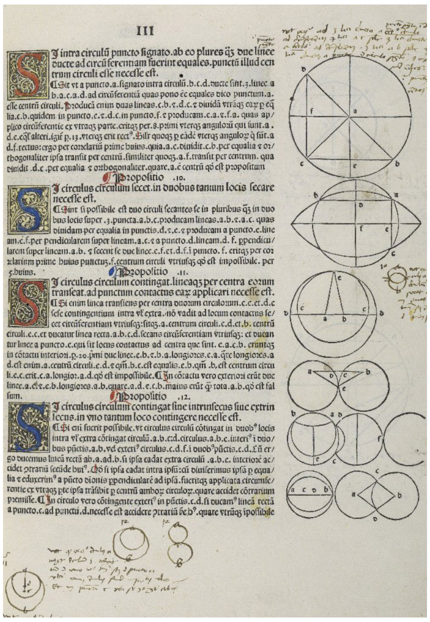
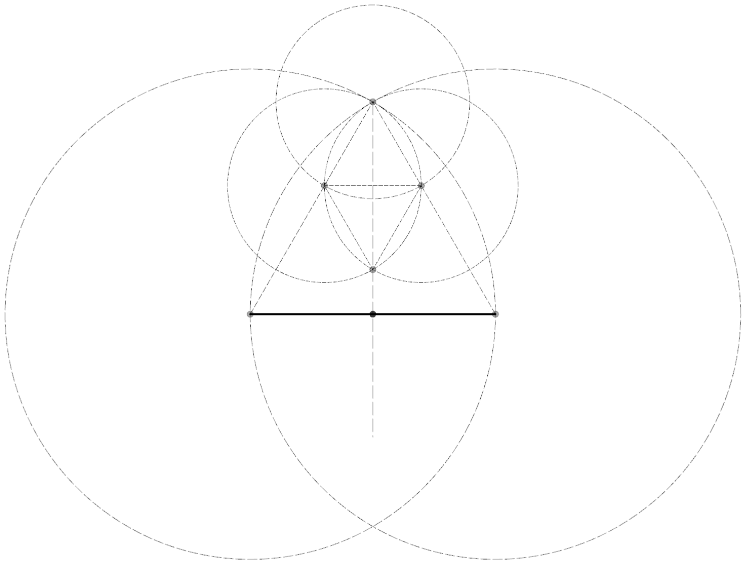


Figure 3.3: Diagrams from the first printed version of Euclid's Elements by Erhard Ratdolt in 1482.

In this mathematical space, and following these rules, Euclid carefully presents and proves 465 propositions or formulas over the course of thirteen books to construct regular shapes and solids, to translate forms in space, to describe the properties of forms, such as their areas, as well as propositions governing arithmetic operations and number theory. Much of his work was first proposed by other mathematicians—Thales of Miletus' theorem which is an essential step to finding the tangent of a circle, for example, is proved in Euclid's Proposition 1:31. The Pythagorean theorem, which is the cornerstone of trigonometric calculation, was also included in the first book as Proposition 47. It is also important to note that the practice of geometry by the Greeks and the Romans was interwoven with elaborate philosophical and aesthetic theories, and was an important component of the understanding of *nature* in the classical sense. Euclid's text, however, is largely quiet on the larger practical or philosophical implications of the system he was describing, and it may sometimes be hard to see the direct application of his set of rules, propositions, and axioms. As one example, when he described what has become known as the Golden Ratio in his work, he dryly asserts that "a straight line is said to have been cut in extreme and mean ratio [Golden Ratio] when, as the whole line is to the greater segment, so is the greater to the lesser."[10] Euclid makes no mention of the ratio's usefulness, or the aesthetic theories based on observations of natural form that make the ratio so appealing, or of its use in architecture or design.

3.4. Euclid's Propositions as Algorithms

In the context of computation, what Euclid produced might be described in today's terms as a very early and comprehensive set of algorithms or codes.



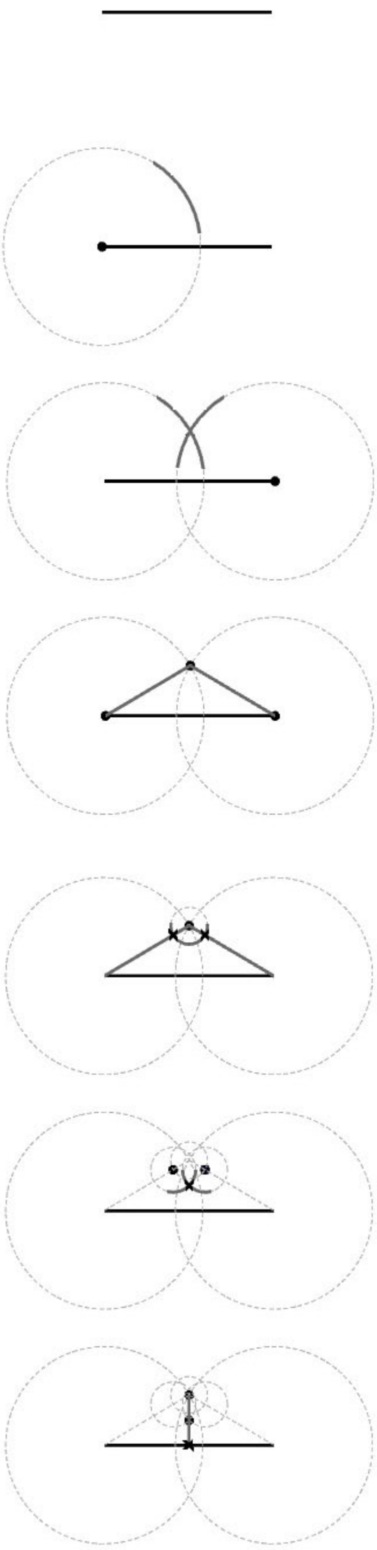


Figure 3.4 Process for finding the midpoint of a line according to Euclid, Proposition 1.10. Above the steps are shown, with a composite of the steps represented at top, right.

A good example is Book I, proposition 10, his method for cutting a line of any finite distance in half. (Fig. 3.4) He starts each proposition by setting out his parameters and variables: “Let AB be the given finite straight-line.” He defines procedures and sub-routines: “Let the equilateral triangle ABC have been cut in half by the straight-line CD [Prop. 1.9]” and concludes each proposition with a sort of ‘end program’ statement—the phrase “which was the very thing it was required to do.” In practical terms, many of these procedures may appear overly complex or cumbersome. In the previous example, one might assume that the easiest method of dividing the line into two parts would be to simply measure the line, divide that number by two, and then measure out that distance again to find the midpoint, or in the context of Egyptian surveying, to stretch the rope, and then to fold it in half to find the midpoint. Instead, Euclid’s method requires inscribing no less than five great arcs to fix four control points in space, before the final line can be drawn that bisects the original line.[11] For Euclid, however, such digressions were necessary to maintain the integrity of the system and to eliminate the creep of human error being introduced into the system, and to maintain overall confidence in the formal assumptions. Also important was to establish a method which would not be applicable just in one particular problem, but in *all* possible problems of the same nature. Such digressions and attention to internal consistency and logic remain fundamental to the task of coding and computer programming.

Another lesson from Euclid’s *Elements* which can be translated to modern computation is that the codes had to be considered on two levels. On the first level, Euclid’s routines contained no extraneous information, no commentary, and were not tied to any specific problems. They could be said to be, much as minimalist art strived to be, *wertfrei*. (see §1.6) They did not give any instructions on how to lay out fields, gardens, cities, artworks, or buildings. They were simple routines of an algorithmic nature with design and spatial implications, but they did not themselves design space. They still required an educated person to bring them together to create spatial structure, making decisions based on theoretical and practical issues. There is, for example, no specific instruction on how to lay out a gridded set of fields, the task for which geometry was, according to tradition, first invented. This is an important consideration to keep in mind both for those who embrace generative tools with too much enthusiasm thinking if they can program an algorithm, they are a good designer, or for those who reject them too soon, based on a fear of machines taking over the task of design. On the second level, however, since Euclid's propositions strove for universality, they could be applied to many types of problems of a very broad nature. Those well versed in geometry could apply the same pattern or rules, for better or worse, to problems ranging from construction and engineering on the one hand, to ethics and moral philosophy on the other. Rather than limiting thought, they allowed for the creative translation of patterns from one discipline to another. Euclid reads as pure mathematics, but it spoke to a metaphysical worldview whose legacy continues to the present.

3.5. Larger Context of the Euclidean Formal System

Even though he composed his text in Egypt and even though the roots of his geometric system could be traced back to the surveying practices of the Egyptians, Euclid's geometric system was largely the fruit of an intense period of mathematical, philosophical, and scientific inquiry originating in the Greek homeland. Here, an increasingly cosmopolitan society in regular contact with both Egyptian and Babylonian influences and ideas sought to formulate a new understanding of the world and its origins rooted not in the traditional myths and epic histories which had up to this point played such a prominent role in Greek thought, but in observation and most importantly reason.

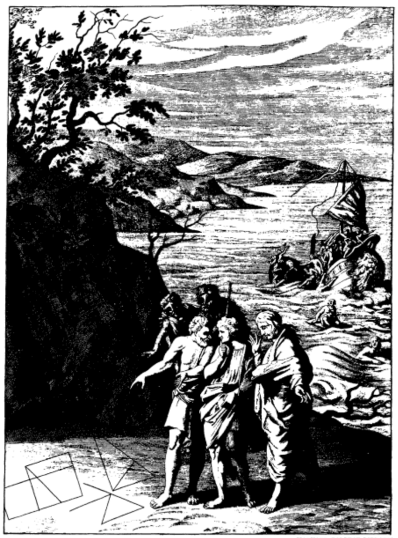


Figure 3.5: Front piece to Clarence Glacken's T*races on the Rhodian Shore*, where shipwrecked travellers are assured by the presence of geometric markings on the island, indicating the presence of other humans.

In his commentary on Euclid's first book of *The Elements*, the ancient writer Proclus gives a genealogy of the Greek mathematical tradition which contributed to the content of Euclid's work, starting with Thales of Miletus, who learned geometry during a visit to Egypt and who was able to use his new knowledge to calculate the height of objects such as the Pyramids, or to measure distances to objects such as ships at sea.[12] Another Greek from Ionia, Pythagoras of Samos, further developed Greek mathematical inquiry at a philosophical school and community he had founded in southern Italy. According to tradition he had deepened his understanding of mathematics and geometry both in Egypt, where he had lived for many years, and in Mesopotamia, where he had been a captive in the royal court of Chaldea. He and his followers believed, according to Aristotle, "that the principles of mathematics were also the principles of all things that be" and "since finally everything in nature appeared to them to be similar to numbers, and numbers appeared to be first among all there is in nature, they thought that the elements of numbers were the elements of all that there is."[13] None of Pythagoras' original writings have survived to the present, but according to tradition, the young philosopher Plato made a special trip to Pythagoras' southern Italian colony with the express goal of acquiring a copy of his writings. Plato would go on to incorporate much of Pythagoras' learning into his own philosophical school, the importance of the emerging mathematical system reflected in the apocryphal inscription at the entrance to the school which stated "Let no one ignorant of geometry enter."[14] Euclid was one of the students who did enter Plato's school, so it is worth understanding Plato's ideas to understand Euclid's task.

Apart from the mathematical influence of Pythagoras, and his training in ethics under the philosopher Socrates, Plato's thinking was deeply affected by the philosopher Parmenides, who wrote a single text, now existing only in fragments, called *On Nature.*[15] This title is shared with two earlier philosophical works, the Miletians Heraclitus and Anaximander, who both described reality in their own versions of *On Nature* in terms of indeterminacy and constant change, in a constant state of *becoming*.

Parmenides, however, argued quite the opposite. He proposed that reality is all encompassing, uniform, and timeless, and that both change and even motion were impossible. His ideas came down to a paradoxical word game dealing with notions of being, arguing what is *is*, what is not *is not*, and that something cannot come from nothing. Since nothing is not, nothing cannot exist. Motion implies moving into a space of nothingness, which cannot exist, so motion must be an illusion. Furthermore, new things cannot enter reality since a new idea must come out of nothing, and again, nothing cannot exist. Any perceived change or motion, or change in state through birth or death, was therefore an illusion of the senses. When rational thought comes into conflict with the senses, the rational argument must prevail.

Despite the seeming absurdity of Parmenides' arguments, many including Plato took them very seriously. This is evidenced most vividly in Plato's dialogues, where Parmenides is the only character to have bested Socrates in a philosophical discussion. Plato himself attempted to solve the Parmenidian dilemma by splitting reality in two, arguing that there was an eternal, unchanging, uniform reality, the "World of Forms," and that our perceived reality, which is the product of creation, is an ill-formed shadow or a defective manifestation of this ideal world. Hence there exists in the "World of Forms" an ideal circle, but any circle we experience or could draw in perceived reality is a corruption of this ideal from the World of Forms. Not only objects such as circles or chairs, but also abstract ideas such as love or friendship, also had an ideal form. And for each object or concept, there was only one single ideal—one ideal circle, one ideal chair, one ideal friendship, one ideal love. Human beings each had a prior existence in this World of Forms and in our current perceived reality it was the task of the philosopher to recall the ideal forms and seek to transform perceived reality to the extent possible to approach these pre-existent ideals.[16] Geometry was an intermediary between the perfect reality of the world of Forms and perceived reality. It is easy to see now why Plato in his school forbade the use of measuring tools in his practice of geometry. Measurement introduced error—as long as the mathematician stays true to the fixing of points through the sweeps of circles, the most perfect form, error in creation could be minimized.

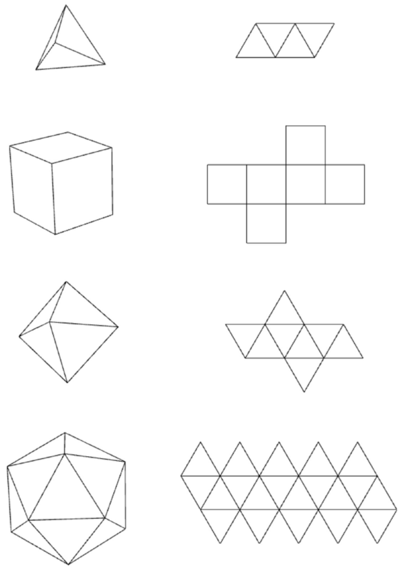


Figure 3.6: Platonic solids corresponding to the four elements.

Another of Plato's ideas which is key to understanding Euclid's task, was that the basic building blocks of matter, the five elements, were associated with what we still refer to as the five Platonic solids. (Fig 3.6) Four of these—the tetrahedron, the cube, the octahedron, and the icosahedron—corresponded to the elements fire, earth, air and water respectively. The fifth solid, the dodecahedron, corresponded to the envelope of the universe. The logic behind assigning the solids to the elements is explained in Plato's dialog Timaeus. Fire has the four-sided form because it is quick, but also sharp. The six-sided cube is the only one of the solids which can tessellate 3-dimensional space, hence it made up the mass of the earth. The two remaining solids are assigned to air and water based on their perceived bulk and smoothness.[17] These four solids could in turn be decomposed into right-angled isosceles triangles, allowing the elements to transition from one form to another, giving a plausible theory for chemical transformations. The five platonic solids are described and modeled in Euclid's thirteenth and final book in *The Elements* where he proves that no other symmetrical multi-facetted solids are possible. It has been suggested that the whole task of the other twelve books was to build up to the construction of these solids, the elements of mathematics describing the elements of reality.[18] This simple yet compelling description of underlying reality being composed of a simple set of interchangeable triangles could only be disproved with the advances in atomic theory in the 19th and 20th century, but it is still interesting to note that 3-dimensional form in contemporary computer environments ultimately relies on a Platonic concept, where all complex forms are broken down into triangles, or in the case of the popular program Minecraft, into the cubes of earth.

3.6. Lucretius *On the Nature of Things*

The legacy of the Euclidean formal system and Plato's theories on Forms in the history of Western thought and design cannot be overstated, but it reflects only a small portion of Classical thinking and was by no means the dominant philosophical paradigm in the Greco-Roman world. Plato's thinking emerged out of an ongoing debate about the nature of reality and the role of reason in discerning reality going at least as far back, as previously mentioned, to the Miletians, who were concerned with ideas of incessant change and unpredictability. Despite his carefully considered solution to the Parmenidean paradox by effectively severing reality into two—a physical and a metaphysical realm—Plato's writings did not end this period of inquiry. Even his most famous student, Aristotle, rejected many of Plato's dogmas and placed a much stronger emphasis on the role of empirical observation to ascertain reality and to describe nature, rather than reasoning out a lofty ideal. Perhaps the strongest contrast to Plato's thought, however, comes in the work of the Latin poet Titus Lucretius Carus and his extensive poem *De rerum naturum* (On the Nature of Things), written in the first century BCE. (Fig. 3.7) Like Euclid's *The Elements,* most of the ideas in *De rerum naturum* were not the product of Lucretius' own original thinking, but represent the culmination of the thought of the Greek school of thought known as Epicureanism after its founder Epicurus. Epicurus himself owed a significant intellectual debt to Democritus, whose theory of atomism solved the Parmenidean paradox by shattering reality not into two, but into an infinite number of tiny, Parmenidean "wholes" called atoms, which were eternal and unchanging themselves, but which moved ceaselessly through the void of space, combining and recombining, and even, according to Lucretius, *evolving.*

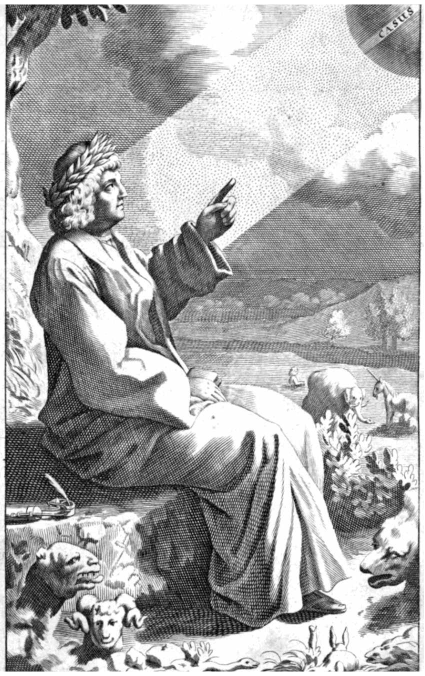


Figure 3.7: Lucretius observes a beam of light, surrounded by real and mythical animals.

In contrast to Plato's world of Forms, which was accessible only through pure *reason*, the Epicurean-Lucretian world of atoms was accessible through careful *observation*—an empirical approach. Taken at face value, this may seem impossible, as atoms are much smaller than what the eye can perceive, but the examples given by Lucretius are quite astute and compelling. He noted how materials seemed to wear down: "the fall of dripping water hollows the stone, the bent iron ploughshare secretly grows smaller in the fields, and we see the paved stone streets worn away by the feet of the multitude,"[19] and that this material needed to have some mechanism to take it away. This was the first insight into the atomic hypothesis. He also observed that despite all the decay in the world, nature seemed to find ways to constantly refresh itself: "thus the sum of things is ever being replenished."[20] Perhaps his most astute observations were a series of seemingly unconnected observations which he connected to form a very early description of the hydrological cycle. He observed that a wet cloth placed in the sun, dries, and that the water, in the form of small atoms, has disappeared. He also observed that the sea, despite constant influx by rivers, never filled up or seemed to increase its level. From this he projected that much like what happens with the cloth on a smaller scale, in the sea water is taken by the sun at a rate fast enough to counteract the inflow of all the rivers in the world. This water in turn moves through the atmosphere falling in the form of rain, replenishing the rivers.[21] This leap from small scale observations to large scale ideals in quite the opposite direction as what the Platonists were proposing represents what Deleuze and Guattari describe as "hydraulic thinking," a thought process diametrically opposed to "royal science."[22]

Much as in the hydrological cycle, nature finds other ways to replenish itself, and even to advance itself. Lucretius *did* believe there were templates for form, but unlike Plato's single templates which existed outside of objects, Lucretius' templates or *seeds* existed within things, and could even be passed down from generation to generation. The modern reader can also sense an early version of evolutionary thinking in Lucretius' writing. While Plato's formal templates were eternal, single, and unchanging, Lucretius seems to suggest that nature could create *new* seeds: "Many bodies and seeds [have been] added to earth since beginning."[23] He correctly sees that an individual's makeup combines elements from the "seeds" or genes of both parents, with an element of random chance.[24] Modern readers also see a hint of natural selection in Lucretius writings, where he proposed that nature tests new seeds, and that "monsters"—what we might call genetic mutants—are not long for this world.[25] While it is unclear if he saw a progressive evolutionary development in nature, he certainly saw an evolutionary principle in his retelling of the development of human, which he certainly saw as organic, changing entities. In contrast to most Greek thinkers, who saw a world in decline from a mythical golden age to the present, Lucretius saw things in quite the opposite light, and he saw human technological advancement from a golden, to a bronze, and then to an iron age as a progressive rather than a regressive development.[26] There is no teleological aim to this development, however, and it is part of what we might in contemporary language call a recursive, non-linear process. All advancement happens in stops and starts. Human progress comes sometimes through trial and error, such as with the development of human speech and language[27] and at other times through astute observation of natural processes such as when, as Lucretius suggests, early mortals attained fire by mimicking nature's fire creation processes,[28] and does not require a divine impulse or teleology. The engine that drives these changes in nature and in culture is randomness, which Lucretius sees not an imperfection or a flaw in nature, but as absolutely essential.

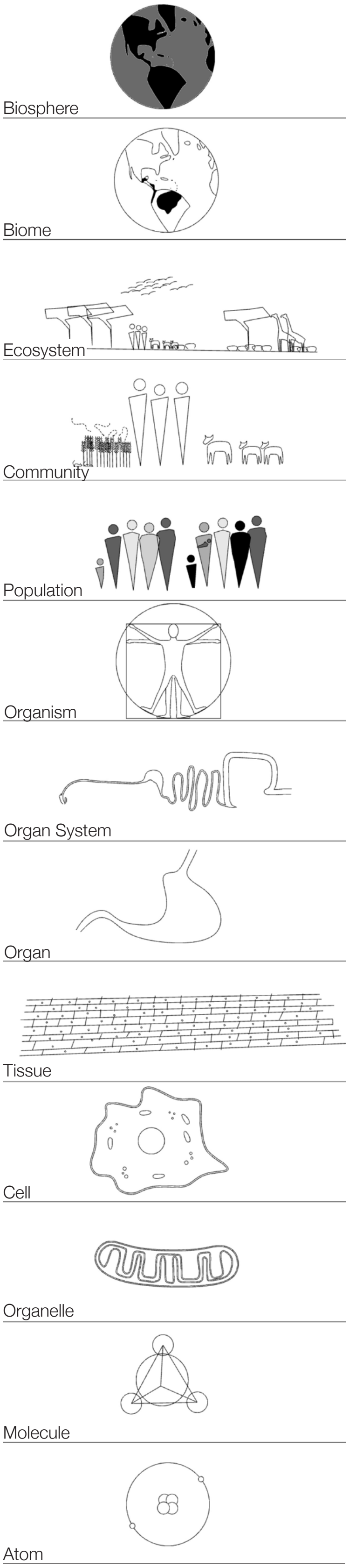


Figure 3.8: Drawing based on Odum's Biological Hierarchy.

This insight on the nature of randomness is one of Lucretius' most astute and oft-cited observations. Lucretius' thought starts with the everyday observation of small particles in a beam of light in a calm room:

> "For look closely, whenever rays are let in and pour the sun's light through the dark from the places in houses: for you will see many tiny bodies mingle in many ways all through the empty space right in the light of the rays, and as though in some everlasting strife sunbeam: wage war and battle, struggling troop against troop, nor ever crying a halt, harried with constant meetings and partings; so that you may guess from this what it means that the first-beginnings of things are forever tossing in the great void."[29]

What Lucretius observed can be described as an early description of Brownian motion (see §A7.1). He goes on to extrapolate from this small, random dance in a dark corner of a house, something with universal consequences. Manuel De Landa finds the quote so profound, he opens his book *A Thousand Years of Nonlinear History* with Lucretius' observation that:

> "When atoms are travelling straight down through empty space by their own weight, at quite indeterminate times and places, they swerve ever so much that you would call it a change of direction. If it were not for this swerve, everything would fall downwards

> through the abyss of space. No collision would take place and no impact of atom on atom would be created. Thus nature would never have created anything.”[30]

While Lucretius’ observation stems from the faulty assumption that the universe is “falling” and that random collisions somehow held it up, the underlying premise, that matter *swerves* with indeterminate movements and that the resulting interactions with other particles leads to the genesis of structure in the universe, corresponds quite well with current quantum theories. (see §7.3)

3.7. Lucretius and Emergence

Taken together, Lucretius “hydraulic” and nonlinear philosophy points towards what we, in contemporary terms, might describe as the thinking of *emergence*, the idea, according to Weinstock, that “humans and all other living beings emerge from, and exist within, the dynamic processes and phenomena of the natural world” and that “energy, information and material flow through all forms of the world, and human forms and culture have coevolved and developed within those flows.”[31] Rod Barnett presents an in-depth exposition of emergence theory in his 2013 text *Emergence in Landscape Architecture*. According to Barnett, emergence is found exclusively in systems that are nonlinear and open, systems that require disturbance in order to grow and evolve.[32] Emergent phenomena are *irreducible,* that is they cannot be reduced to their constituent elements. Citing Odum, he recalls that cells are more than their constituent molecules, ecosystems more than the populations inhabiting them, and regions more than the individual landscapes contained within. (Fig. 3.8) While more than the sum of their parts, emergent phenomena remain dependent on their more fundamental constituents—a cell cannot escape the mechanics of molecules—a principle Barnett describes as *supervenience.* At the same time, a higher level entity can affect *downward causation* on lower level entities—changing ecosystem dynamics affects lower level populations for instance, while the evolving needs of regions, for example, will alter its constituent landscapes. This nonlinear interaction is fundamentally *unpredictable,* and ultimately can lead to *novelty*, which Barnett describes as the state when a “critical level of complexity” has been reached “such that it cannot be described without recourse to a new conceptual or theoretical apparatus, then the system is said to incorporate emergent phenomena.”[33]

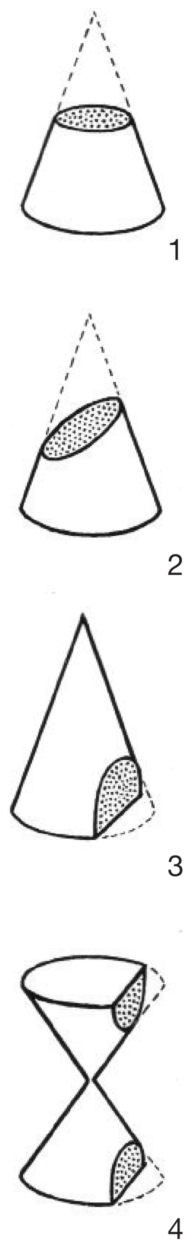


Figure 3.9: Afer Euclid, authors such as Achimedes and Apollonius extended geometrical knowledge, such as with the definition of conic septions. The 1)circle and 2) ellipse are closed forms, whereas the 3) parabola and 4) hyperbola are open, infinite forms.

3.8. What Would a Lucretian Formal System Look Like?

This chapter started with a brief description of the Euclidean formal system, which grew out of Platonic philosophy, and which in turn served as a tool to both expand and reinforce the thinking inherent in his school of thought. No equivalent “Lucretian” formal system to stand in contrast to the Euclidean one can be said to exist. We can ask ourselves, however, what such a system might look like. Deleuze gives some hints citing the geometer Archimedes as also possessing aspects of Lucretius’ “hydraulic” thought. This categorization is likely due to Archimedes’ fascination with the workings of fluids, with the infinite, and with forms expressing qualities of the infinite, such as spirals and parabolas. Archimedes devised a *method of exhaustion* similar to the modern process of integration, for example, predating Leibniz and Newton’s Calculus by nearly 2000 years, and was one of the few thinkers ever to have attempted a reckoning of how much matter is in the universe. His answer that the universe could hold 10^{63} grains of sand, which is equivalent to 10^{80} atomic nucleons, is by a striking coincidence roughly equivalent to the Eddington number of 10^{80} atomic nucleons, the current best estimate of the amount of matter in the observable universe.[34] The work Archimedes began on conic sections was followed up by the geometer Apollonius, who defined relationships between circles, ellipses, parabolas, and hyperbolas, the later two forms of the infinite. (Fig 3.9)

The "baroque" forms of Archimedes and Apollonius might still miss the mark for Lucretius, and notions of form related to pure shape may not be very significant at all. A telling passage from Lucretius himself comes from his observation that words in a poem or letters in the alphabet have no inherent meaning except in relation to other elements: "For the same letters signify sky, sea, earth, rivers, sun, the same too crops, trees, living creatures; if not all, yet by far the greater part, are alike, but it is by position that things sound different. So in things themselves likewise when *meetings, motions, order, position, shapes* are changed, things too are bound to be changed."[35] Notice here the word "shape" is mentioned last; more important in Lucretius' mind are "meetings, motions, order, and position." These words all reflect encounters and relationships. Even the word shape can be seen as a word with relational meaning in Lucretius' thought. His atoms are not like Euclid and Plato's elements—inert triangles with no innate mechanisms for bonding—but were themselves shaped and formed with protrusions such as hooks and eyes, mechanical bonds that served particular functions and which gave the various types of matter their peculiar properties. One might say that the performance of his atoms' shapes was more important than their concrete formal properties. A Lucretian formal system then, would stress dynamic relationships and interactions.

One of the hypotheses, or more correctly one of the hopes of those who stress the role of the computer, or more specifically the algorithm, in design is that it can fill a role similar to the Euclidean formal system in discerning "truth" in complex, nonlinear systems of the type described by Lucretius, and that this understanding will transcend individual disciplines and pursuits, which much like the Euclidean formal system can apply its logic to problems.

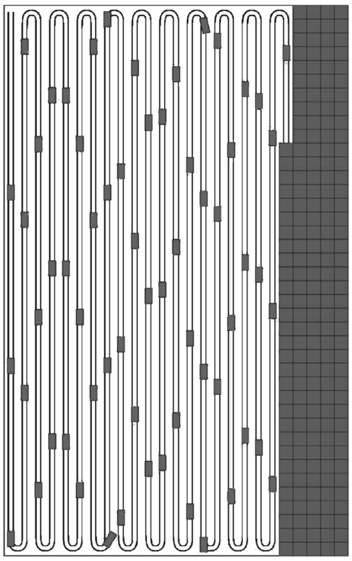
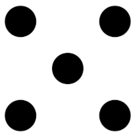


Figure 3.10: Boustrophedon weaving (the back and forth plowing motion of fields) is an internal logic of agriculture which can tend to favor grid-like structures. Here an algorithm „simulates" the process of harvesting a field of hay, leaving bales at specific intervals on a rectangular field, *top*, and on irregular fields, *bottom.*

3.9. Formalism and Geometricism as Emergent Phenomena

At this point, it is worth looking at a few examples of how systemic thinking, in terms of both formal systems and emergent vernacular practices, informed the design of landscapes in several ancient societies, and how attitudes in a Euclidean or Lucretian vein might be reflected in several ancient landscapes. Briefly presented are both examples of "formal," planned landscapes, and more "informal," emergent landscapes. It is worth noting, however, that this oft used categorization stands on a very unstable footing, as formalism itself can be seen as an emergent phenomenon, and almost every culture has developed a rich system of abstract geometric art and pattern, often quite independently, if not a well-developed systemization of geometry itself. Most notable might be the Chinese *Nine Chapters on the Mathematical Art,* which independently developed a range of mathematical propositions growing out of practical problems relating to surveying, area calculation, commerce, and construction, and which as a practical system of geometry was perhaps every bit as powerful as the Euclidean one.

The use of particular formal devices seems to have also *emerged* quite independently in a range of cultures around the globe. The grid, for example, the formal device *par excellence,* was not an original invention of the Greeks or Romans despite their extensive use of the method. True, Roman towns and Greek colonies were laid out with grids, but we see the same thing, for example in China, in the Indus valley, and even in Mexico. The logics of the grid seem in turn to be closely tied with the logics of agriculture. The Chinese pictogram for field "田" is a small grid, walled gardens in ancient Iran stem from a grid-like topology oriented in terms of overall topography,[36] while the efficiencies of irrigation and the drainage of fields almost always demand an overall grid-like structure. At its core, agriculture also employs a grid-like system of planting with deep vernacular and cultural associations. Ethnobotanist Wade Davis offers us just one of many examples of this, where the traditional planting pattern of the Kogi people in Colombia, where the men would plant a series of agricultural rows in one direction, while the woman would plant similar rows but in another direction, and how these two systems came together to "weave" a fabric-like, gridded pattern.[37] (Fig. 3.10) Another pattern to *emerge* from agricultural practice is the quincunx, which in isolation looks like the five on a six-sided die, but when repeated, the quincunx produces a pattern with a similar logic to another regular tessellation, the hexagonal pattern of honeycombs, convection cells, or soap bubbles. (Fig. 3.11) The pattern optimizes the volume of circles and spheres, and as such ancient writers already recommended planting orchard trees in this pattern to maximize canopy growth with respect to neighbors.[38] The connection between fields and fabrics—Deleuze's striated spaces—is further developed in Chapter 9. Some observations on the emergence of grids as a convenient technological solution in the case of the layout of irrigation systems, and as a cultural practice associated with agriculture and the optimization of harvests through regular plantings, will be returned to shortly after exploring emergent landscape geometries at other scales—in the garden, the broader cultural landscape, and in the city.



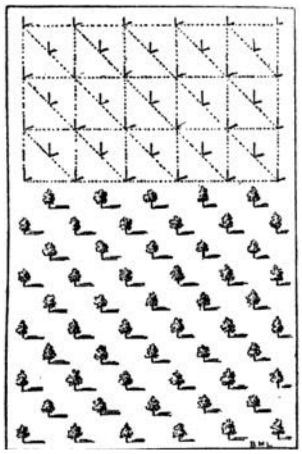


Figure 3.11: The quincunx, derived from the pattern denoting the number 5 on a die, when repeated produces a pattern on a hexagonal grid, one of the three regular Euclidean tessalantions. Image from Sir Thomas Brown's *The Garden of Cyrus or the Quincunzial Lozenge, or Network Plantations of the Ancients, naturally, artificially, mystically considered* (1658).

3.10. The Garden

The walled garden is one of the most well-known landscape typologies in the ancient world with a rich tradition dating back to the earliest civilizations. In light of the two strains of Greek philosophical thought, this brief look at the garden only considers a few examples from this part of the world. There is scant archaeological evidence of how Greek gardens may have been laid out, and much of what we know about them comes from literary sources. From the scant evidence, we can assume that most early Greek gardens were functional spaces with a generally formal, geometric layout structured by watercourses, which for reasons of economy were laid out in straight lines.[39] Geometricism seems to have dominated garden design throughout the period but there are a few notable exceptions. One may have been the garden at the philosophical school of Epicurus, which represented a significant departure from previous gardens in the city. Pliny the Elder emphasized in his writings Epicurus' aim of "creating the illusion of the country in an urban setting" which suggests an early attempt "to create a garden for some aesthetic effect rather than one solely devoted to fruit and vegetable production."[40] This "pleasure garden" became so strongly associated with Epicurean thought that the school itself came to be known as "The Garden,"[41] much as Plato's school was associated with Geometry. Another garden motif to emerge in the late Classical and Hellenic period was "the meander." (Fig. 3.12) Named after the winding Meander River (Gr. Maíandros) near Miletus, the stream was famous for its especially sinuous nature. One would like to think that the pre-Socratic philosophers, so concerned with the ever changing nature of reality, would have been inspired by the river's chaotic pattern, or that this was the river Heraclitus, who lived in the region, would have referred to when he asserted that "you could not step twice into the same river."[42] Regardless, the pattern emerges in many situations in nature with variable, dynamic flows of matter and energy, and is a signature of chaotic processes (§8.3). The earliest instance of the meander in a garden as a design element was in Syracuse, where a series of

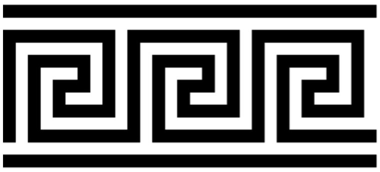


Figure 3.12: The meander is a frequent pattern in Greek art and later garden design. Named for the sinuous *Maindros* river near Miletus, it represents the dynamic forces of nature.

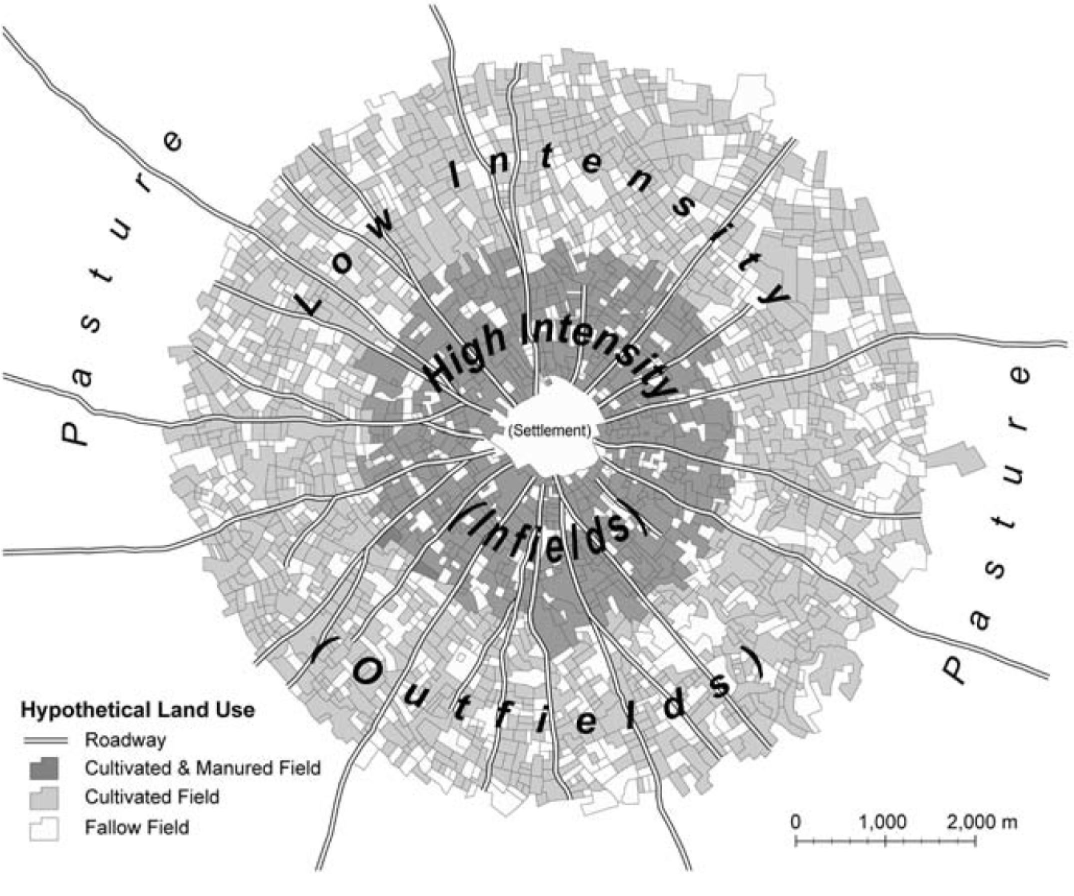
sinuous paths were described with this name, but it also made a prominent appearance in the royal park and gardens of the city of Alexandria, this time as a winding water-channel or canal, offering a stark, informal contrast to the rigid geometry of the planned city.[43] It is interesting to note, with these scant examples of informality in the garden, that informality was a deliberate, planned decision, while formal elements entered the garden largely instinctively and as an expression of long-held cultural traditions. In this way, geometrical "formal" gardens could be considered more emergent than their "informal" counterparts.

3.11. The Cultural Landscape

In the broader landscape of the ancient world, three general types of emergent geometries can be identified. In generally flat, agricultural landscapes, especially when associated with hydraulic systems, gridded geometries tended to dominate. Girot suggests the grid-like pattern of irrigation systems was derived from the orthogonal geometries of walled gardens themselves,[44] but the internal, gridded logic of planting, associated by many cultures with the weaving of fabrics, may have also played a role. The persistence of grid-like structures in flat, hydraulic landscapes to this day, such as in the Fenlands of England, the Netherlands, or in the North China Plain points to the fact that hydraulic technology itself may have been the most important catalyst for the adoption of grids, but in general internal and external forces can be said to be at play.

While such geometries worked well for the technologies associated with agriculture, they were less helpful for organizing space on a broader scale or for facilitating movement, an emergent practice which runs counter to the logic of grids. In broader scales where topography is not a significant

Figure 3.13: Idealized Settlement Pattern in Bronze Age Mesopotamia. The logics of movement from the center to the hinterland and the internal logics of agriculture shape the general structure.
Jason Ur, „Emergent Landscapes of Movement in Early Bronze Age Mesopotamia." 195.



constraint, one could hypothesize that based on purely internal logics, settlements would tend to organize themselves in a hexagonal or 'quincunx' pattern. This pattern would emerge naturally as each town tries to maximize its agricultural or resource gathering hinterland while minimizing travel times from this hinterland to the settlement center. (Fig. 3.13) Existing landscape features associated with the topography, hydrology, and the biospheres of sites naturally alter this idealized pattern, but we will ignore this complication for now. In this diagrammatically hexagonal landscape, daily tracks of movement from the hinterland and to the settlement center and back create an emergent, radial road network.[45] When two adjacent settlements carry out trade, the radial networks naturally connect, and as certain settlements develop competitive advantages over others, a network of movement based on the initial radial pattern of daily migrations emerges. This generally radial plan of the landscape of movement enters into a dialogue with the striated, grid-like landscape of settlement and a pattern that synthesizes the logic of the two tends to emerge through time. (Fig. 3.14)

Finally, as hinted at in the previous section topography and natural hydrology play an important role in the organization of patterns in the broader landscape. The effects of topography are too varied to generalize, with waterways sometimes encouraging settlement and at other times discouraging it, and with hilltops and ridges sometimes becoming the preferred locus of settlement centers, while at others the valleys. What is important to recognize here, however, is that a series of cultural practices, some with stratifying, territorializing, and internal logics, such as agriculture, and others with disruptive, deterritorializing, and external logics, such as trade, commerce, and movement, play out in a performative field which is shaped by existing and evolving context, or broader field. This notion will be further explored in part two, especially in Chapter 9 on smooth and striated space.

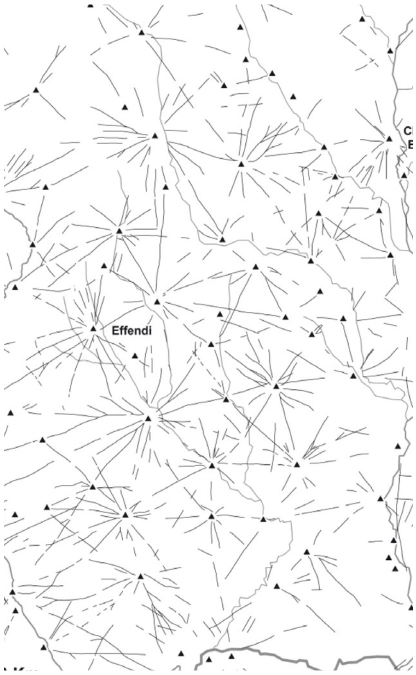


Figure 3.14: On a broader scale, the road networks of various centers which have maximized their respective hinterlands begin to connect to each other to form the basic of an emergent road network.
Jason Ur „Emergent Landscapes of Movement in Early Bronze Age Mesopotamia." 188.

3.12. The Urban Landscape

Similar to the broader landscape, internal and external logics shaped the formal and informal planning and growth of cities in the ancient world. Most cities in the core zone of Greek civilization grew organically from small villages, often at or near sites of even earlier human occupation, based on some of the logics discussed in the previous section. To understand how Greek ideals affected town planning, it is perhaps more helpful to look at later examples of Greek colonial settlements. Two examples are particularly interesting. Alexandria was a noted Hellenistic colonial capital where the Greek conquerors, like the Romans who followed them, used the efficient logic of the grid. The town of Alexandria, for example, was laid out based on a grid with little regard for the underlying topography, nor for the surrounding coastline of the city. (Fig. 3.15) As previously mentioned, the royal gardens incorporated the anti-geometric motif of the meander, but even this represented a deliberate, planned decision, and was not part of an emergent process. It is interesting to note that Alexandria, like most planned towns from this period, developed gradually away from its initially rigid master plan and by the medieval period, could be characterized as an informal settlement, interestingly occupying a piece of land which had also naturally "emerged" over time through the process of sedimentation around an engineered causeway. The process of "informalization" which took place in Alexandria and numerous other cities in the ancient Greco-Roman world was not, however, chaotic and disordered, and was the result of the interaction of various rules, codes, and customs in a non-linear, processes.

The process whereby settlements in this part of the world evolved their informal character was the object of a study by Besim Hakim who

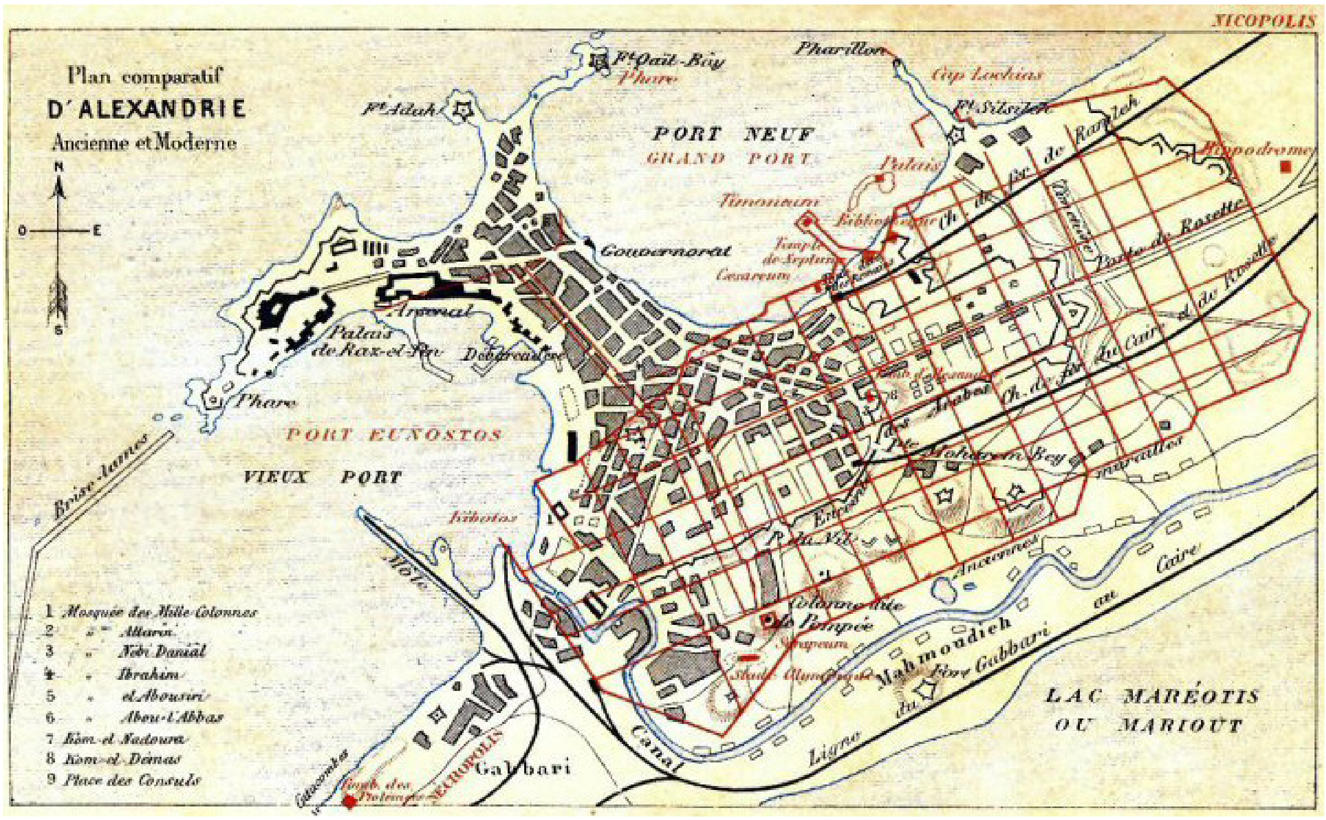


Figure 3.15: Mahmoud Bey's 1885 plan of Alexandria with original streets show in red. By the medieval period, the center of the city had shifted to land which in the ancient period was underwater, but which emerged from the bay after centuries of sedimentation caused by the construction of a causeway (H de Vaujany's guide-book: Description de l'Egypte, Alexandrie et la Basse-Egypte, Paris 1885).

studied a planning code written by a Byzantine architect Julian of Ascalon to govern the continual development of the city he called home. We would describe it today as an early set of urban design rules, where new buildings were granted a degree of freedom so long as they observed certain interactions with local neighbors. According to Hakim, the goal was "to deal with *change* in the built environment by ensuring that *minimum damage* occurs to preexisting structures and their owners, through stipulating fairness in the *distribution of rights and responsibilities*…particularly [among] those who are proximate to each other." This would ultimately "ensure *equitable equilibrium* of the built environment during the process of change and growth."[46] The code incorporated Byzantine law, local customs and vernacular practices, as well as the architect's informed reasoning. Although no master plan existed, views from the houses of existing owners, particularly of the sea, of gardens and trees, and of public paintings, as well as wind corridors in both summer and winter, were protected. Neighbors were required to coordinate the drainage of rainwater and sewage (separately) from their sites, and also had to make sure these elements did not conflict with the public realm, and new planting also had minimum setback requirements depending on tree species to ensure roots did not damage neighbors walls, or that tree branches did not allow burglars access to second and third story windows. The treaties tried to balance the rights of existing residents, while allowing new construction to take place.[47] The results of Julian's treatise after several centuries was an urban fabric that was greatly admired both for its urban and architectural qualities. The treatise was also adopted and adapted in many other cities in the eastern Mediterranean, and had over 1400 years of impact in this part of the world, contributing to the growth and development of many well-loved cities and towns. The complex urban fabric resulting here exhibits many of the hallmarks of complex-adaptive systems, where local interactions are prioritized—think locally, act locally—but where a recognizable global pattern emerges. Furthermore, feedback loops between existing structures and proposed future construction, acting in an iterative manner, produce a complex end result through time whose exact dimensions cannot be foreseen, but whose overall character remains stable. (Fig. 3.16)

Hakim took the lessons he learned from Ascalon, and combined with several other case studies proposed a focus in urban design on *generative processes,* where the focus is on developing instructions on "what to *do*, what *actions* to take to build…rather than detailed drawings that tell us what the *end*-result is supposed to be."[48] Much like Julian of Ascalon's treatise, the task of urban designers should be to find a series of "meta-principles, derived from a locality's history and customs" to govern change, especially in historic districts and settings. While Hakim proposes no computational process to simulate the growth of ancient cities through generative processes, others have taken up the task. An early example whereby a designer attempted to extract the traditional codes of vernacular processes to generate urban form is seen in the work of Celesino Soddu, who in the early 1990s published a number of articles touting an engine he had produced to recreate medieval Italian hill towns using the "genetic code" of such settlements.[49] (Fig. 3.17) A much more influential example, owing to its brevity and transparency, is found Parish and Müller's highly cited paper "Procedural Modeling of Cities" which incorporated a number of well-known algorithmic methods with ideas from Hillier's *Space Syntax* and Stiny's "shape grammars*"* to create an engine for generating cities.[50] Their methodology was very successful and their research was purchased by ESRI to develop their City Engine, a tool for generating cities based on procedural rules and for testing the potential impact of establishing certain regulations on the long-term development of the urban fabric. (see §10.4)

3.13. Reflections on Planned and Emergent Landscape form in the Ancient World

In reflecting on some of the general patterns emerged at the scale of the garden, in the broader landscape, and in the city, several generalizations can be made which might inform approaches to landscape form in the modern world. This is done with the recognition that we are very far removed in time, space, and culture from the ancient world, but perhaps some "universal" truths can still be ascertained. The first observation stems from the question of why planned cities, most of which are organized along strict geometric principles—usually employing the grid—tend to become "informalized" through time, in both ancient and modern contexts. De Landa provides a hint when, quoting Kostof, he notes that "the grid is the best way to organize a homogenous population with a single social purpose."[51] De Landa then notes that heterogenous populations organize themselves "in an interlocking urban pattern that *interconnects* them without homogenizing them."[52] In other words, the grid works well to optimize one goal, one social purpose, or to quickly solve one specific problem. It does not, however, optimize form based on the many other processes and interconnections happening in the city, especially in cities with diverse populations, a diverse economy, with many actors having diverse sets of goals.

This observation can be drawn out to the presence of regular geometries in agricultural landscapes or in gardens. Formal geometries represent a quick optimization, but only based on a single factor. An orchard planted in the quincunx problem, or rows of wheat or corn planted in grid-like lines, optimizes production of produce in many, but does not optimize for any other purposes, nor does it account for long-term optimization. A gridded series of canals in a hydraulic landscape optimizes irrigation in dry

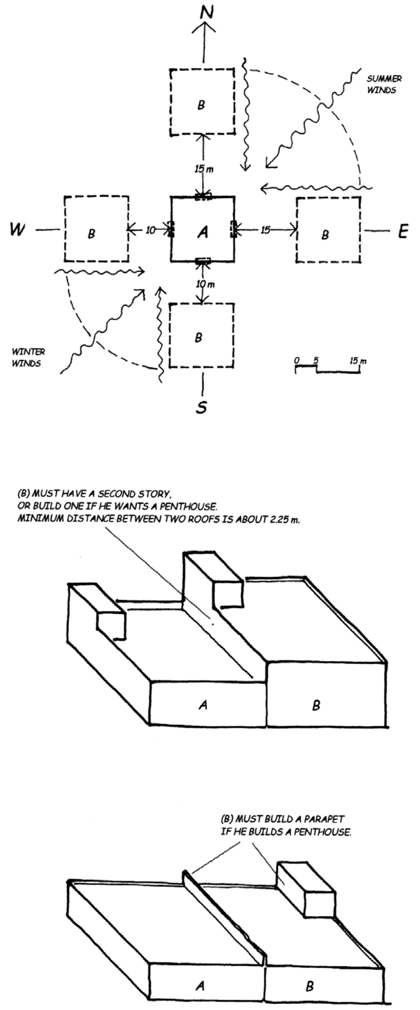


Figure 3.16: According to Hakim, simple local rules or building codes, when part of a long-running evolutionary process can generate the complex, rich geometries of the medieval Near Eastern city.
Besim Hakim, 2001, 2007.

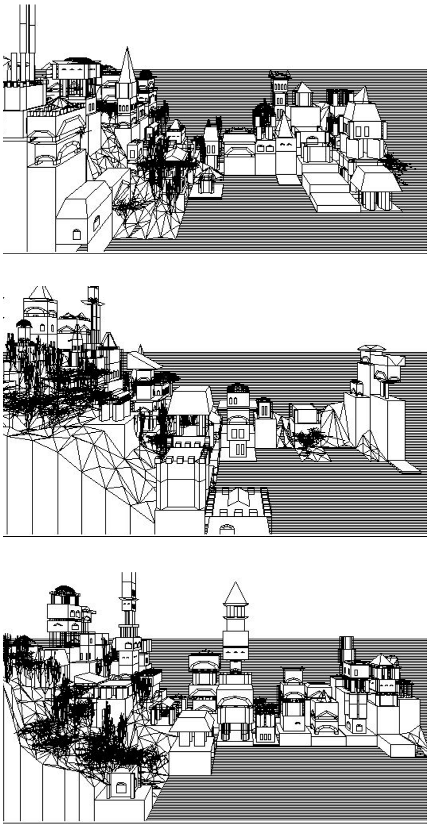


Figure 3.17: Soddu‘s algorithmically generated Italian hill towns.

Coutesy of Celestino Soddu.

climates, or drainage in wetlands, but does not optimize, for example, the living conditions of fish or other aquatic organisms that might live in these canals. Regular formal structures, in summary, tend to be quick, mono-functional solutions to narrowly defined problems, but do not account for the broader complexity of landscapes, of cities, of ecosystems, or of societies. Alternate formal or generative systems which account for diverse actors with a wide range of goals, such as is present in Julian of Ascalon’s development codes, presents a way to systematically optimize without a rigid geometric framework. Similarly complex codes that can optimize for a number of variables can be explored quickly in computer simulations.

3.14. Mathematics and the Foundations of Geography

Before leaving the ancient world, a few more innovations which are of interest to the formal understanding of landscape, and which will provide a foundation for the coming chapters should be introduced. Even in the West, immediately after Euclid, invention would soon push the geometric system to a new level. While theoretically infinite, Euclidean methods when applied to measuring and surveying the landscape were limited for all practical purposes by the maximum length of a surveying rope, and the practicality of tracing arcs across a landscape that wasn’t perfectly flat and which was filled by intervening obstacles, such as cows, bushes, and houses. The landscape of the Nile with its broad, flat plain and regular erasure of traces in the landscape, in retrospect, was a perfect landscape in which the principles of geometry could be invented. Most landscapes, however, lack such “ideal” conditions, and the formal geometric system begins to break down. The projection of the geometric system onto the broader landscape required some new insight which would allow for use of the system on a nearly infinite scale. The insight was buried in the work of Euclid himself, who noted the relationship between the angles of a right triangle, and its chord. Using ratios now known as sines, cosines, and tangents, if one knew the length of any one side and any one of the angles in addition to the right angle, one could calculate all of the other angles and lengths using a simple algorithm. This simple observation led to a new branch of geometry, known in the renaissance as Trigonometry, but unleashing in the Hellenic world at least, a brief burst of scientific insight which laid the foundations for the disciplines of geography and cartography.

The first effective use of trigonometry allowed Eratosthenes, another Greek based in Egypt, to for the first time to estimate the size of the earth itself. He also is credited with devising the first global coordinate system, positioning cities in terms of degrees of latitude and longitude. Such a coordinate system was used by Ptolemy to create his famous world map. No copy of the map survives to the present, but we can reconstruct his map in the present because he devised what might be described as an early digital database to log the coordinates of almost 10,000 places known at the time.[53] A diligent reader can then, in much the same way as a modern GIS system, reconstruct the map based on this digital information. (Fig. 3.18)

3.14. Summary

This chapter has introduced two semi-legendary figures from the ancient world, Euclid and Lucretius, who represent two systems of approaching form and structure in the designed environment. Euclid, who codified the first well-developed formal system of the Western world, represents a formalist approach to knowledge and systems, where the internal workings of the system are of paramount importance. While such a system can be applied and adapt to external problems, the internal integrity of the system

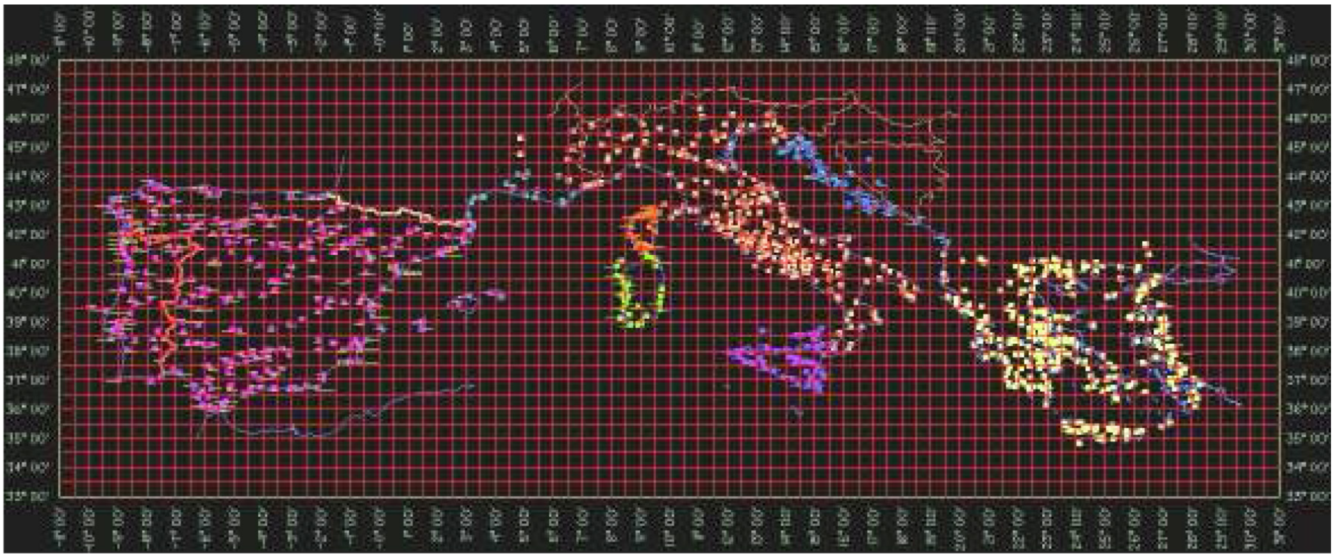


Figure 3.18: A GIS Image mapping the place names mentioned in Ptolomey's *Geography*. His coordinate system can be seen as a forerunner of modern GIS datasets used to create maps based on numerous datapoints.

Courtesy Angeliki Tsorlini.

has to be maintained at all costs and is of primary concern. On the other hand, Lucretius represents a structuralist approach to knowledge and systems, where exterior relations are prioritized over any internal being or motive force. While terms from the modern age can only be loosely applied here, in Lucretius' writings systems are seen as interconnected, ecological, and evolving.

The internal workings of systems, their *interiority* to inject another term from philosophy, along with the systems of external relations can be seen in the unplanned emergence and in the intentional design of gardens, landscapes, and cities in the ancient world. Formalist approaches tended to forms or structures optimized for single economic or societal purposes, but through time, the complex structural relations of natural and society tended to evolve complex form in the broader landscape and in cities. As society became more complex, especially in the Hellenistic period, designed complexity or informality became evident as an aesthetic goal, as in the later Greek gardens, and in city planning, as introduced in the work of Julian of Ascalon.

Algorithmic approaches are traditionally seen, at least in their internal workings, as falling into the mathematical tradition began by Euclid, whose propositions can be viewed as an early collection of algorithmic patterns. This is only part of the picture, however, and generative approaches based on *exterior relations* and nonlinear evolutionary processes, adapting logic from, for example, the codes of Julian of Ascalon, can be just as valuable an approach to approaching algorithmic form as the purely internal approach advocated by Euclid. Julian of Ascalon's system of, small, formal codes working on an evolving context, in conclusion, can be said to be an early model of how a design process in general and an algorithmic process specifically may combine elements of formalism with the relations of structuralism to generate a productive third category—that of performance. The balance between pure interiority and pure exteriority, in other words, is not just a philosophical goal, but can be an approach to designing and exploring pattern and form in computational models as well.

Endnotes

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2 See Herodotus, 2:109, Cosgrove, "The Measures of America", in *Taking Measures Across the American Landscape,* James Corner and Alex Maclean (New Haven: Yale University Press, 1996), 5.

3 original Greek Στοιχεῖα (Stoicheia) Euclid's Elements of Geometry: The Greek Text of J.L. Heiberg (1883-85), translated Richard Fitzpatrick.

4 Euclid, *Euclid's Elements of Geometry: The Greek Text of J.L. Heiberg (1883-85*), translated Richard Fitzpatrick. (self published, 2007).

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26 *Ibid*, 224.

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29 *Ibid*, 68-69.

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Chapter 4 – Leibniz | Von Humboldt

"Es gibt nicht Ödes, nichts Unfruchtbares, nichts Totes in der Welt, kein Chaos, keine Verwirrung, außer einer scheinbaren, ungefähr wie sie in einem Teiche zu herrschen schiene wenn man aus einiger Entfernung eine verworrene Bewegung und sozusagen ein Gewimmel von Fischen sähe, ohne die Fische selbst zu unterscheiden" – G.W.L.[1]

4.1. Introduction

According to the standard narrative, the foundation of modern Western thought was laid with the Renaissance and the Scientific Revolution, while the edifice itself was formed with the advances of the Enlightenment—which glorified reason, empirical enquiry, and science—and with a counter-movement broadly termed Romanticism, a philosophy glorifying deep feeling, intuition, and art. At the same time, according to Bruno Latour, the development of knowledge within these movements led to an increasing compartmentalization of learning and a loss of holistic thinking bridging the sciences and humanities. An increasingly irreconcilable gulf between the categories of *nature* and *culture* further contributed to specialization of knowledge and discreet categories of thought.[2] In the design of the built environment, this trend is especially evident. Architecture—which was once a broad ranging discipline encompassing the design and engineering of everything from buildings, to cities, to gardens, to machines and even optical instruments—became increasingly segmented, while at the same time the technological means for manipulating the natural landscape became ever more powerful. By the early nineteenth century, with the advent of industrialization and the reaction of the Romantics, the stage was set for an official divorce within architecture, with civil engineering and landscape architecture emerging as separate disciplines.[3] For the manipulation of the landscape, civil engineering took the machines and the equations—in short the Enlightenment—while landscape architecture took art and the emerging environmental ethos—the fruits of Romanticism. Civil engineers labored to control nature by superimposing culture upon it in the form of massive infrastructural and public works projects, while landscape architects endeavored to change culture by infusing it with nature, in the form of urban parks and gardens.

This caricature is misleading as argued by Latour in *We Have Never Been Modern,* and we should return to a position where both in thought and in action, natural and culture are seen as inextricably intertwined, and where “the production of hybrids, by becoming explicit and collective, becomes [our] object.”[4] We should “continue to identify with the intuition of the Enlightenment,” but give it the “anthropology it deserves.”[5] Hints as to how this can happen can be found in the lives and writings of two German *Universalgelehrter*—Gottfried Leibniz and Alexander von Humboldt—father figures of the German Enlightenment and German Romanticism respectively. The two figures while associated with two widely different intellectual movements from two very different time periods, exhibit the full range qualities often associated with the two broad movements. Leibniz

Figure 4.0: (*page opposite*) The Großen Garten at Herrenhausen in winter. Many of Leibniz‘s ideas stem from his meditations in this Baroque landscape, which he in turn helped shape.

Figure 4.1: Gottfried Wilhelm Leibniz

and von Humboldt both possessed a sharp intellect capable of enlightened reason informed by empirical observation, but also had a deep reverence and feeling for the awe and complexity of nature. Both advocated for and used and developed technology to understand and harness the power of nature, but at the same time painted a picture of the universe as a dynamic and relational space much bigger than humanity, with its ends transcending our own.

Anchored in these two characters, then, this chapter endeavors to do three things: first, to trace the further developments of the mathematical and logical formal system which led the development of technological advances in the early modern period and that eventually laid the groundwork for computation, second, to explore the emergence of the modern ecological paradigm which is a successor to Lucretius' relational thinking, and third, to see how these intersected in the design and technological manipulation of landscapes at the dawn of the civil engineering and landscape architectural professions. Finally, the question is posed of whether computational and ecological thinking can help bridge the gulf between landscape design and landscape engineering.

4.2. Gottfried Wilhelm Leibniz

On the side of the historical museum of Hannover, Germany, the city that Gottfried Wilhelm Leibniz called home for most of his adult life, one finds the famous quote cited at the beginning of this chapter, asserting a vision of nature full of life and vitality, and at the same time free from chaos and error. Chaos is only an illusion, a confused perception of phenomena observed only from a distance. Leibniz's almost animistic view of nature set him in direct conflict with the canonical figures on the Enlightenment, such as Voltaire, Hobbes, and Newton, who instead promoted a "dead," mechanistic, and clockwork vision of the universe, with no teleological ends outside of what man chose those ends to be. In an ironic twist of history, however, the same Leibniz who believed matter was comprised of an infinite variety of souls, or natural automata, "which infinitely [surpass] all artificial automata,"[6] also set the stage for the development of the artificial automaton that has come to define our age—the computer.

In the English-speaking world, Leibniz is not a household name, but anyone with an interest in higher math might remember him as being one of the two inventors, along with Isaac Newton, of infinitesimal calculus, the third of the three major branches of mathematics. Whereas geometry can be described as the mathematics of space, algebra the mathematics of operations, calculus is the mathematics of dynamics—motion and change. Calculus can also be used to describe complex forms: "pleats, curves and twisting surfaces."[7] While Leibniz shares credit for the development of infinitesimal calculus with Newton, who developed his own version of it called fluxions, it is Leibniz's version which was first published and whose formal notational system is still used to this day. Students of philosophy will recognize him as perhaps the most consequential German philosopher before Kant, and although he is generally grouped into the rationalist and idealist tradition of Platonism—Leibniz himself cites Plato as his most influential philosophical interest[8]—his philosophy, and especially his thinking on *dynamics* goes much beyond Plato. In current philosophical discourse, many see in Leibniz a "philosophy that bridges the pre-Socratics, Lucretius, and neo-Einsteinian thinkers."[9] Leibniz "stands as the first philosopher able to deal with the experience of events and the world of atomic dynamics."[10] He stands on the bridge between the classical-medieval and modern worlds, and in contrast to most philosophers, his thinking seems increasingly relevant and fresh as it ages. Less well known are Leibniz's associations with both garden design and landscape engineering, and how his complex philosophy and scientific ideas were shaped by and tested by his direct encounters with the landscapes in which he both worked and reflected.

4.3. Mathematical Developments between Euclid and Leibniz

Before looking at Leibniz's mathematical and philosophical ideas and his attitudes to nature and landscape in more detail, a very brief summary of key developments in these fields may be helpful. As described in the last chapter, after Euclid published his treatise on geometry, a brief flourishing of mathematical discovery in figures such as Archimedes, Apollonius, and Eratosthenes enriched the formal vocabulary of geometry with more complex forms and computational methods and furthermore allowed for application to problems of landscape on a much broader scale, such as the systematic cataloging of geographical information. Once better instruments for measuring were developed starting in the Renaissance, such as optical instruments allowing the incredibly precise measurement of minute angles, and barometric instruments allowing for exact measurements of altitude, trigonometry would usher in the golden Age of European navigation, exploration, trade, and conquest. It would also allow for transformations of landscapes on a scale never before possible. The Greco-Roman mathematical system, however, was severely encumbered by its unwieldy number system, especially handicapped by the lack of the now seemingly obvious concept of zero, such that after the brief Hellenic flourishing, no new developments in mathematics would take place for over a thousand years. The situation only changed once new insights came from outside the western world.

While the West remained in a state of mathematical paralysis, developments continued in the Middle East, especially under the Persian mathematician al-Khwarizmi (c.780-850). It was he who is credited with synthesizing the Indian decimal numeral system, which included the concept of zero long absent from the number system of the West, with learning from the Greek world to describe his own system of numerical operations now known as algebra.[11] As previously noted, (§1.4) such were his contributions to mathematical operations and logic that the Latinization of al-Khwariymi's name, *Algoritmi*, is the source of our word "algorithm." Translations of his work only entered the West in the mid 12th century, and the Hindu-Arabic numeral system used in his work only became popular after Fibbonacci's work *Liber Abaci* (1202). As discussed in Chapter 1, those who could perform the pen and paper calculations using decimal mathematics became known as *algorists*, who only gradually supplanted those using the more inefficient method of operations requiring the use of an abacus.

The introduction of the decimal system and the gradual adoption of algebraic methods revolutionized European mathematics, first in the fields of banking and commerce, but the system would soon rejuvenate the spatial disciplines of geometry and trigonometry as well, and fundamentally alter the overall system of mathematics with Descartes' invention of what has become known as the Cartesian coordinate system in his work *Le Geométrié* published in 1637. Descartes' coordinate system made it possible to link geometry with algebra and to translate between the two systems by describing forms as algebraic functions. This new system became known as "analytic geometry," Euclid's system being recategorized as "projective" geometry. In projective Euclidean geometry, a circle, for example, would be described in terms of its center point and its radius. The Cartesian coordinate system would describe this circle in terms of x and y dimensions on a graph as a function of radius, with the general formula for a circle being $x^2+y^2=r^2$. (Fig. 4.2) Descartes system of notations, formulas, and the Cartesian coordinate system would be essential to the development of

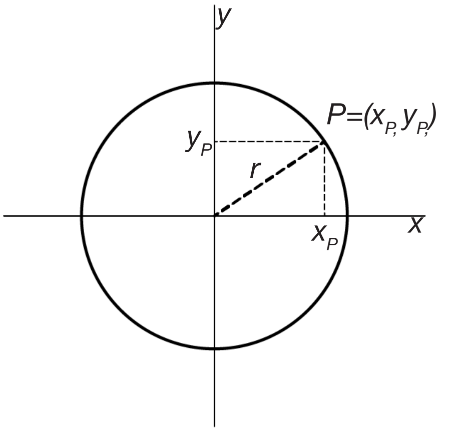


Figure 4.2: A circle described through algebraic methods in the cartesian coordinate system.

calculus, and later was to become essential in the description of forms in digital space.

4.4. Leibniz and Mathematics

Descartes' coordinate system and his innovation of expressing geometric forms as equations paved the way for the development of infinitesimal calculus by Leibniz and Newton.[12] (Fig. 4.3) The calculus as first developed by these two thinkers revolves around two distinct processes, differentiation and integration, both of which make use of the convergence of infinite series and infinite sequences to overcome problems with division by zero. These two processes in turn allow for the analysis of complex curves in ways impossible with standard algebra and geometry, with integration allowing for the calculation of areas under curves, and by extension the area of any complex form that can be described with an equation. Differentiation allows one to find the instantaneous tangent, or slope of a curve. By linking geometric curves to abstract concepts of motion and time, differentiation can be used to describe *dynamics*, changes in motion such as acceleration. The insight of infinitesimal calculus was not that a curve could be integrated or differentiated—methods had already been developed for both of these processes before Leibniz and Newton—but that the two processes were fundamentally related, with the integral being linked to specific anti-derivatives of a curve. This insight was to have many practical applications for science and engineering, and also inspired generations of designers, where the dynamic forms of complex curves began to supplant the stable forms of Euclidean geometry. The level of abstract thought as well as the labor-intensive nature of performing the calculations, however, would eventually further the gulf between science, engineering, and design, as explored later in this chapter.

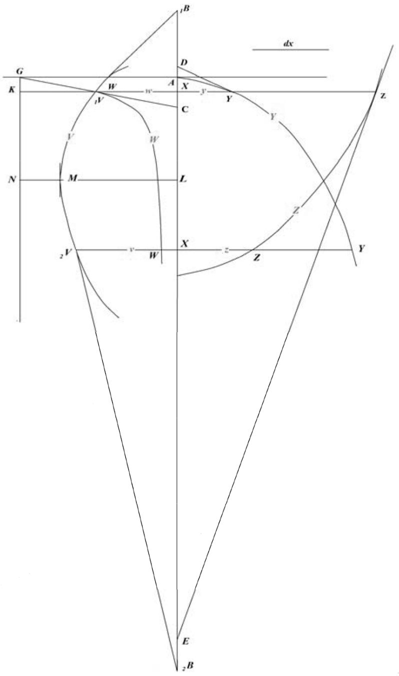


Figure 4.3: Diagram from Leibniz's text *A New Method for Finding Maxima and Minima,* outlaying the fundamentals of infintesimal calculus for the first time.

The controversy whereby Leibniz and Newton both claimed priority for the development of infinitesimal calculus does not need to be discussed in detail here; much has been written on the topic since the late 17th century but scholars generally agree that both reached their conclusions independently around the same time. Their use or application of infinitesimal calculus was, however, quite different. For Newton, the system was a tool to aid in understanding his primary objective, the description of the laws of motion. That it served him well as a tool is beyond doubt, but tellingly, his landmark text *Principia mathematica* described his laws of motion largely in geometric terms, making no overt references to the tool that facilitated his discoveries.[13] For Leibniz, however, the project of developing a formal language *was* the insight and the discovery. This was part of a larger project of perfecting the formal language for performing mathematical analysis, which also included his development of the binary numeral system[14] and the tools of conditional logic, i.e. Boolean logic (see §6.5). That he spent much of his adult life perfecting his formal system, trying to build a consensus on symbols through correspondence with a wide range of the mathematicians of his day, shows the importance he placed on this.[15] As a result of his efforts, according to a recent text on advanced computational algorithms, "he invented more mathematical terms than anyone else, including *function*, *analysis situ*, *variable*, *abscissa*, *parameter*, and *coordinate*."[16] His ultimate reasons for doing this are open to some speculation, with the project of developing a machine whereby reasoning could be mechanized or automated to quickly and efficiently solve questions or disputes having already been introduced. **(§1.4)** That an improved formal system would ease the labor of the mind was indisputably a goal. In a letter to his friend Tschirnhaus, he describes how "in symbols one observes an advantage in discovery which is greatest when they express the exact nature of a thing briefly and, as it were, picture it; then indeed the labor of thought is wonderfully diminished."[17] Leibniz believed that by perfecting the formalization of mathematics, to find an unambiguous formalization of the language of nature, mankind itself would be "perfected." He optimistically asserts that:

> "I dare say that this is the last effort of the human mind, and, when this project shall have been carried out, all that men will have to do will be to be happy, since they will have an instrument that will serve to exalt the intellect not less than the telescope serves to perfect their vision."[18]

The search for a clear formal system and the automation of reason stand as two monumental achievements of Leibniz, and according to Bertrand Russell, represent his greatest contribution to Western thought, with Russell somewhat dismissive of other aspects of Leibniz's philosophy.[19] However, recent authors argue that his contributions to mathematics and logic cannot be regarded without reference to his complex and imaginative philosophy.[20] In both his mathematics and in his philosophy, one finds both are inextricably bound with concepts of the infinite, continuity, dynamics, identity, and necessity. It is also clear that Leibniz wanted to find an approach to science and reason that did not remove metaphysics from physics, and where nature was not seen as a mechanistic clock where bodies acted only through the interaction of *dead forces*. As a response to Newton's *Principia mathematica,* Leibniz proposed in his 1695 "Essay in Dynamics" *(Specimen dynamicum)* that in addition to the dead forces described by Newton—centrifugal force, gravity, and spring forces—bodies also contain active or living forces—a fundamental vitality intrinsic to every particle of matter.[21] In all his work, he sought to find common ground with the philosophers from ancient to modern, advocating an approach in which:

> "the best of the old is combined with the best of the new" which would "stop us from appearing more eager to destroy than to build, save us from being continually bounced from one bold new theory to another, uncertain what to think, and restrain the urge to form sects, an urge that is encouraged by the empty glory of novelty."[22]

In retrospect, it is this thinking which may have emboldened his critics in the "calculus controversy" and continually damning critiques even after his death by the likes of Voltaire, who deified Newton and made Leibniz an object of buffoonery in his satirical novel *Candide*. Leibniz's seeming conservatism, however, has proven to be nothing of the sort, and the last century of science has moved physics away from Newton's dead forces occupying an *absolute space* towards a Leibnizian physics of active forces acting in *relational space.* And while it is unclear to what degree Leibniz's philosophy shaped the development of Einstein's own theory of relativity, the 19th century struggle to understand Leibniz's cryptic philosophy opened the door to a new conception of space and time, with Einstein later declaring himself a Leibnizian.[23]

4.5. Leibniz's Philosophy – Monads, the Garden and the Pond

Leibniz philosophy is complex and not easily accessible. He was a prolific writer, but only a fraction of what he wrote was ever published.[24] Despite having completed several full-length books, only one was published in his lifetime, the ponderous and forbiddingly abstract tome *Theodicy* (1710). Perhaps the most well known Leibnizian text is the relatively brief and

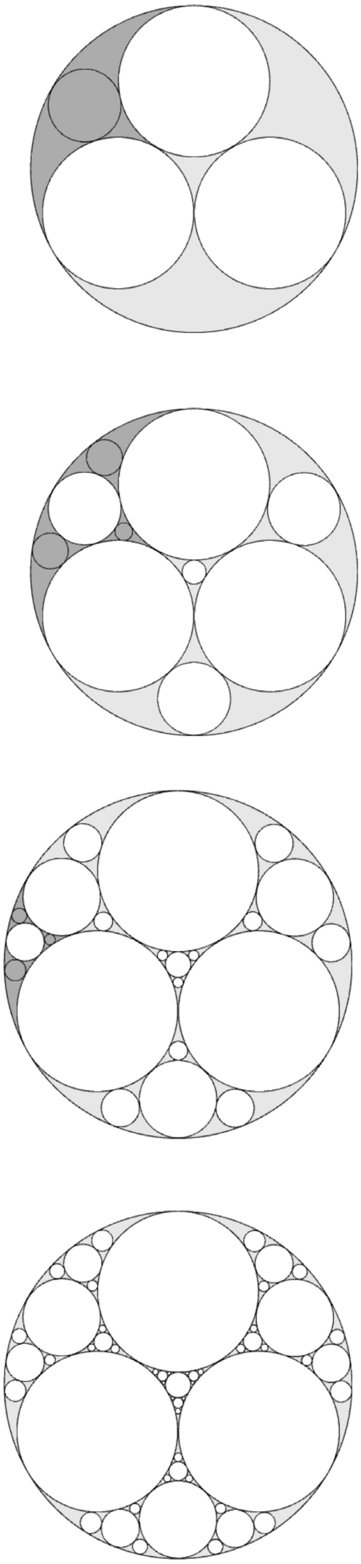


Figure 4.4: An algorithmic method described by Leibniz for packing circles was cited by Madelbrot as an early fractal description, and echoes his philosophy of infinite repetition through scales.

accessible "The Monadology," written two years before Leibniz's death and published posthumously shortly thereafter. It condenses many of the key ideas of *Theodicy* and makes several innovative leaps at the same time. The major innovation of the text was, as the title suggests, that all matter was comprised of an infinite number of *monads* which were the "real atoms of nature…the elements of things."[25] In earlier writings, Leibniz had rejected atomism, but here we find what he really is rejecting is a specific notion of the atomic hypothesis. He rejects the idea that the fundamental building blocks are simple solid particles, indestructible but fundamentally inert, and instead asserts that the monads are living *souls*. Furthermore, every monad is unique, an expression of his principle known as "the indiscernibility of identicals," which observes that "in nature there are never two beings which are perfectly alike and in which it is not possible to find an internal difference."[26] Unlike other versions of atomism, Leibniz's monads are also subject to change, in fact continuous and gradual change is demanded by nature.[27] Here we already find many divergences in Leibniz's thought from classical philosophy. Plato, for example, separated souls from matter, and created a series of ideal forms, which were unique templates existing on another plane but whose ideal expression could never be found in the four polyhedral expressions of imperfect matter. Lucretius diversified the range of possible elements, positing atoms with many different shapes, but these were also inert particles with no vitality, except for their occasional random "swerve." Leibniz brings the soul back into matter, and furthermore, each soul is individually unique, and this uniqueness is *necessary*. The soul is an "active, *vital* force that stands above all material concepts" but is not a "bizarre spiritual force" transcending mechanistic explanations.[28]

Leibniz's monads also seem to have no single discreet size or constitution, and appear to exist at multiple levels and scales. This is perhaps the most innovative point of Leibniz's conception of matter where he explains that:

> "It appears that in the smallest particle of matter there is a world of creatures, living beings, animals, entelechies, souls. Each portion of matter may be conceived as like a garden full of plants and like a pond full of fishes. But each branch of every plant, each member of every animal, each drop of its liquid parts is also some such garden or pond."[29]

This is just one of many observations by Leibniz of the principle of self-similarity, that similar patterns or processes seem to repeat themselves at various scales. A similar observation was found twenty years before "The Mondadology" in "Essay on Dynamics" where Leibniz declares that:

> "each body, however small, is elastic, and is permeated by a fluid consisting of bodies that are even smaller than it is. This means that there are no elements of bodies, no perfectly fluid matter, and no unintelligible solid spheres of some supposed 'second element' of fixed and unchanging shape; on the contrary, the analysis of bodies continues to infinity."[30]

The modern reader sees this principle verified to a point. Bodies are made of cells, which are made of molecules, which are made of atoms, which are made of hadrons, which are made of quarks, and at each level, one never finds the solidity of matter, only new types of chemical reactions, bonds, charges, and forces, which ultimately is the substance of reality: "force is absolutely real in a way in which space time and motion are not."[31] When the classical atomistic view of a "billiard ball" universe was upended with the discoveries of quantum mechanics, (see §7.3) Leibniz's philosophical musings seemed vindicated.

His writings have inspired others working in a range of contemporary mathematical fields; he was a notable influence on the work of Benoit Mandelbrot, who pioneered the field of fractal geometry in the late 1970s and early 1980s.[32] (§6.11)(Fig. 4.4) There has been recent interest in how his concept of monads may relate to concepts in the philosophical discourse surrounding emergence, with hints of the concepts of downward causation and supervenience observable in his model (§3.6), if not full blow emergence itself.[33] As described in the previous chapter, emergent phenomena are—like monads—indivisible. Bodies, ecosystems, landscapes, societies and cities cannot be understood wholly in terms of their parts without the vital relations that hold them together; neither can they be created *ex nihilo.* There is, according to Leibniz:

> "no absolute birth [generation] nor complete death, in the strict sense…what we call births [generations] are developments and growths, while what we call deaths are envelopments and diminutions."[34]

The emergence of new phenomena, developments and growths, is for Leibniz encapsulated by the garden, and according to Horst Bredekamp in *Leibniz und die Revolution der Gartenkunst* it was specifically in the gardens of Herrenhausen in Hannover that Leibniz developed and refined his complex philosophy. His principle of individuality, or "the identity of indiscernibles," was derived after a conversation between the princess Sophie and an unnamed nobleman. They wondered if it was possible to find two leaves that were identical, with the princess skeptical that they could be found, while the nobleman believed it would be easy. Leibniz then diligently began to examine the leaves, finding that while all were similar, no two identical ones could be found.[35] According to Bredekamp, this principle derived from the garden—that all things are essentially and permanently distinct—is a fundamental critique against Newton and his *absolute* notions of space and time, filled with "dead" forces.[36] The generation of this uniqueness is a continual process in nature of *growth* and *development.* (see Chapter 10)

Leibniz's critique of Newton reaches its full expression perhaps not in the space of the garden, but in the metaphor of the pond. In a letter to a friend shortly after publication of "Essay on Dynamics," Leibniz used the pond to express his concept of space: "I imagine that everything is *continuous* as well as *contiguous,* that is that things differ in degree and in appearance. The whole world is like a pond of matter in which there are different currents and waves."[37] Years later in a famous correspondence with Newton's ally and colleague Samuel Clarke, Leibniz explains that:

> "I don't say that matter and space are the same thing. I only say, there is no space, where there is no matter; and that space in itself is not an absolute reality. Space and matter differ, as time and motion. However, these things, though different, are inseparable."[38]

The pond metaphor was especially important for Deleuze in his reading of Leibniz. We will return to Deleuze's concepts of space in chapter 9, but whereas the garden seems to correlate with striated spaces of growth, development, and increasing articulation, the pond is a smooth space. Accordingly:

> The pond "no longer refers to elastic waves that swim through them like inorganic folds, but to fish that inhabit them like organic folds. For Leibniz, as for the Baroque, the principles of reason are veritable cries: Not everything is fish, but fish are teeming everywhere…Universality does not exist, but living things are ubiquitous."[39]

Bredekamp sees Leibniz's fish ponds mentioned in "The Monadology" as as perhaps drawing their inspiration from the four large ponds in the Großen Garten at Herrenhausen, and concludes that "*dieser Prozesscharakter aller Mechanik verdeutlicht, dass die topographische Struktur des Großen Gartens von Herrenhausen für Leibniz weniger mit dem Prinzip einer mathematischen Geometrie als vielmehr einem dynamischen Begriff des Faltentheorems verbunden gewesen sein musss."*[40] This very unorthodox reading of the formal garden is a topic Bredenkamp further develops, rejecting the reading of the formal garden as a rigid, autocratic structure, but sees it instead as a space of freedom and multiplicity. Life, in the form of leaves and fish, is everywhere, and each has its own purpose and own ends, and the ends of the fish especially, often bewilder and challenge our notions of what nature should be, as we will see in Leibniz's *Protogaea.*

4.6. Nature as Process – Leibniz's *Protogaea*

Leibniz was never a full-time philosopher or academic, and his mathematical and philosophical writings were tangential to his position as a court official for the Dukes of Braunschweig-Lüneberg who were the rulers of Hannover. One of his tasks was to write a history of the ducal family, to establish and perhaps to embellish their noble pedigree and hence strengthen their political claims. Leibniz used this opportunity, exceeding his initial mandate, to write an extensive prologue describing the natural history of the land ruled by the Hannoverian house, what has proved to be an early work of geology and natural science. This prologue was finished more than twenty years before his death, but like most of his work, only published posthumously. *Protogaea* provides a window into the state of late 17th century geological science, and while Leibniz claims no expertise in the field, demonstrates his optimism

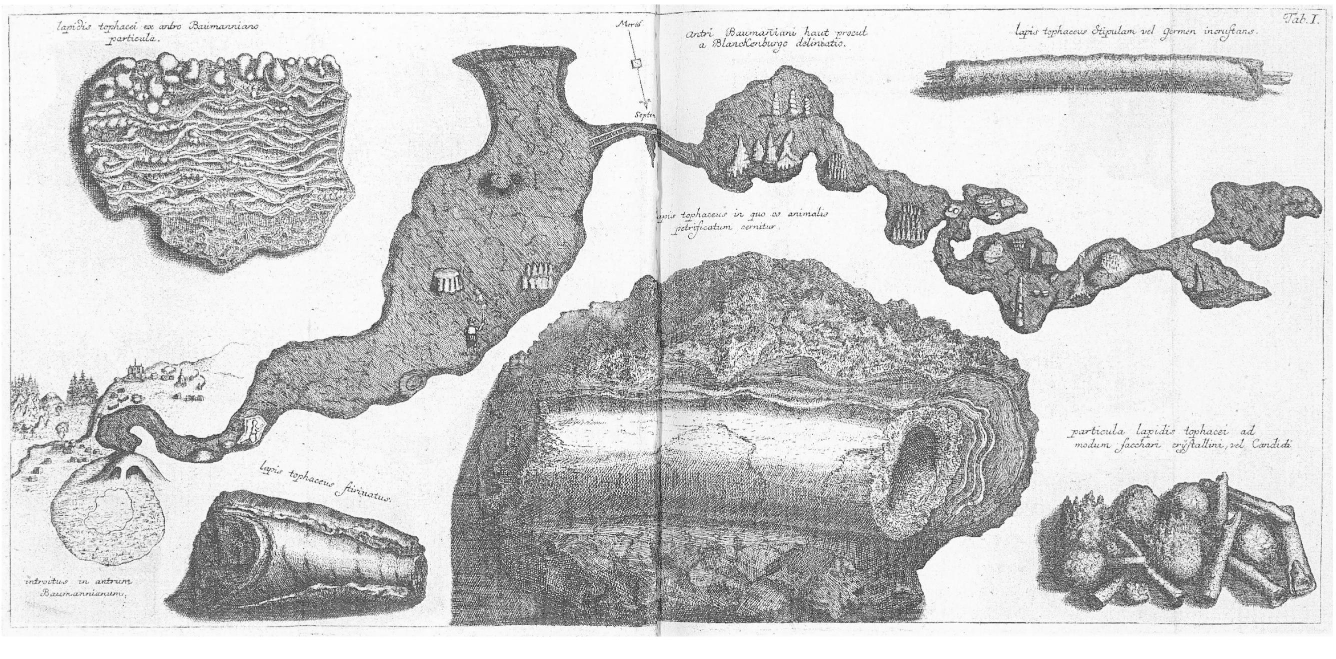


Figure 4.5: Engraving of the Baumann cave in the Harz mountains, from Leibniz's *Protogaea,* frontpiece.

for further developments in the science along with a few brilliant insights that represent original scientific speculation. Much of Leibniz's speculation into natural history comes from another set of duties that he carried out on behalf of his ducal patron.

The Harz Mountains at the time had one of the most technologically advanced mining systems in the world and constituted a large source of the income of Hannover's ruling house. For several years, Leibniz was engaged in a scheme to supplement the water-powered pumps which pumped water from the deep mines of the mountains with new sources of power derived from the wind. This would allow for year-long operation of the mines, even during the long winter months when the surface water which powered the pumps froze. The profits from extending the mining season would be split by the duke, Leibniz, and the mining company, and Leibniz planned to use his share of the profits to found an academy which would be tasked with the development of computational machines.[41] The scheme failed and with it Leibniz's academy proposal, but in the process he gained insights into the inner workings of the earth.

Leibniz's observations in *Protogaea* are a pioneering work and can be described as "one of the most outstanding works on geology and paleontology of the century."[42] While the text is prone to philosophical musings at points, his conclusions are based on reflective and empirical observations of earth's strata and the fossil record. He recognizes that the strata represent epochs in the earth's natural history, partly based on his observation of the drilling of a well in Modena Italy, where the well drillers go through various layers of human and vegetal habitation.[43] Although he does not posit an age of the earth, he suspects the earth must be much older than what scripture allows. This is a conclusion he is initially hesitant to accept but the fossil record ultimately convinces him despite his deep religious impulses.[44] At first, he like many presumes the fossil record to be a "trick of nature," since nature can and does produce surprisingly complex forms without organic processes. What ultimately convinces him otherwise, however, is a careful examination of a swarm of fish fossils buried in rock near Eisleben in Saxony. He describes how:

> "I have here in my hands a barbell, a perch, a bleak, sculpted in stone. Not long ago an immense pike was dug out of a quarry, its body bent and its mouth open, as it had been caught alive and turned to stone by the power of Gorgon. I have also seen sea fish like the ray, the herring, and the lamprey…here most take refuge in games of nature, trying to use our ichthyomorphic stones as an indubitable example of the playful genius of nature…but the argument of close resemblance supports just the opposite position. For the imitated fish perfectly resemble real fish, right down to the finest details of their fins and scales."[45] (see Fig. 4.6)

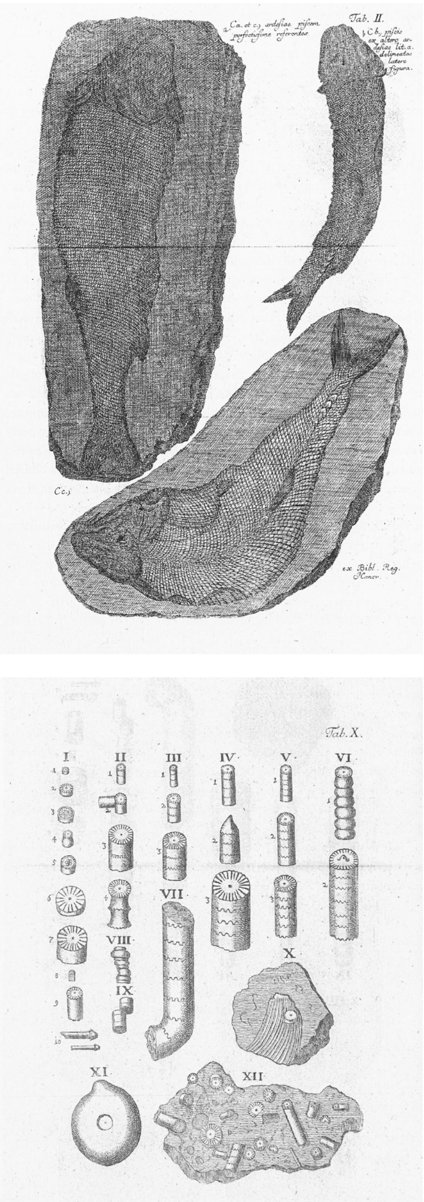


Figure 4.6: Engraving of fossils found in the Harz Mountains, from Leibniz's *Protogaea,* 46, 94.

Here again we see the swarm of fish at first seeming to point to chaos, but upon closer inspection revealing a new, if not easily easy to accept truth. In the end, Leibniz does accept this new truth, stating "I do not dare to assert anything with certainty, except one thing, which suffices for us here: namely, that coppery fish are the imprints of real ones."[46]

Based on other observations, he is convinced that earth's creation cannot be defined by a single event, but must instead be seen as a continual process.[47] He admits he does not fully understand all the forces in play, but he describes internal fires,[48] tectonic processes,[49] as well as the erosive forces of wind and water, with accompanying deposition. What is now land was once sea, and what is now sea, was once land.[50] He notes that "rivers, which carry material with them, certainly rob higher terrain, so that the Frisians are enriched every day at our expense."[51] At one point, he entertains what would now recognize as the evolution of species: "There are those who take the freedom to conjecture so far that they have imagined how once, when the ocean covered everything, animals that now live on land were aquatic; then, as the water departed, these animals became amphibians, until their descendants eventually left that original home" but he pursues the idea no further here as it "conflicts with sacred writers."[52] He is hopeful future generations will continue his work, concluding optimistically: "For us, nature thus stands in place of history. But our written history repays nature's grace, so that her brilliant works, which still lie open before us, will not be ignored by posterity."[53] A full picture of nature's majesty can only be formed from an ongoing collection of views and observations: "for when everyone contributes curiosity locally, it will be easier to recognize global origins."[54]

Protogaea was completed a few years before the "Essay on Dynamics" and long before "The Monadology" was conceived, but one sees in these later works hints as to how his thinking was influenced by these early experiences observing the natural world. For Leibniz, the earth is not solid, but similar to the smallest particles of matter, is in various states of fluid movement and action. Bodies from small to large, including the earth, "are in a perpetual flux like rivers, and parts are entering into them and passing out of them continually."[55] (see Chapter 13)

4.7. Leibniz's Multiplicity of Perspective

Leibniz's belief expressed in *Protogaea* that a global picture of reality could only come through many individual observations also finds a unique expression in his other texts, such as in "The Monadology," where he expresses that:

> "the same town, looked at from various sides, appears quite different and becomes as it were numerous in aspects [perspectivement]; even so, as a result of the infinite number of simple substances, it is as if there were so many different universes, which nevertheless are nothing but aspects [perspectives] of a single universe, according to the special point of view of each Monad."[56]

This attitude is expressed in a slightly different form in *Theodicy* but the attitude is the same:

> "It is as in those devices of perspective, where certain beautiful designs look like mere confusion until one restores them to the right angle of vision or one views them by means of a certain glass or mirror. It is by placing and using them properly that one makes them serve as adornment for a room. Thus the apparent deformities of our little worlds combine to become beauties in the great world."[57]

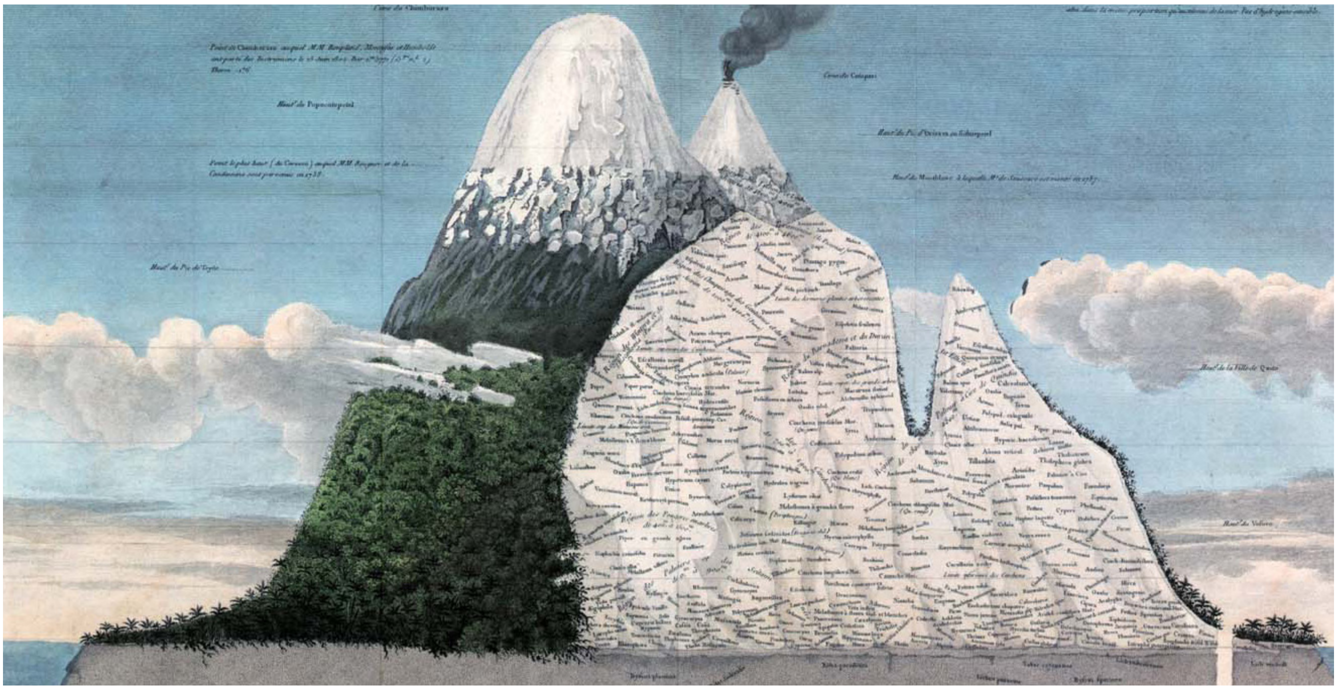
The ideas on perspective that Leibniz expresses here would only find an expression in art nearly 200 years later with cubism, but with Leibniz, multiplicity, simultaneity, and perceived instability are not to be feared, rather they reflect an almost universal theme in Leibniz's thoughts on nature and landscape, that the variations, apparent deformities, and seeming imperfections observed in the world contribute a total picture which reflects "the best of all possible worlds."

4.8. Alexander von Humboldt's Plant Geography

A little less than a century after Leibniz's death, another pivotal German thinker and natural scientist set out on a five-year voyage to South America with the intention of systematically observing and documenting a part of the world then little known to European science. Alexander von Humboldt describes his motivations thus: "*Was mir den Hauptantrieb gewährte, war das Bestreben die Erscheinungen der körperlichen Dinge in ihrem allgemeinen Zusammenhange, die Natur als ein durch innere Kräfte bewegtes und belebtes Ganze aufzufassen.*"[58] He further describes how nature is full of interdependent forces, many of which appear unrelated upon initial inspection, or when observed only in isolation.[59] Later writers would see in von Humboldt's researches and writings the birth of the modern discipline of ecology. Kwinter, in reflecting on von Humboldt's "Essay on the Geography of Plants," observes that "to von Humboldt we owe the habits of thinking about form and nature as an expression of interactions that more or less incorporate, or synthesize the environment itself. In von Humboldt, I would situate the notion, later dear to Romantic theorists and artists alike, that form is an expression of forces. Hence the beginning of ecological thinking."[60]

Humboldt is most well-known today for his work with plant geography. Before von Humboldt, the study of plants focused on the Linnaean categorization of species and on the intrinsic qualities of individual specimens, what Nordenskiöld describes as "floristic" plant geography. Von Humboldt opened up a new type of plant geography, focusing on a study of "vegetation rather than flora, … a collective phenomenon, produced by many species together."[61] For von Humboldt, cataloging a new genus or species was "far less interesting than an observation of the geographical relations of the vegetable world, or the migration of the social plants, and the limit of the height which their different tribes attain on the flanks of the Cordilleras."[62] Throughout his travels, von Humboldt took careful measurements each time he took a sample of vegetation, documenting variables such as temperature, humidity, altitude, and even sky color with the most precise instruments he could buy. His major epiphany came when

Figure 4.7: The T*ableaux Physique* produced under von Humboldt's direction proposed a unified system for the distribution of plants based on latitude, elevation, and weather patterns.



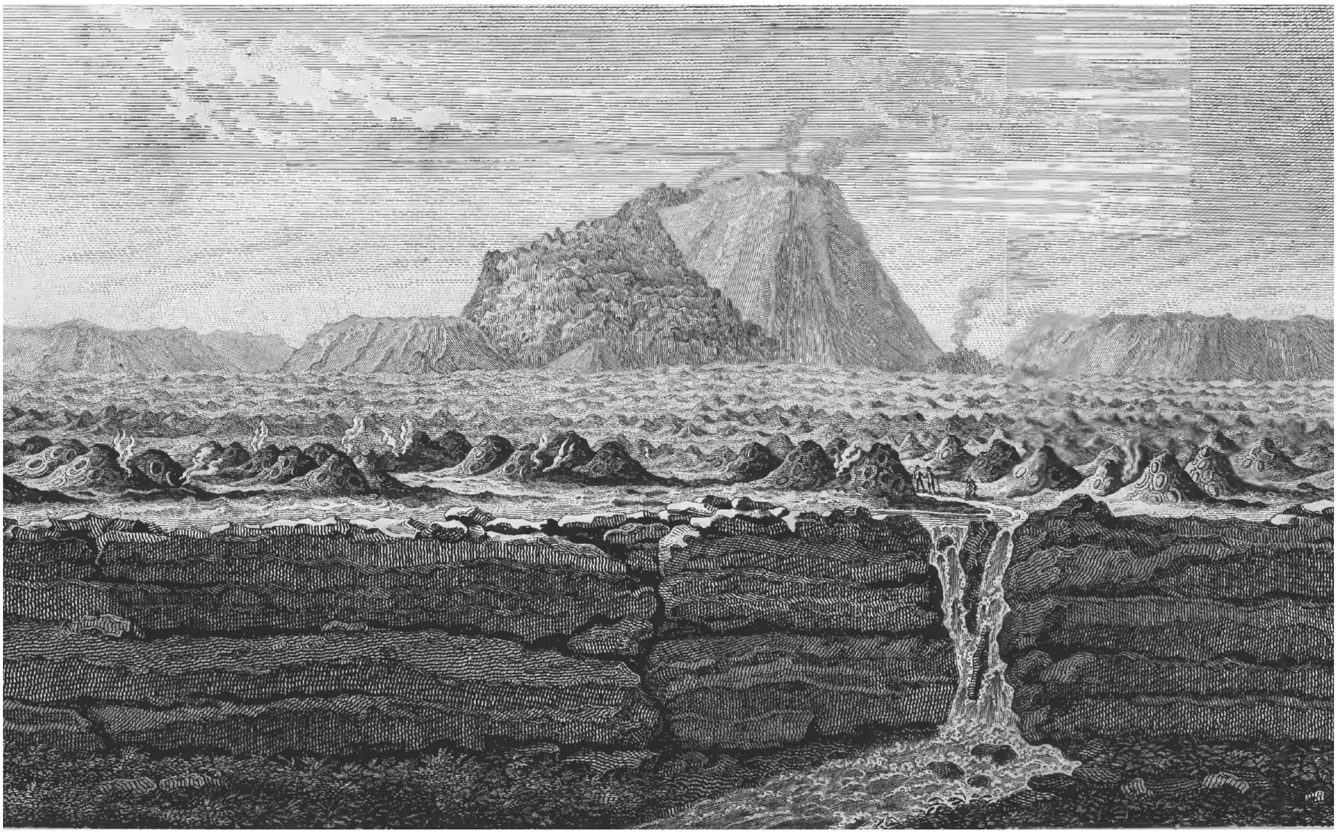
scaling the Andean range in Ecuador, where he observed clear boundaries between plant communities as one climbs in elevation. In the lower reaches of the range, the vegetation mirrored other parts of the tropics. But as one ascended, the communities changed, going through regions with similar vegetal characteristics to parts of Europe, and concluding with high alpine vegetation with mosses and lichens similar to what he had seen in the Alps. Combining his measurements with measurements observed by others, he was able to synthesize his findings into a single conceptual framework, first shown in his *Tableau physique* (Fig. 4.7) and later expressed in maps as isotherms: a clear and global relationship between vegetation and geography. (Fig. 4.9) Humboldt first expressed the idea of isotherms as "long bands, whose irresistible extension causes the population of states to decrease, the nations to be separated, and creates stronger obstacles to communication than do mountains and seas."[63]

4.9. Von Humboldt and Humanism

While von Humboldt often makes the argument of empirical objectivity, he did not believe phenomena should be studied in an isolated setting. A major innovation in von Humboldt's scientific endeavors was also that he believed science had to transcend strictly "natural" criteria and include cultural aspects as well, with the geography of plants being closely linked to both "the political and intellectual history of mankind" as well as humanity's aesthetic impulses.[64] Humanity's relationship with nature, whether by physically altering the environment or by observing it as an aesthetic object, had positive and negative ramifications.

Humboldt's writings are laced with references to landscape poetry and landscape painting, with a major part of *Kosmos* vol. 2 dedicated to the subject, along with a few references to landscape gardening. Based partly on

Figure 4.8: (*Bottom*) Louis Boquet, engraver, „Vulkan Jorullo“ from von Humboldt‘s *Vue de Cordillères, et Monumens des Peuples Indigènes de L‘Amerique*, 1816.



his own personal experience, he believed that these art forms could awake aesthetic impulses which would motivate a more detailed study of nature and its relations. He also believed landscape painting could serve as a scientific tool, as images could at times convey the interrelations between numerous concepts much better than words could: "*das Sinnliche an das Unsinnliche anzuknüpfen*."[65] The bulk of his first volume of *Kosmos* describes nature in terms of a single, unifying painting, the *Naturgemälde*. His other volumes are illustrated with engravings which he commissioned and which were based on his own sketches. Humboldt did not see consideration of aesthetic questions as alien to the pursuit of science, and as part of his relational thinking, he felt environment deeply affected the attitudes of those who lived in them:

> "How different is the aspect of a vast prairie surrounded with a few clumps of trees from that of a dense, dark forest of oaks and pines? How different are the forests of temperate zones from those of the equator where the naked and thin trunks of palm trees soar above the flowering mahogany trees and resemble majestic porticos? What is the intellectual cause of these feelings? Are they produced by nature, by the large size of these ensembles, by the outline of their shapes, or by the plants' posture? How does this posture, this more or less rich or cheerful aspect of nature influence the habits and sensibilities of peoples?"[66]

Based on his writings, it appears von Humboldt believed our aesthetic reaction to landscapes was universal; if von Humboldt was stirred by a tropical rainforest, everyone should be. The modern reader would reject this conclusion. Yi Fu Tuan in *Topophilia*, for example, makes the argument that while aesthetic impulses are deeply ingrained, they have a strong individual and cultural bias—Tuan hated the rainforest, and felt a deep connection with the desert, for example.[67] Von Humboldt's observation that the various aspects of nature induce strong aesthetic impulses, and that culture is inextricably linked with nature and cannot be clearly separated from it, however, still rings true.

Von Humboldt's relational thinking reaches a high level of prescience in his observations that humans could change their environment with unintended, but inevitable negative consequences. Andrea Wulf sees in his description of the desiccation of Lake Valencia in Venezuela one of the first recognitions and descriptions of human induced climate change.[68] In his *Personal Narrative,* he observed that the lake, which had once been almost as big as Lake Geneva, had shrunk considerably during the last fifty years. Many local residents thought some underground passage was draining the lake faster than streams could replenish it, and they wanted von Humboldt to investigate this cause. After studying the phenomenon, von Humboldt became convinced the lake was not shrinking because of some natural process or mysterious underground channel, but due to over-exploitation of the land by humans. He recognized that the removal of forests around the lake had altered the natural balance in the local water cycle, and that further degradation of the soil caused by erosion was quickly making the surrounding countryside less and less productive. He furthermore completely rejects a plan by colonial administrators to drain the lake for agricultural use by diverting the streams feeding the lake through a canal into the nearby Rio Pao. If such destructive practices continue, the once fertile Valencia valley would become as arid as the surrounding deserts.[69]

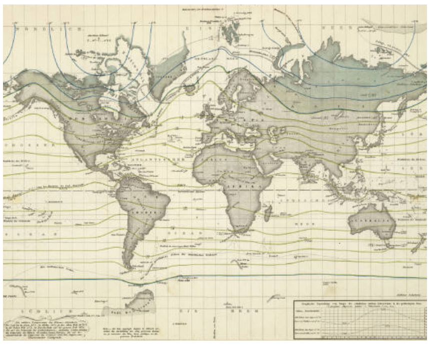


Figure 4.9 : The world's first isothermic map published under the direction of Alexander von Humboldt in 1817.

Figure 4.10: Von Humboldt, „Luftvulkan von Turbaco."
Figure 4.11: Von Humboldt.„Basalt-felsen und Wasserfall von Regla.
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4.10. Von Humboldt's Legacy

Von Humboldt's epiphanies would not have been possible had he focused, like most botanists of his day, on the minute description of plant features, a the hallmark of his discipline at the time. While von Humboldt recognizes the value of such focused study, he makes a compelling argument for zooming out, for "painting with a broad brush" while linking all disciplines from the natural science as well as the humanities together.[70] This approach to science, which links meticulous measurements and empirical rationalism with the broad view of the epic voyage, would later inspire a wide range of additional scientific discoveries throughout the 19th century. The musings of the nature writer Henry David Thoreau, the advocacy of the conservationist John Muir, and the groundbreaking discoveries of the naturalist Charles Darwin would not have been possible without a Humboldtian perspective, and all three cite von Humboldt as a major influence.[71]

Von Humboldt developed over the course of his life, and especially through his travels, a deep connection to the various peoples and cultures he encountered, as well as what we today might regard as a sense of environmental and social justice. He abhorred the practice of slavery, seeing it first hand through his travels, and could not understand how the United States, with its form of government rooted in the thinking of the Enlightenment could tolerate the practice. One particular text which featured a condemnation of slavery was censored by American publishers to soften the criticism, whereupon von Humboldt published and angry editorial disavowing ownership of the book since his main thesis had been removed.[72]

4.11. Von Humboldt, Leibniz, and Ecological Thinking

Alexander von Humboldt's goal of painting a broad-brushed view of nature as an interacting series of forces form an important part of modern ecological thought. An argument can be made that the roots of von Humboldt's ecological consciousness can in fact be traced further back to Leibniz, and the selective reading of Leibniz's philosophy in the previous sections certainly points in that direction. His notions of relational space, continuity and gradual change in nature, his appreciation of diversity and infinite variety, and his thoughts on dynamics all align with much of current ecological thinking. Von Humboldt, while not a particularly strong admirer of Leibniz's thinking—Leibniz was considered a bit old-fashioned at the time—the legacy of Leibnizian thought could be said to have permeated German intellectual thought to such a degree by von Humboldt's time that many of Leibniz's ideas may have been inherited subconsciously.[73] Von Humboldt's relational thinking, however, was arguably on quite a different level than Leibniz's. One of the greatest difficulties in Leibniz's conception of monads, and which makes it difficult to ascribe to him true ecological thinking, was his notion that the monads were "windowless," independent, and unaffected by other monads. Monads continually change, but this change is based on a series of deterministic inner rules, and as Pauline Phemister notes, in monads "each mathematical rule generates one and only one sequence of numbers, so too, each monad's law generates one and only one sequence of perceptions."[74] It is almost as if Leibniz's monads are tiny computers processing data according to an internally evolving algorithm, but with no input from the external world. Phemister continues observing that: "In the universe as Leibniz conceived it, no creature physically affects any other. Instead, all living things merely co-exist in a pre-established harmony."[75] There can be no ecological crisis, for example, in a world where the annihilation of some monads has no impact on the inner world of another, and hence, no ecology.[76] For von Humboldt, on the other hand, everything is *affected* by relations and these seem more important to him than any intrinsic essence in natural objects.

Both perspectives have value. Individuals, as Leibniz posits, are not *essentially* changed by relational circumstances. If someone hates bananas, being around banana trees will not necessarily make them a lover of bananas, or worse yet, transform them into a banana. A Leibnizian might argue that the term "windowless" is misunderstood—monads do have perceptions after all, but these perceptions can evoke a thought or feeling *that is already inside them*, not necessarily create a new thought. The modern discovery of the genetic code also supports a Leibnizian position. While populations of organisms evolve through time, for example, individuals do not, having a genetic code more or less fixed at conception, and thereafter they grow, develop, and diminish largely according to fixed, internal, biological rules.

4.10. Goethe, Metamorphosis, and Morphology

An interesting synthesis of a Leibnizian and a Humboldtian perspective on relational spaces, as well as a synthesis of Enlightenment reason with Romantic feeling, might be found in the work of von Humboldt's friend and mentor Johann von Goethe. In one of his most well- known poems, *The Metamorphosis of Plants* (1790), Goethe muses about the process of plant development in a few brief stanzas, and then continues to write an extensive commentary on what this means. A key excerpt describes how plants contain an individual and unique essence inside them, but through a gradual process of *unfolding* the form develops:

> Werdend betrachte sie nun, wie nach und nach sich die Pflanze,
> stufenweise geführt, bildet zu Blüten und Frucht.
> Aus dem Samen entwickelt sie sich, sobald ihn der Erde
> stille befruchtender Schoß hold in das Leben entläßt,
> und dem Reize des Lichts, des heiligen, ewig bewegten,
> gleich den zärtesten Bau keimender Blätter empfiehlt.
> Einfach schlief in dem Samen die Kraft, ein beginnendes Vorbild
> lag, verschlossen in sich, unter die Hülle gebeugt,
> Blatt und Wurzel und Keim, nur halb geformet und farblos;
> trocken erhält so der Kern ruhiges Leben bewahrt,
> quillet strebend empor, sich milder Feuchte vertrauend,
> und erhebt sich sogleich aus der umgebenden Nacht. [77]

In reflecting on the poem and the subsequent commentary, Kwinter observes how:

> "Goethe supplies a single model of algorithmic explanation for the diversity of vegetal forms in the world as well as for the diversity of organ forms within a single plant and family. Stem, leaves, calyx, and petal (and all forms in between) are related as organizational points in a space made up of three interacting fields of influence: a flexible *type*, a continuous *gradient*, and a closed but repeating *cycle*."[78]

The flexible type is something intrinsic to the plant, its DNA, its monadic essence. It is a "folded," layered, and self-contained *object* which inhabits a field of forces, the *continuous gradient.* Through a recursive process or a repeating *cycle* of "unfolding" in the field, the object expresses its internal essence through a "communicative interplay" whereby "every plant and plant part is an expression of one point and moment in this matrix of interactions."[79] Later, Goethe would coin the term *morphology* to describe this process, describing it as "the study of form and process, growth and form,

form and function…Goethe stated: 'The formative process is the supreme process, indeed the only one, alike in nature and art.' (quoted in Whyte, 1968)"[80] Goethe saw in his concept of morphology the potential to bridge nature and art, where art sought to understand and imitate the creative urges of the natural world. He held that the term *Gestalt*, if used at all, should be "held fast for but an instant" and that then it should surrender to a process of *Bildung,* formation and transformation.[81] In reflecting on Goethe's writings and their applicability to the digital age, Achim Menges describes how "the characteristics of natural behaviour—conceptualised as interaction, iteration, generation and variation—to which Goethe alludes, and the manner by which they are deciphered is fundamental to the exacting of computation in design. Important is not only the set of instructions, but also the *meta*-instructions which describe the transformational activities giving rise to an overall functioning system."[82] These ideas will be further explored in part two of this thesis.

4.11. Leibniz and the Designed Landscape

At this point it will be valuable to briefly touch on some of the significant trends in garden and landscape, as well as infrastructural design as both landscape architecture and civil engineering emerged as distinct professions. Human beings have been shaping and reshaping the overall landscape for thousands of years, but, as argued in the last chapter, most large scale landscape changes were the result of cumulative local processes, which ultimately had global impact. Large scale infrastructural projects certainly existed in the ancient world (Roman roads and aqueducts, the Great Wall and Great Canal of China), but this trend accelerated to a scale never before seen after the Enlightenment, largely because of the very tools of precise measurement that made Leibniz's and von Humboldt's scientific inquiry possible. In the time of Leibniz, the trend was at its beginning. By the time von Humboldt died in 1859, the effects in Europe at least, were in full swing.

Clarence Glacken sees in Leibniz a typical attitude towards nature for his time, a mixture of "the Christian idea of man being a finisher of nature, using his brains and his hands, imitating on a small scale the acts of God in the universe"[83] and a technocratic zeal to use instruments, such

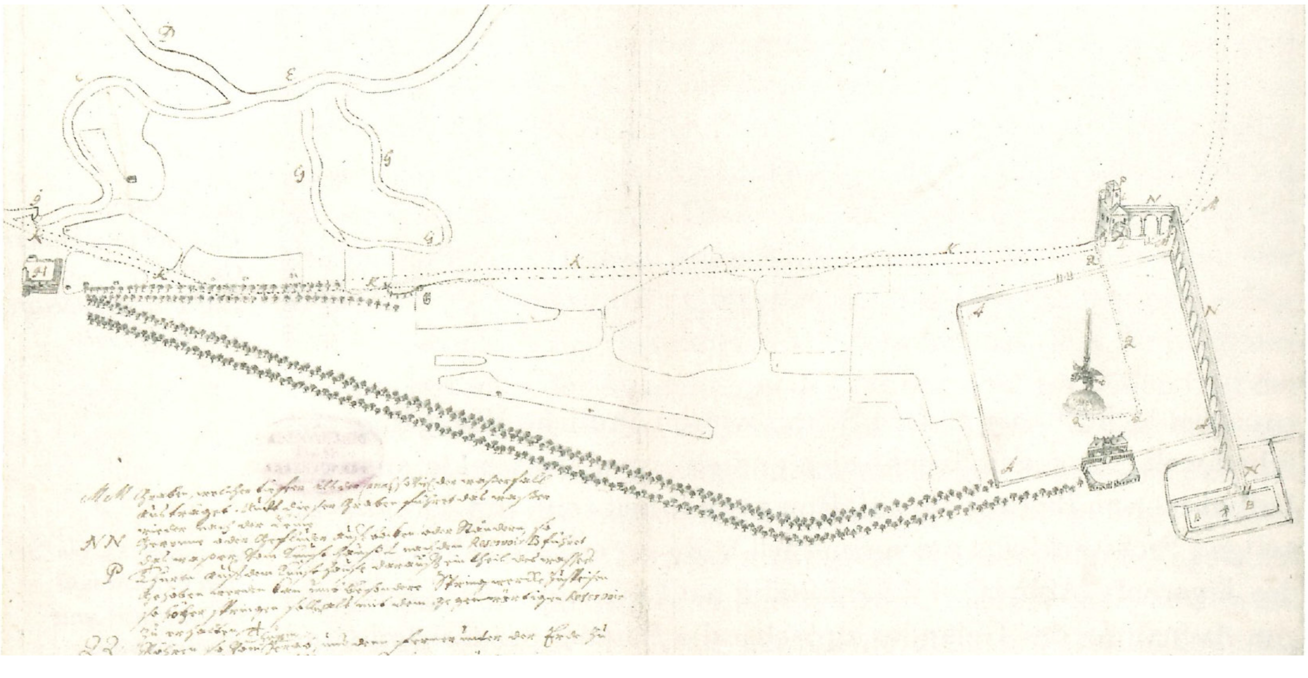

Figure 4.12: Site study by Leibniz for engineered waterworks between Hannover Altstadt and the Herrenhäuser Gärten to power its fountain.

as the microscope or the telescope, to understand nature's secrets, and to harness them.[84] Glacken hints, however, that several significant departures from the standard narrative of man vs. nature can be observed in Leibniz's thinking. Leibniz's belief that all living things possessed souls, and that there was no error in nature, contrasts with the typical Enlightenment worldview where only humans had the faculty of reason and hence valid ends, and where nature could, like a clock, be endlessly re-fashioned and engineered without consequence to suit human needs. Glacken notes that while Leibniz is famous for noting that ours is "the best of all possible worlds, it may not necessarily be best for human beings."[85] This reflects a world-view also characterizing Lucretius's thought wherein mankind is not necessarily the central teleological aim of nature.[86] When humans do tap into nature, it should never be a direct assertion of control.

We see this in Leibniz's own engineering proposals (he lived in an age where one could both a civil engineer and a philosopher). A fascinating study of this compiled by Horst Bredekamp evaluates Leibniz's involvement with an engineering project to build the highest fountain then known in Europe at the Großen Garten at Herrenhausen. Early proposals had suggested a water wheel *in* the River Leine to get the water pressure for the fountain, but Leibniz instead proposed a canal running from the Hannover *Altstadt* to Herrenhausen to power the fountain. (Fig. 4.12) He believed it was foolish to directly intervene with the river's "*natürlichen Freiheit"* which occasioned frequent flooding and ice floes, but that rather an indirect intervention into the flow of the river was best. He also rejected other proposals to build underground pipes, preferring the canal infrastructure since it was visible and could be used for other purposes. The canal could fulfill practical ends such as powering mills of other landowners along the canal's three-kilometer course or for transporting goods from the city to the palaces, but it could serve aesthetic purposes as well, allowing pleasure cruises, innovative waterworks to rival Tivoli or Frascati, and perhaps most important to Leibniz, a nocturnal show of illumination along the canal's long run.[87] Leibniz's approach resonates with the current generation of landscape architects, who are seeking ways to create multi-functional rather than mono-functional infrastructure, and had his project succeeded, it may have been a model for another kind of infrastructural development. Instead, the engineers won the arguments against Leibniz on cost grounds, and a pipe was built to power the fountain. As Leibniz predicted, it did not deliver the required water-pressure. It was only after building a second infrastructural scheme, an adaptation of Leibniz's canal plan but without its multi-functionality, that the fountain could be powered.[88]

This text has already mentioned von Humboldt's observations on the ecological consequences of land exploitation, but Leibniz had interesting thoughts on this as well. While he lived before an Industrial Age powered almost exclusively by fossil fuels, Leibniz's writings suggest he would have been against the indiscriminate use of these non-renewable resources. In Lower Saxony, he lamented the extraction of peat from swampland, finding folly in those who would trade a few years of profit off a public land, leaving behind essentially useless ponds of swampy water after the peat had been extracted.[89] He speculated the peat *might* eventually grow back, but based on a 232 feet deep boring he had observed in Amsterdam, where only one layer of peat was observed in the long landscape history represented by the deep cut, he remained skeptical.[90] Leibniz's philosophy is characterized by his belief in the regenerative powers which maintained nature's vitality, and of the fundamental productivity of nature, but apparently he did think it was possible for nature to be overexploited, leaving sterility in its wake.

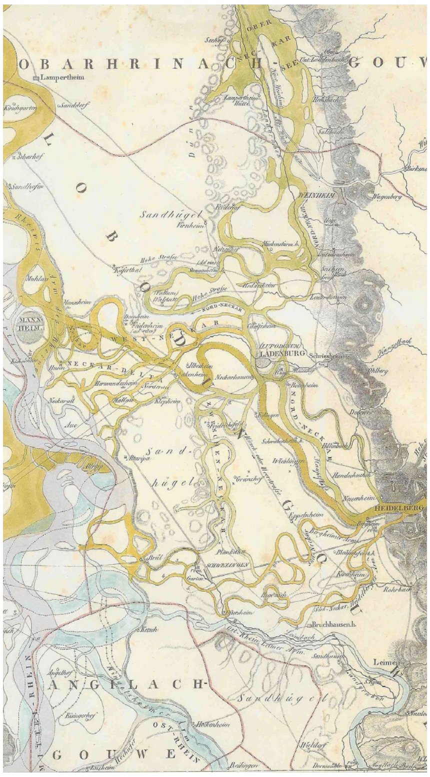

Figure 4.13: Detail from an 1850 map of the historic flows of the Rhein and Neckar rivers between Heidelberg and Mannheim.

4.12. Von Humboldt and the Designed Landscape

Von Humboldt never seems to have taken an active role in the design of landscapes either as an artist or an engineer. He was interested primarily in the natural world, but as touched upon previously, he recognized humans had significant and long-lasting impacts on the landscape. Von Humboldt was able to see the consequences of natural resource and human exploitation overseas but it is not clear if he was able to see these same consequences at home. In his childhood, he would have been able to feel the affects of his sovereign Frederick the Great's "enlightened absolutism," a legacy that stretched into his early career in the civil service as a mining inspector. While the north German landscape is an artifact of thousands of years of human occupation, there was probably no period of greater change for this part of the world than in Humboldt's lifetime, as documented brilliantly by David Blackbourn's *The Conquest of Nature: Water, Landscape and the Making of Modern Germany.* (2006). Blackbourn documents how massive hydraulic engineering projects fundamentally transformed the sparsely inhabited swamplands of north Germany into a mixture of farmland, cattle pasture, and fen colonies, while elaborate river engineering schemes transformed Germany's biologically productive but temperamental rivers into a network of sterile navigational channels.[91] (Fig. 4.13) These infrastructure projects, which were made possible through the use of the same instruments von Humboldt would use to carry out his own studies into the beauties of nature,[92] were used to brutally conquer and subdue the last remaining wild landscapes in Germany and were carried out only at the cost of countless human lives.[93] And while Prussia had no official slavery, this was largely only a semantic distinction. It is possible that von Humboldt had a negative view of the ongoing "conquest of nature" in his homeland, but his status in the Prussian aristocracy and his financial-backing from members of the Prussian elite may have prevented him from making any direct criticism. The fact that he was so eager to escape the confines of his homeland, and that he spent much of his adult life outside of his homeland, writing in French but not in his native German, may give some hint as to where his sympathies lie.

Considering he was a natural scientist seeking to bridge disciplines, and his deep interest in the aesthetic potentials of vegetation, von Humboldt had comparatively little to say about the emerging disciplines of garden and later landscape architecture. He devoted perhaps a third of his second volume of *Kosmos* to landscape poetry and landscape painting, but devoted only a brief section to landscape gardening. He was not a stranger to the subject, and as an aristocrat he would have had access to many of the finest gardens in Germany and later in and around Paris. His ambivalence towards landscape gardening, however, may have stemmed from the artificiality he perceived in the composition of plants in gardens of the time. After noting how the composition of plants in landscape painting is inevitably inferior to the compositions observed in nature, this is still better than what is seen in gardens. He notes that *"Der Landschaftsmalerei ist es allerdings gegeben ein reicheres, vollständigeres Naturbild zu liefern, als die künstlichste Gruppierung cultivirter Gewächse es zu thun vermag. Die Landschaftsmalerei gebietet zauberisch* über *Masse und Form."* [94] He goes on to note, however, that some gardens are able to achieve astonishing effects, and that gardens in contrast to paintings have the advantage of being "real" and are thus able to effect the senses in other ways. His bias in gardens is certainly towards informal gardens, preferring the English landscape garden style, and he comments favorably on Prince Pückler-Muskau's park near Görlitz. He favorably quotes from texts on Chinese landscape design, which comprise about half of his overall analysis of the subject. We might assume his quote of the Chinese author Lieutscheu betrays his own preference:

> *"Was sucht man in der Freude an einem Lustgarten? In allen Jahrhunderten ist man darin übereingekommen, daß die Pflanzung den Menschen für alles Anmuthige entschädigen soll, was ihm die Entfernung von dem Leben in der freien Natur, seinem eigentlichen und liebsten Aufenthalte, entzieht. Die Kunst den Garten anzulegen besteht also in dem Bestreben Heiterkeit (der Aussicht), Ueppigkeit des Wachsthums, Schatten, Einsamkeit und Ruhe so zu vereinigen, daß durch den ländlichen Anblick die Sinne getäuscht werden. . . alle Symmetrie ist ermüdend; Ueberdruß und Langeweile werden in Gärten erzeugt in welchen jede Anlage Zwang und Kunst verräth."*[95]

Nevertheless, for von Humboldt, unlike Leibniz, the garden was a shadow of the natural world, with its intricate web of relations. Leibniz found freedom and an endless cascade of little worlds down to the microscopic in the garden, endlessly zooming in to encounter an infinity of perspectives, whereas von Humboldt could find such freedom only in his epic voyages through an expansive world of largely untouched nature, contributing to a unitary and broad brushed picture of the cosmos.

4.13. Leibniz and von Humboldt - Tools and Perspectives

This section began with the proposition that increased specialization and more complex tools and methods for creating has created a gulf between design disciplines that is not always productive. In order to work together, strategies need to be found to bridge gaps in understanding and approach and to develop not only hybrid projects, but hybrid modes of practice as well. With the pervasiveness of computation, disciplines have a chance to reassess modes of practice and collaboration through the tools that they use. Is there something that can be taken away from the working methods of Leibniz and von Humboldt that will help here? The tool which epitomizes Leibniz's thinking is his *unified formal system*, best represented by the infinitesimal calculus. The linking of curves to time and motion is not a mere abstraction, but represents a unified reality of space, time, matter, and motion. This tool, however, reveals a multiplicity, *an infinite number of perspectives*. Von Humboldt in contrast used numerous tools to measure the landscape and to derive what could be described as an *infinite number of information data points*, but these all contribute to a *unified, single perspective*.

The unified system of mathematics best represented by infinitesimal calculus plays an important part in modern engineering, but the products of this engineering often fail to represent the multiplicity of perspectives. Problems are often optimized for a single factor; a river channel that is optimized for navigation, for example, is non-optimal for the fish that once lived there. Valuable lessons can be taken from Leibniz's few design proposals where he revealed an interest in accommodating or representing a multiplicity of perspectives, with practical and aesthetic considerations all contributing to the whole. In contrast, the use of complex geometries by designers often neglects the formal logics which underly those geometries. With computation, many of the laborious calculations that made working with complex geometries with analog methods are abolished. NURBS and Bezier curves both make use complicated formulas in the background which make working with these shapes trivial, but methods to discipline the use of these geometries need to continue to be considered. Likewise, algorithms make it possible to optimize engineered solutions to meet several ends simultaneously, and design solutions no longer have to be overly simplified to make the labor of calculation easier. (see §11.5)

Landscape architects can also learn lessons from the link between von Humboldt's data points and his unified perspectives. For von Humboldt, the perspective did not necessarily represent a single reality, but an ideal composite. By recognizing the link between the perspective and information in von Humboldt's thinking, landscape architects may be able to move on beyond the scenographic qualities which Antoine Picon argues have dominated the profession for so long (see §2.4). The perspective should not represent a stable and permanent reality, but should instead highlight "the dynamic and instable fields and forces that shape the earth and constrain human interventions on its geography."[96] Digital tools make this stronger link between image and dynamic information possible. According to Picon, this kind of use of digital tools will also begin to erase the distinction between nature and culture, as "information ignores the distinction between the natural and the artificial."[97]

4.14. Summary Conclusions

This chapter has introduced only a few of the key ideas of Leibniz, von Humboldt, and Goethe, primarily to examine in a historical context how the ideas of form, information, and performance introduced in Chapter 2 might relate to these concepts, and ultimately how these concepts manifest themselves in the design of landscapes. Leibniz's contributions are seen largely through the lens of his contributions to the development of the West's system of formal logic, and how his ideas on forms relate to space. Von Humboldt, also a relational thinker, demonstrates the importance of the vast store of information in the environment, and how this continuous gradient field of information both affects the "unfolding" of form-giving systems in the environment, and is in turn affected by them. Finally, the brief introduction of Goethe's performative concept of morphology seeks to reconcile the two approaches. This will contribute to the framework for the algorithmic explorations in the latter parts of this thesis. It might be interesting to briefly speculate on what the two principals of this chapter may have thought of an algorithmic approach to the design of landscapes. Leibniz undoubtedly would have welcomed such an approach, with his thinking, philosophy, and mathematical explorations still considered an invaluable resource for the computational paradigm. It is a little less clear what von Humboldt might have thought, but he would not have necessarily been against the prospect. While he was himself not a mathematician, he admired the craft and was sympathetic of the attempt to create rationalist constructs to understand or simulate nature. His writings express the view, however, that the tremendous "complication" of problems one observes in nature, with so many levels of interacting forces, would ultimately doom such a project.[98] And while von Humboldt suffered from a kind of "measurement-mania," the adjective he frequently associates with wilderness in his writings is "unmeasurable" and in his *Views of Nature,* he describes how "nature everywhere [speaks] to man in a voice that is familiar to his soul" and what spoke to his soul, "escapes our measurements."[99] Something that cannot be measured can also not be computed. In the design of landscapes, however, an approach which moved beyond the artificiality of composition exhibited by rigid formal structures, or inartful massings of plants bearing little relationship the relational structures he observed in his travels, may have resonated with him more than the gardens of his time.

Endnotes

1 Quote on Hannover Historical Museum, part of a light installation by concept artist Joseph Kosut.
English translation: “Thus there is nothing fallow, nothing sterile, nothing dead in the universe, no chaos, no confusion save in appearance, somewhat as it might appear to be in a pond at a distance, in which one would see a confused movement and, as it were, a swarming of fish in the pond, without separately distinguishing the fish themselves.”
Gottfried Leibniz, “The Mondadology,” in *The Monadology and Other Philosophical Writings.* trans. Robert Latta (Oxford: Clarendon Press, 1898), 217-271, §69.

2 Bruno Latour, *We Have Never Been Modern.* Trans. Catherine Porter (Cambridge, MA: Harvard University Press, 1993), 29-48.

3 The first professional society of Civil Engineers was the Institution of Civil Engineers in London, founded in 1818 with a Royal Charter in 1828. The first use of the term “Landscape Architecture” is usually credited to Gilbert Laing Meason, who used the term in an art history book *On the Landscape Architecture of the Great Painters of Italy* (London, 1828).

4 Latour, 141.

5 *Ibid*, 142.

6 Leibniz, “The Monadology,”, §64.

7 Tom Conley. “Translator’s Forward,” in Gilles Deleuze, *The Fold: Leibniz and the Baroque* (London: Athlone Press, 1993), xi.

8 Gottfried Leibniz, “Letter to Louis Bourguet,” 22 March 1714 (GP III 568).

9 Conley, xiii.

10 *Ibid*, xii.

11 Boyer, *A History of Mathematics* (New York: John Wiley & Sons, 1968), 256.

12 Gottfried Leibniz. “A New Method for Finding Maxima and Minima,” From Actis Erud. Lips. Oct. 1964, p. 467-473. Trans. Ian Bruce, 2014.

13 Niccoló Guicciardini, “Did Newton use his calculus in the *Principia*?” *Centaurus: An International Journal of the History of Science and its Cultural Aspects.* Vol. 40, Issue 3-4, October 1998, 303-344.

14 Gottfried Leibniz, “Explication de l'Arithmétique Binaire,” *Die mathematische schriften von Gottfried Wilhelm Leibniz,* vol. VII, ed., C.I. Gerhardt, (Halle: H.W. Schmidt, 1863), 223-227.

15 Florian Cajori, *A History of Mathematical Notations.* Vol. 2 (New York: Dover Publications, 1993), 180-181.

16 Serkan Kiranyaz, Turker Ince, Moncef Gabbouj, *Multidimensional Particle Swarm Optimization for Machine Learning and Pattern Recognition.* (Berlin: Springer, 2013), 19. Emphasis added in lieu of original quotations.

17 Gottfried Leibniz, Letter to Tschirnhaus, as quoted in Cajori, 184.

18 *Ibid,* 185.

19 Bertrand Russell, *The History of Western Philosophy* (New York: Simon & Schulster, 1945), 595-596.

20 Donald Rutherford, *Leibniz: Nature and Freedom* (Oxford: Oxford University Press, 2005), 4.

21 Gottfried Leibniz, “Essay on Dynamics: showing the wonderful laws of nature concerning bodily forces and their interactions, and tracing them to their causes.” Trans. Jonathan Bennett, 2006.

22 *Ibid.*

23 Joseph Agassi, “Leibniz’s place in the history of Physics,” *Journal of the History of Ideas,* 30,3 (Jul-Sep 1969), 331-344.

24 The Leibniz Cannon is large and still growing. Several completed texts were published in the decades after his death. In the mid-1800s, fourteen massive volumes of essays and letters were released, seven volumes of *Philosophische Schriften* and seven volumes of *Mathematische Shriften* under the direction of Carl Immanuel Gerhardt. Starting in 1923, the definitive editions of Leibniz’s work have been published in the *Akademie-Ausgabe.* As of the end of 2017, there are 64 volumes completed and this total is expected to exceed 120 once completed. This means the total time for the *Akademie Ausgabe* project will approach 200 years! The writings are primarily in Latin, French, and German, with additional contributions in English, Dutch, and Italian, making a comprehensive view of Leibniz’s work an almost impossible task.

25 Gottfried Leibniz, ‘‘The Monadology,” §3.

26 *Ibid,* §9.

27 *Ibid,* §10-14.

28 Leibniz, “Essay on Dynamics,” 7.

29 Leibniz, “The Monadology”, §66-67.

30 Leibniz, “Essay on Dynamics,” 13.

31 *Ibid*, 12.

32 Benoit Mandelbrot, *The Fractal Geometry of Nature* (New York: W.H. Freeman and Company, 1983), 405, 419.

33 A strict reading of Leibniz’s writings being as they are firmly rooted in 17th century theism would not have supported the contemporary conceptions of emergence. A loose reinterpretation might. See for example: Edward Slowik, “Leibniz and the Metaphysics of Motion,” *Journal of Early Modern Studies,* 2:2. (2013), 75. Also: Uwe Meixner, “Agent-Causation-Neither Upward Nor Downward,” *Philosophical and Scientific Perspectives on Downward Causation*, Michele Paolini Paoletti, Francesco Orilla, eds. (London: Routledge, 2017).

34 Leibniz, “The Monadology,” §73.

35 Horst Bredekamp, *Leibniz und die Revolution der Gartenkunst* (Berlin: Verlag Klaus Wagenbach, 2012), 73-75.

36 *Ibid,* 75.

37 Gottfried Wilhelm Leibniz, "Letters to Des Billettes. December 4, 1696" In: Loemker L.E. (eds) *Philosophical Papers and Letters. The New Synthese Historical Library (Texts and Studies in the History of Philosophy)*, vol 2. (Dordrecht: Springer, 1989), 472.

38 Gottfried Wilhelm Leibniz, "The Controversy between Leibniz and Clarke, 1715-16." *Leibniz: Philosophical Papers and Letters.* 2nd edition. ed. Leroy Loemker (Dordrecht: Kluwer Academic Publishers, 1989), 708.

39 Gilles Deleuze, *The Fold: Leibniz and the Baroque* (London: The Athlone Press, 1993), 9.

40 Bredekamp, 76. Author's translation: "The process-character of all physics makes clear that for Leibniz, the topographical structure of the Garden of Herrenhausen must have been less connected with the principle of mathematical geometry than with a dynamic concept of a theory of folds."

41 Martin Davis, *The Universal Computer: The Road from Leibniz to Turing* (London: CRC Press, 2012), 1-3.

42 F.C. Haber as quoted in S. Elden, "Leibniz and geography: geologist, paleontologist, biologist, historian, political theorist and geopolitician." *Geographica Helvetica,* 68 (2013), 85.

43 Gottfried Leibniz, *Protogaea,* trans. Claudine Cohen and Andre Wakefield (London: The University of Chicago Press, 2008), 127.

44 Elden, 82.

45 Leibniz, *Protogaea,* 45-47. Elden, 84.

46 *Ibid,* 53.

47 *Ibid,* 11-13.

48 *Ibid,* 5.

49 *Ibid,* 55.

50 *Ibid,* 115-117, 119, 121.

51 *Ibid,* 117.

52 *Ibid,* 15.

53 Leibniz, *Protogaea*, 141.

54 *Ibid*, 3.

55 Leibniz, "The Monadology," §71.

56 *Ibid,* §57.

57 Gottfried Leibniz, *The Theodicy: Essays on the Goodness of God, the Freedom of Man and the Origin of Evil.* Trans. E.M. Huggard (Peru, Illinois: Open Court Publishing, 1996), §147.

58 Alexander von Humboldt, *Kosmos: Entwurf einer physischen Weltbescreibung* (Frankfut am Main: Eichborn, 2004), 3. English trans. E.C. Otté. (1864) "The principal impulse by which I was directed, was the earnest endeavor to comprehend the phenomena of physical objects in their general connection, and to represent nature as one great whole, moved and animated by internal forces."

59 *Ibid,*

60 Sanford Kwinter, "Combustible Landscape." in *Projective Ecologies,* Chris Reed and Nina-Marie Lister, eds. (New York: Actar, 2014), 337.

61 Malcolm Nicolson, "Alexander von Humboldt, Humboldtian Science and the Origins of the Study of Vegetation." *History of science; an annual review of literature, research and teaching* 25:2 (May 1987), 167, 168.

62 Alexander von Humboldt. *Personal Narrative of Travels.,* vol. 1 trans. Helen Maria Williams (London: Longman, Hurst, Reese, Orme, and Brown, 1814), iv.

63 Alexander von Humboldt and Aimé Bonpland, *Essay on the Geography of Plants* (London: University of Chicago Press, 2009), 66.

64 *Ibid,* 73.

65 Alexander von Humboldt. *Kosmos* vol. 2, 225.

66 von Humboldt, *Essay on the Geography of Plants*, 73.

67 Yi Fu Tuan, *Topophilia* (New York: Colombia University Press, 1974), xi-xii.

68 Andrea Wulf, *The Invention of nature: Alexander von Humboldt's New World* (New York: Vintage Books, 2015), 57-60.

69 Alexander von Humboldt, *Personal Narrative of Travels to the Equinoctial Regions of America,* vol. 2. trans. Thomasina Ross (London: Henry G. Bohn, 1852), 7-15.

70 *Ibid,* 64.

71 Andrea Wulf, 8.

72 Philip Foner, "Alexander Von Humboldt on Slavery in America," *Science and Society* 47, 3 (Fall 1983), 337-339.

73 for a more thorough discussion of Leibniz's impact on von Humboldt, see Margot Faak, "G.W. Leibniz im Urteil Alexander von Humboldts." *Humboldt im Netz,* 13 (2006), 102-110.

74 Pauline Phemister, "Leibniz and Ecology," *History of Philosophy Quarterly,* 18:3 (Jul. 2001), 242.

75 *Ibid,* 243.

76 *Ibid.*

77 *Gaze on them as they grow, see how the plant / Burgeons by stages into flower and fruit, /Bursts from the seed so soon as fertile earth / Sends it to life from her sweet bosom, and / Commends the unfolding of the delicate leaf / To the sacred goad of ever-moving light! / Asleep within the seed the power lies, / Foreshadowed pattern, folded in the shell, / Root, leaf, and germ, pale and half-formed. / The nub of tranquil life, kept safe and dry, / Swells upward, trusting to the gentle dew, Soaring apace from out the enfolding night.* Johann Wolfgang von Goethe, *The Metamorphosis of Plants,* trans. By Douglas Miller (Cambridge, MA: MIT Press, 2009).

78 Kwinter, *Combustible Landscape,* 338.

79 *Ibid.*

80 Michael Batty, *Fractal Cities: A Geometry of Form and Function* (London: Academic Press, 1994), 43.

81 Johann Wolfgang von Goethe. "Formation and Transformation." in *Computational Design Thinking,* Achim Menges, Sean Ahlquist, eds. (London: Wiley, 2011), 30-31.

82 Achim Menges and Sean Ahlquist, introduction to "Formation and Transformation." in *Computational Design Thinking,* Achim Menges, Sean Ahlquist, eds. (London: Wiley, 2011), 30.

83 Clarence Glacken, *Traces on the Rhodian Shore* (London: University of California Press, 1967), 506.

84 *Ibid,* 506-507.

85 *Ibid,* 507.

86 Titus Lucretius Carus, *On the Nature of Things.* trans. Cyril Bailey (Oxford: Clarendon Press, 1910), 192-193.

87 Bredekamp, 45-62.

88 *Ibid,* 61-64.

89 Leibniz, *Protogea,* 137.

90 *Ibid,* 139-141.

91 David Blackbourn, *The Conquest of Nature: Water, Landscape, and the Making of Modern Germany* (London: W.W. Norton & Co., 2006).

92 *Ibid,* 43.

93 *Ibid,* 66, 73-75.

94 von Humboldt, *Kosmos*, 225. "It undoubtedly enters within the compass of landscape painting to afford a richer and more complete picture of nature than the most skillfully-arranged grouping of cultivated plants is able to present, since this branch of art exercises an almost magical command over masses and forms." trans. E.C. Otté, 1866.

95 *Ibid,* 237-238.

96 Antoine Picone, "Substance and Structure II: The Digital Culture of Landscape Architecture." *Harvard Design Magazine*, 36. (2013), 125.

97 *Ibid*, 129.

98 von Humboldt, *Kosmos*, 36. *Die grübelnde Vernuft versucht muthvoll und mit wechselndem Glücke, die alten Formen zu zerbrechen, durch welche man den widerstrebenden Stoff wie durch mechanische Constructionen und Sinnbilder, zu beherrshen gewohnt ist. Wir sind noch weit von dem Zeitpunkte entfernt, wo es möglich sein könnte, alle unsere sinnlichen Anschauungen zur Einheit des Naturbegriffs zu concentriren. Es darf Zweifelhaft gennant warden, ob dieser Zeitpunkt je herannnahen wird. Die Complication des Problems und die Unermeßlichkeit des Kosmos vereitlen fast die Hoffnung dazu. Wenn uns aber auch das Ganze unerreichbar ist, so bleibt doch die theilweise* Lösung des *Problmens, das Streben nach dem Verstehen der Welerscheinungen der höchste und ewige Zweck aller Naturforschung.*

99 Alexander von Humboldt, *Views of Nature,* 217-218.

Chapter 5 – Von Neumann | Alexander

"An automaton can not be separated from the milieu to which it responds. By that I mean it is meaningless to say that an automaton is good or bad, fast or slow, reliable or unreliable, without telling in what milieu it operates. The characteristics of a human for survival are well defined on the surface of the earth in its present state…but it is meaningless to argue how the human would survive on the bottom of the ocean or in a temperature of 1000 degrees centigrade. Similarly, in discussing a computing machine it is meaningless to ask how fast or how slow it is, unless you specify what type of problems will be given to it." – John von Neumann[1]

5.1. Introduction

At the time of this writing, global prosperity is higher than it has been at any time in human history. Yet headlines in the papers do not reflect the optimism which should attend the unprecedented wealth being generated in contemporary societies. We read of massive and growing income inequality, the threat of job losses from automation, environmental degradation, the threat of climate change, and the threat of war and nuclear annihilation. We ask ourselves, who should technology serve? Can we survive technology? On the other hand, we ask how should we organize our communities in the digital age, when traditional social structures are falling apart and new ones mediated by rapidly evolving modes of communication are emerging? These are not new questions, but the answers seem to be changing just as fast as the technologies themselves. How did we get here and how do we move forward? Hints might be found in the thoughts and writings of two figures among many who have played a large part in the development of the technologies and paradigms which characterize the digital age, mathematician and computer pioneer John von Neumann, and mathematician turned architect Christopher Alexander. In some ways, the two figures could not seem more different. Von Neumann, a powerful Cold War bureaucrat, was optimistic about the limitless potential of technology and of the strict rationalism and logic imbedded in his discipline of mathematics but was skeptical of human nature and mankind's capacity to use these tools. Alexander, a utopian thinker was skeptical of his profession and of innovation for innovation's sake but was optimistic of the potential for humans to organize themselves in communities along tried and true principles, based largely on deep seated feeling. Von Neumann is credited with developing the template for modern computer hardware, but Alexander has become an inspiration for countless individuals developing the computer's software. Despite their fundamentally different world views, both figures proposed unique bottom-up models for the organization of complex systems which can be used to counter the increasing instability characteristic of human society at the dawn of the third millennium, in an attempt to bring order to a dynamic world moving quickly towards an unknown destination.

Figure 5.0: (*page opposite*) São Paulo by night. The 20th and early 21st centuries have produced urban forms unlike anything seen before in human history. Cities and landscapes around the world are changing faster than culture or nature can adapt, leading to a host of problems, but also new opportunities.

5.2. John von Neumann

When asked to consider the two most impactful inventions of the 20th century one could easily answer with the computer and the atomic bomb. One an engine of unparalleled productivity—a creative force that in the most optimistic sense has ushered in new societies and even "new natures"; the other an engine of mass destruction, with the potential to annihilate both nature and society completely. Few realize, however, how closely the emergence of these two inventions were tied together, and that both in large part were shaped by a relatively uncelebrated Hungarian-American mathematician, John von Neumann. Von Neumann's mind operated much like the inventions he helped shape. Like the computer, he had perfect recall, able to recite chapters from books years later after only one reading. According to colleagues, his mind operated at incredible speeds, able to solve new problems almost as soon as they were presented to him.[2] Von Neumann had a blind, almost optimistic view of the potentials of technology; when a colleague pointed out that there are some problems that can never be solved by a machine, von Neumann replied "name me the problem, and I'll devise a machine that can solve it."[3] He asserted that "technologies are always constructive and beneficial, either directly or indirectly."[4] On the other hand, he had a deeply pessimistic view of the qualities of human nature. On the surface, this side of him did not show. He was not the tortured genius lost in his equations. On the contrary, he was extremely well liked by his peers, sociable and sometimes crude, given to parties, gossip, self-deprecation and horseplay.[5] But as a secular Jew in a period of rising anti-Semitism in Germany and Austria where he studied and worked, and as a member of the bourgeoisie-elite in his native Hungary, which was being rocked by social unrest fueled by Marxist ideology, he was forced to flee Europe and find a new home in America, leaving the destructive ideologies which were unraveling the social fabric of the old world behind.

Von Neumann was first and foremost a mathematician, but he exhibited a very broad-based outlook within his discipline, and with his knowledge of chemistry and biology and his deep love of history, he was able to contextualize his work, making major contributions to both theoretical and applied mathematics. In a tribute to von Neumann published shortly after his death, his friend and colleague Stanislaw Ulam credits him with major contributions to set-theory, modern algebra, the theory of functions of real variables, measure theory, topology, continuous geometry, operator theory, the theory of lattices, theoretical quantum physics, fluid dynamics, among others. His contributions in applied mathematics extended to economics, meteorology, nuclear physics, computer science, automata theory, as well as several fields which he originated, notably game theory.[6] While his major contributions to pure mathematics lay outside the scope of this work, much of his contributions in applied mathematics touch directly on many of the critical problems which face contemporary society, as well as contemporary theories on organizing both the environment and human societies. Ulam reflected:

> "Surveying von Neumann's work and seeing how ramified and extended it is, one could say with Hilbert: 'One is led to ask oneself whether the science of mathematics will not end, as has been the case for a long time now for other sciences, in a subdivision of separate parts whose representatives will barely understand each other and whose connections will continue to diminish? I neither think so nor hope for this; the science of mathematics is an

> indivisible whole….’ Von Neumann's work was a contribution to this ideal of the universality and organic unity of mathematics.”[7]

While von Neumann’s contributions to the development of the “universality and organic unity” of mathematical thinking remains obscure to most, his contributions to the development of the first computers, a machine with the potential to reveal and synthesize a broad range of knowledge like never before is well-known.

Figure 5.1: Women of the ENIAC team holding early computer components. Before the widespread use of digital computers, woman often were largely responsible behind the scenes for performing the tedious calculations for the famous mathemeticians and engineers that they worked for.

Pictured are Patsy Simmers, Gail Taylor, Milly Beck, and Norma Stec. Not pictured are the female ENIAC programmers, Kay McNulty, Betty Jennings, Betty Snyder, Marlyn Meltzer, Fran Bilas, and Ruth Lichterman

5.3. Von Neumann and Computation

Who invented the computer? If we were to credit the construction of an actual, fully programmable, and fully automated computer to a single individual, it would have to be Konrad Zuse’s invention built in Germany in 1941 and destroyed through allied bombing later in the war. Due to this fact and the reality that post-war German society was hardly in a position to inaugurate the digital age, the impact of Zuse’s invention was limited. The computer as developed by Zuse was also the culmination of practical and theoretical advances carried out by numerous individuals over the course of several centuries all across the Western world.. In §1.3 the work of Alan Turing was introduced whereby Turing defined the requirements for universal computation in order to give a negative answer to Hilbert’s Entscheidungsproblem, but the computational machine which he described, where an infinitely long tape on which 0’s and 1’s are written and erased, looks nothing like the modern computer. In addition to Turing and Hilbert, Leibniz (§1.3, §4.1-4.7), Boole (§6.5), and Gödel (§1.3) are also mentioned at various parts of this thesis and had made other significant contributions to the development of computation and the logics that govern it. A few other individuals not discussed elsewhere who played a significant role in developing modern computation include Gottlob Frege with his contributions to logic, Georg Cantor with his work on set theory and early conceptions of fractal mathematics (§6.11), and Charles Babbage with the construction of his analytical engine.[8] [9]

The advent of the computer age proper, however, can well be credited to von Neumann, who was involved in the construction of many of the early machines in the United States and who also was one of the first to unlock its potentials to solve incredibly complex and significant technological problems.[10] Tangential to his work on the Manhattan project, where he made significant contributions to the development of the world’s first atomic weapons, von Neumann became involved with another classified military project in 1944, the development of the ENIAC/EDVAC computers at the University of Pennsylvania. (Fig. 5.1) After about a year of involvement consulting for the project, he described the team’s findings in the *First Draft of a Report on the EDVAC*. The report is credited with defining the modern computer’s general architecture and the specifications for the first components. Key to this architecture were the control and arithmetic processing units which would become known as the CPU, and a separate “memory” cache based in part on Turing’s theoretical model.[11] (Fig. 5.2) Von Neumann’s draft report, which was only intended for internal use, was leaked to the public, allowing others to imitate the design, kicking off the computer age in earnest.

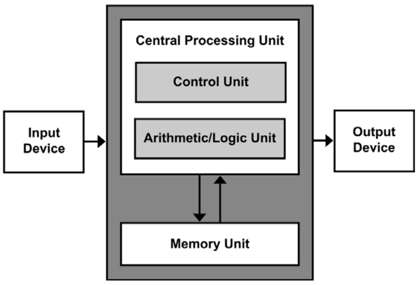

Figure 5.2: Schematic diagram of the computer‘s general architecture, still widely referred to as the “Von Neumann architecture.”

Von Neumann can also be credited with recognizing the tremendous power of the computer to solve the types of problems which had vexed mathematicians and scientists for several generations. He describes how 19th century science, which made use of linear equations to great effect, had reached a practical barrier to expanding knowledge once non-linear methods had to be used, such as problems in one of von Neumann’s own fields of

Figure 5.3: Von Neumann, now in a wheelchair suffering from terminal cancer, is awarded the Medal of Freedom for his services to the country by President Eisenhower.

expertise, fluid dynamics.[12] Von Neumann himself used these first machines to solve complex non-linear equations specifically for the development of the much more powerful second generation of nuclear weapons, the thermonuclear hydrogen bomb, developing numerous algorithmic methods still used today, such as various methods with pseudo-random numbers (see §7.6).

5.4. Game Theory

Outside of computation, one of von Neumann's most innovative and controversial contributions to modern society was his development of a mathematical approach to human behavior known as "game theory." It started as a logical analysis as to the best course of action one should take in simple parlor games, published in 1928 under the title "Zur Theorie der Gesellschaftsspiele." This text introduced theorems for optimal strategies in several game scenarios, such as if one knows an opponent's wager, what would be the best course of action to minimize losses in the face of a worst-case scenario (minmax theorem).[13] By 1944, however, he was ready to broaden his observations to not just simple games, but to human interactions in general. Together with economist Oskar Morgenstern, they introduced their new mathematical paradigm in *Theory of Games and Economic Behavior* which would serve as the basis of a new calculus for the social sciences which they hoped would revolutionize the field in the same way infinitesimal calculus had revolutionized physics.[14] Game Theory ignored the altruistic virtue of self-sacrifice in shaping human behavior, instead reducing human behavior and the societal and economic systems which they shaped into another set of solvable equations, where each actor was expected to follow predictable patterns of selfish behavior to minimize loss or maximize gains at each other's expense. They challenged the fundamental economic concept of utility, whereby actors are only assumed to want to maximize satisfaction, and instead introduced scenarios whereby every human interaction was seen fundamentally as a zero-sum game.

Game Theory would eventually become a core element of not just economic thinking, but also of statecraft. It was von Neumann who introduced the concept of Mutually Assured Destruction (MAD), the political theory which would shape the action of states throughout the Cold War. Essentially the only game that mattered in geopolitics was the détente between the two superpowers, and if the United States was clear in showing their hand, the Soviets would be forced to play their own hand in a way which minimized their losses in the face of the worst-case scenario of assured destruction.[15] The full callousness of his minmax principle was perhaps most starkly demonstrated in his involvement with the deployment of the first nuclear weapons. He had been an integral part of the Manhattan project, and it was he who in the end calculated the optimal height for the bomb's detonation in order to maximize its destructive potential.[16] As a member of the committee that selected the sites for the first and so far only uses of nuclear weapons, he favored targeting the city of Kyoto for the first bomb, the cultural and spiritual capital of the Japanese people, in order to maximize the demoralizing effect. He was ultimately over-ruled, but in von Neumann's mind, maximum destruction and morale damage now would minimize human death later.[17]

5.5. Self-Replicating Machines

In addition to attempts to develop a rational calculus for human behavior, von Neumann was an early pioneer in theorizing machines capable of artificial intelligence. Like Leibniz in "The Monadology," von Neumann was interested in a comparison between natural automata, such as the human brain, and artificial automata. Also like Leibniz, he realized natural automata

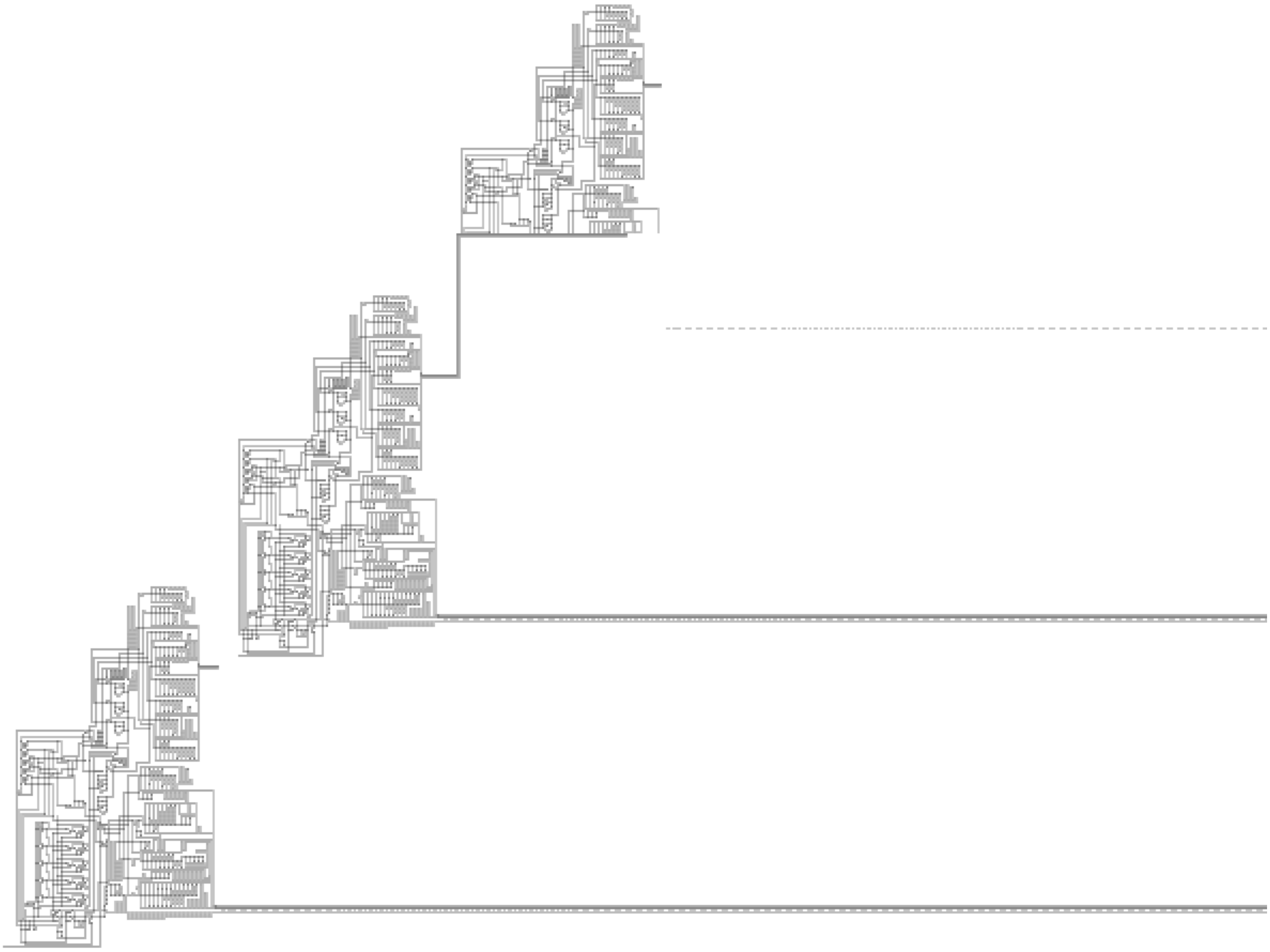

Figure 5.4: Drawing derived from von Neumann's description of a self-replicating cellular automata. "Genetic material" is transfered to the next generation of machines through a single-strand tape where random mutations are intentionally introduced to spur the machine's gradual evolution.

possessed a degree of complexity and development which far surpassed the capabilities of artificial ones, but von Neumann felt that by studying life processes, humans could work towards creating artificial intelligences which rivaled their natural counterparts. He was especially interested in studying how the human brain worked, making frequent metaphors between the operations of the brain and computers starting with his *First Draft* in 1944 and continuing into two publications released posthumously, *Computer and the Brain* and *Theory of Self-Reproducing Automata*. He recognized that neurons connected in a network, through very simple processes of stimulation and inhibition of their neighbors, were able to perform the logical operations necessary to govern life and thought in a manner which paralleled the workings of a CPU.[18] He believed it would be very difficult for humans to engineer an equivalent system in artificial automata, but to work around this, he took another innovative cue from nature—the necessity of inheritable mutation.[19]

Just a few years before the discovery of DNA, he had theorized that all lifeforms possessed a genetic code, and that similar codes could be invented for artificial automata.[20] In ribbon-like strands, this code would allow one automaton to construct a copy of itself in exact detail. (Fig. 5.4) This was not the only brilliance of his proposal, as he also proposed that this code should be subject to random mutation so that the automaton could produce offspring each generation slightly different than itself. It did not matter if the offspring were better or worse than their parents, only that they were different.[21] If most of these offspring were statistically worse than the parent, but only a small percentage were statistically better, an evolutionary process should take place, whereby through selection, eventually the automata would evolve into *highly* complex organisms which exceeded the understanding of their human inventors.[22] This would naturally involve conflict and competition between the independent organisms, which "furnish[es] an important mechanism of evolution."[23] He proposed a few models for the architecture for these self-replicating automata subject to the processes of evolution, but the most influential of these was a simple model known as the *cellular automaton*.

In the cellular automaton model, the self-replicating machine is composed of a grid of "cells" where each "cell" is connected to its four immediate neighbors. The cells have various states (von Neumann proposed 29 states) and at each time step, the current state of each neighbor is updated based on the state of its neighbors. This model would inspire an algorithmic process, greatly simplified and usually with far fewer than 29 states, also known as the cellular automaton which has been used to model and simulate living processes in a variety of contexts. (see §6.13) A few years after von Neumann's *Self Replicating Automata,* the German inventor of the first universal computers, Konrad Zuse, extended von Neumann's model and even went so far as to propose that digital models such as the cellular automaton represented quantum space and reality better than the classic "analog" model of Newtonian physics, and that the universe itself might be itself a massive calculating apparatus like the cellular automaton.[24] We will return to this concept repeatedly in this and in future chapters, but two key insights should be highlighted here. First, von Neumann proposed that despite human ingenuity, the most effective way to develop truly complex systems would be through bottom-up and evolutionary processes. Second, global behavior can perhaps be best predicted, described, and controlled through *local* interactions. This tension between the global and the local and the cumulative effect of actions and interactions, is a recurrent theme in von Neumann's thinking.

5.6. Can We Survive Technology?

As discussed, von Neumann believed computers would fundamentally progress our understanding of and our ability to intervene in systems, especially fluid systems, which operate on the basis on non-linear processes. But this intervention in social and natural systems with ever more advanced technological tools would inevitably come at a cost. In a fascinating article *Can We Survive Technology?* (1955), Von Neumann asserts that "The great globe itself is in a rapidly maturing crisis—a crisis attributable to the fact that the environment in which technological progress must occur has become both undersized and underorganized."[25] He believed that the limits of human expansion were rapidly being reached and would soon precipitate a number of global crises. Technological solutions to these crises, while being beneficial in some respects, would also tend to increase instability.[26] Von Neumann mentions energy and automation as two drivers of technological innovation, but while technological innovation can solve some problems in the short term, it might only exacerbate others. It is also unclear, according to Von Neumann's article, if we will be able to sufficiently control our technological solutions. Von Neumann also recognizes human society is fast reaching a critical threshold with regards to energy consumption, observing that the industrial revolution cannot continue for much longer based on the consumption of fossil fuels. He notes that nuclear power could provide a "free" source of energy in the future, but he wonders if humans adequately contain it. Nuclear energy, he notes, is the energy of nature, but "there is reason to believe that the minimum space requirements for her way of operating are the minimum sizes of stars. Forced by the limitations of our real estate, we must in this respect do much better than nature."[27]

Concerning automation, he recognized that despite the limited computing power of machines of his day, this would inevitably increase, and that eventually automation would have a tremendous impact on industrial economies. Von Neumann is also famous for introducing the concept of the "singularity," a concept popular with theorists of artificial intelligence. According to von Neumann, "the ever accelerating progress of technology and changes in the mode of human life, gives the appearance of approaching some essential singularity in the history of the race beyond which human affairs, as we know them, could not continue."[28] This concept of the "singularity" makes a direct reference to the phenomenon of event horizons of black holes, a point we cannot see past. We have little ability to predict if what happens is a good or a bad thing. Optimists see the singularity as a point when robotics, computation, and artificial intelligence solve all of humanity's problems; pessimists see ecological and social collapse in a dystopian future, or in science fiction, the enslavement of humanity by the very machines created to solve our problems.

Von Neumann's essay is especially interesting in the context of current efforts to understand and deal with the consequences of human induced climate change. After his involvement with the Manhattan project and the later development of the hydrogen bomb, he became fascinated with using the computer to predict and perhaps even control the weather. He believed that a global superpower which had this ability would have even more power than that afforded by nuclear weapons, and even predicted future "climate warfare." In the course of his studies of computerized weather forecasting, he was one of the first observers to recognize the direct connection between the burning of fossil fuels, the release of carbon-dioxide into the atmosphere, and changes in global climate. He recognized a precarious balance between events which could thrust us into a new Ice Age, or an opposite increase in temperature which would result in the melting of the ice caps, producing a "world-wide tropical to semi-tropical climate."[29] Von Neumann believed one could develop methods to control or alter this delicate balance through artificial means, but also recognizes an inherent moral dilemma in the proposition:

> "What could be done, of course, is no index to what should be done; to make a new ice age in order to annoy others, or a new tropical, "interglacial" age in order to please everyone, is not necessarily a rational program. In fact to evaluate the ultimate consequences of either a general cooling or a general heating would be a complex matter. Changes would affect the level of the seas, and hence the habitability of the continental coastal shelves… what would be harmful and what beneficial…is not immediately obvious."[30]

Although von Neumann was specifically theorizing over climate engineering, the top down manipulation of the weather, bottom-up processes which he identified in other parts of his work would have similar consequences to global climate, with von Neumann predicting that complex and unpredictable changes to climate would "merge each nation's affairs with those of every other, more thoroughly than the threat of a nuclear or any other war may already have done."[31]

In addressing global challenges, von Neumann believes that one cannot address the dilemmas introduced by technology by banning progress or halting innovation; since all innovation is interconnected, halting progress in one sphere would buy only a few years at most before another sphere catches up. We would have to as a global society all decide to halt all progress altogether, or find ways to live with it. He somewhat pessimistically concludes: "What safeguard remains? Apparently only day-to-day or perhaps year-to-year—opportunistic measures, a long sequence of small, correct decisions…We can only specify the human qualities required: patience, flexibility, intelligence."[32] Von Neumann himself did not survive technology. Likely because of his involvement with the Manhattan project and the first nuclear tests, he developed cancer at an early age and died at the age of 53.

In his short lifetime, von Neumann had a monumental impact on the course of the 20th century—much more so than his current renown might suggest. Few question the extent of his genius, but he remains a controversial figure to those who knew him or have studied him. Perhaps his legacy is most directly tarnished from what he himself acknowledged was a significant weakness. The sympathetic biographer Norman Macrae acknowledges that he lacked the dreaminess and "irrational intuition" which characterized scientists who introduced whole new paradigms to thought, such as Albert Einstein.[33] Despite working in the same building, von Neumann eventually distanced himself from Einstein because the latter would often become involved in lost causes to which he had become emotionally attached.[34] According to his assistant, for von Neumann "it seemed impossible to be unclear in thought or expression."[35] As such he had no patience for emotional challenges to reason, such as when he advocated for the atomic strike on Kyoto, or later when he would argue for a preemptive nuclear attack on Russia. By all accounts, von Neumann possessed a photographic memory which could contain almost limitless amounts of information, but he seems to have lacked the ability to tap into the irrational dreaminess that comes from imperfect memories and forgetting.

In his *Theory of Self-Replicating Automata*, von Neumann remarks that the brain seems to be divided into two parts—a calculating, logical part ("the switching part") and the memory. Von Neumann said it was somewhat easy to see and to understand the logical part of the brain, but "as to the memory organs, we haven't the faintest idea where or what they are."[36] Von Neumann repeatedly reiterated the importance of the memory in his computers, but the interface between the "switching part" of the computer and the memory remains the most problematic part of his computer architecture—a technical challenge called the von Neumann bottleneck and with which computer scientists continue to struggle. In many ways, then, this computer architecture is emblematic of the man himself and his legacy. His contributions to mathematics and computation were a crowning achievement of the 20th century's technocratic dream—of the formalist project—but it remained blind to the larger human experience with its complex of cultural associations and memories—the semantic structuralist associations of culture and history.

5.7. Christopher Alexander's Critique of Modernity

A few years after von Neumann's early death, an influential figure with training in the mathematics and computer science which von Neumann had so revolutionized began to make waves in architectural discourse. In the mid-1960s at the height of architectural modernism and in the first doctoral dissertation granted at Harvard's GSD, Christopher Alexander began to make an argument which fundamentally denounced his profession as a destructive force, arguing that architects were intervening in systems which they did not understand, and that their inventive solutions, while solving some problems, created a whole new series of problems in return. Although his later work, especially *A Pattern Language,* is well-known in the profession, the core of his argument was already being developed in a book based on his dissertation, *Notes on the Synthesis of Form* (1964). The argument, which is repeated in his later works, goes something like this: In most pre-modern cultures, which Alexander calls "unselfconscious cultures," strategies for living are evolved through an extensive process of trial-and-error over the course of multiple generations until eventually the culture finds optimal solutions to a particular problem. This "unselfconscious process" works well as it "has a structure that makes it homeostatic (self-organizing), and that it therefore consistently produces well-fitting forms, even in the face of change."[37] In contemporary culture, which he calls self-conscious, cultural change is happening too fast for this evolutionary process of form-finding to be successful: "the culture that once was slow-moving, and allowed ample time for adaptation, now changes so rapidly that adaptation cannot keep up with it. No sooner is adjustment of one kind begun than the culture takes a further turn and forces the adjustment in a new direction. No adjustment is ever finished. And the essential condition on the process- that it should in fact have time to reach its equilibrium - is violated."[38] Solutions need to be found to unique design problems on a daily basis, but designers do not have the capacity or the intuition to first understand all the forces at play in a problem (the context), and then come up with an optimized formal configuration to address the context. Alexander argues that "to achieve in a few hours at the drawing board what once took centuries of adaptation and development, to invent a form suddenly which clearly fits its context- the extent of the invention necessary is beyond the average designer."[39]

When designers do intervene, according to Alexander, it is often under the guise of the scientific rationality present in modern thinking, which Alexander asserts in later works finds its most pernicious expression in the philosophy of Rene Descartes, which promotes mechanistic and reductive solutions to problems which are at odds to promoting wholeness, vitality, and life.[40] He sees this reductive thinking expressed when projects have circumscribed goals, often in line with the specialization of a particular individual, but which deem that specialization as the only valid criteria—an ecologist who thinks ecology is of primary importance, a traffic planner who thinks transportation is key, or an energy expert who only looks at the building's final energy consumption as a valid design goal, with all else being *only a matter of opinion.*[41] Another example of this type of thinking might be seen in von Neumann's "zero-sum" games, or the politer term of a "cost-benefit" analysis. For von Neumann, a few big wins can compensate for many small loses; what is important is coming out ahead in the final tally. For Alexander, it is better to have many conventional or unremarkable solutions to a problem, rather than a big "win" (a brilliant idea) that is coupled with a number of smaller compromises or losses. This is because "misfits" between form and context stand out and cannot be overlooked: "The incongruities in an ensemble are the primary data of experience."[42] Alexander introduces a calculus where a fit is a "0" and a misfit is a "1." For everything that is important on a project, only a series of "0s" is acceptable and a single "1" dooms the project; "Fit is the absence of misfits."[43]

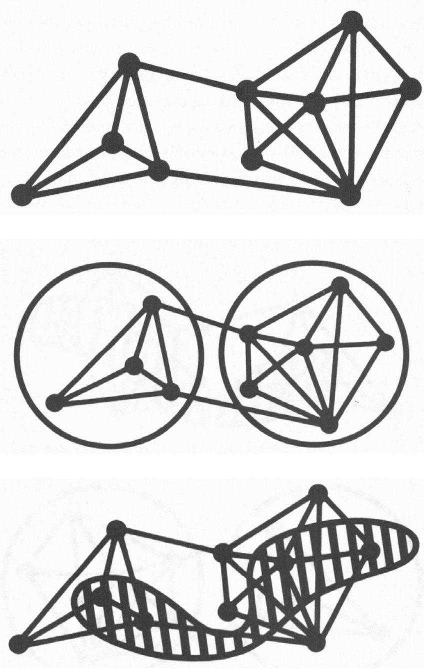

Figure 5.5: Diagrams from Alexander showing a hypothetical network, top. The middle diagram shows a sensible isolation of the system into two parts, while the bottom diagram demonstrates an illogical boundary condition.

Notes on the Synthesis of Form, 64-66.

5.8. Alexander's Pattern Language

With this background, Alexander develops his theory of how designers should operate in contemporary society. While he realizes it is naïve and unrealistic to go back to the method of gradual evolution present in "unselfconscious cultures," he does take several cues from them. First is his principle of isolating problems. Premodern peoples were part of much simpler systems, and adaptation takes place more rapidly in smaller evolutionary "gene pools." Fortifying his argument with concepts from mathematical topology and set-theory, he explains that in richly connected systems, adaptation has little chance of taking place. Extremely isolated systems on the other hand adapt immediately, but this is not useful as such an adaptation has no hope of contributing to the broader picture of wholeness in such isolated instances. What is important to Alexander, is to group problems into logical sets based on the nature of existing connections and to tackle problems based on logical boundary conditions, and to resolve problems in these smaller sets before moving on to adjacent sets. (Fig. 5.5) A careful analysis of the context, the heterogeneous field of forces, can give clues to how to isolate the problem, and understanding these fields is nevertheless critical to understanding what might be an acceptable "fit" to the problem. In Batty's analysis of Alexander's work, "good design or good decision-making in a broader sense must be based on an understanding of the ways the system evolves through the elements within its hierarchy."[44] Identifying this hierarchy, while never easy, is crucial to further steps.

Once boundaries and sets are defined, Alexander proposes a method of abstraction similar the method which Hillier would later devise, (see §2.3) whereby designers bring both the context and formal solutions into a discursive realm, in effect at a conceptual level higher than the final design solution. (Fig. 5.6) This transcendence of the project's mundane requirements is necessary as, according to Alexander, "the data alone are not enough to define a hypothesis; the construction of hypotheses demands the further introduction of principles like simplicity (Occam's razor), non-arbitrariness, and clear organization."[45] Hypotheses are then used, according to Alexander, to define concrete "patterns" that address specific design problems, goals, and relationships. Alexander stipulated that every pattern should follow the same basic template, establishing a "relationship between a context, a system of forces which arises in that context, and a configuration which allows these forces to resolve themselves in that context."[46] Furthermore, each pattern must be something that can be drawn; "if you can't draw it, it isn't a pattern."[47]

There is no limit to the number of these patterns, and designers are encouraged to spend most of their effort in *defining* these patterns, with eventual implementation becoming straightforward once the patterns are defined and agreed upon. Alexander in his most famous work *A Pattern Language* proposed a series of 251 examples of these patterns which he and a group of colleagues had developed. They range from global ideas—pattern 1 proposes reorganizing the world's political boundaries to abolish the nation state and to instead organize society into more than a thousand micro-states or regions of 2-10 million people each—to the small scale; the book ends with a description of how chairs should be arranged in a room. In between, patterns to structure regions, cities, towns, neighborhoods, streets, gardens, buildings, and rooms are all introduced, again not as a definitive list, but as a model and a template for further research and discovery. The process of defining the patterns, however, should not be undertaken in isolation, but must be carried out in conjunction with a project's end users; here the designer is a facilitator, not an inventor. The patterns must be understood as being part of a language, and much like human language, they only work when they are understood by all the members of the community.

Although Alexander is often seen as somewhat of a *misfit* in his own discipline of architecture—a notion which introduces a certain paradox in itself—intellectually his work can be seen as a clear outgrowth of a number of nascent strands of thought from the 1960s. Although *Notes on the Synthesis of Form* never cites Claude-Levy Strauss or his work *La Pensée Sauvage* (The Savage Mind, 1962), Alexander's emphasis on structure, relationships, and language, along with his fetishization of the vernacular, reflects the emerging challenge of post-modern structuralism to modernism's formalism. In the *Timeless Way of Building,* structuralist ideas derived from the work of Noam Chomsky and George Miller inform the development of a "language-like approach to design."[48] He explicitly references systems theory several times in his text, and his emphasis on "pattern" and "process" can be seen as borrowings, directly or indirectly from Watt's definitive text *Pattern and Process in the Plant Community* (1947) which introduced these two key terms into the discipline of ecology.[49] All these notions are seen in his epilogue, where he reaffirms that: "there is a deep and important underlying structural correspondence between the pattern of a problem and the process of designing a physical form which answers that problem. I believe that the great architect has in the past always been aware of the patterned similarity of problem and process, and that it is only the sense of this similarity of structure that ever led him to the design of great forms."[50]

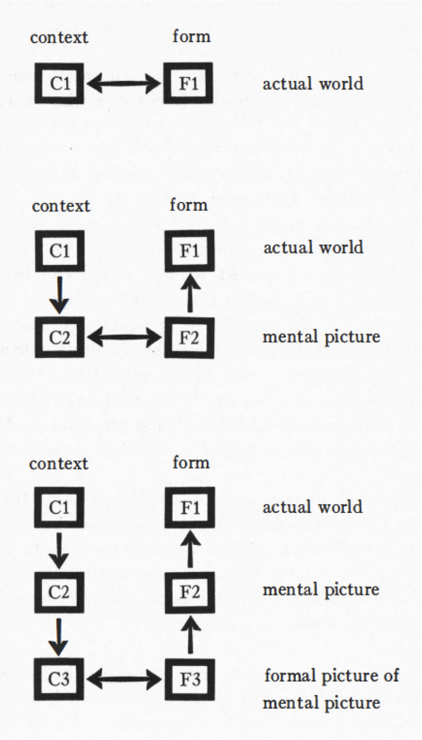

Figure 5.6: Diagrams from Alexander showing the direct engagement between context and form in a nondiscursive context, top. The second diagram shows a faulty discursive paradigm where the engagement between context and form happens intellectually. Alexander advocates an approach, bottom, where the intellectual/mental picture is further abstracted into a formal, well-defined pattern, and that here the discursive dialogue between form and context should take place.

Notes on the Synthesis of Form, 76

5.9. Alexander and Computation

Alexander's mixed legacy in the professions of architecture, landscape architecture, and urban design is well-known, but cannot be adequately addressed within the scope of this chapter. Less well known in the spatial design disciplines, perhaps, is the strong legacy that Alexander's work had on the development of new software programming paradigms and on the development of online communities, especially of "wikis" like Wikipedia, with Ward Cunningham, an early developer of the wiki concept, citing Alexander as a key early influence.[51] [52] Cunningham and Mahaffey speculate, based on an analysis of Google searches, that Alexander's concept of "design patterns" and "pattern languages" has had a significantly larger influence on software developers than on architects.[53] This shows in the overall structure of wikis, which share the following characteristics with Alexander's patterns:

> "A. Both are open-ended sets of information."
> "B. Both are topical essays with a characteristic structure."
> "C. Both are structured to be easily creatable, shareable and editable by many people."
> "D. Both are (in principle) evolutionary, falsifiable and refinable."
> "E. Both aim to create useful ontological models of a portion of the world."[54]

The vast success of such online communities (Wikipedia is just one of many) show the value for having relatively simple patterns to curate the vast, complex, and evolving system of knowledge in the digital world. It should also be reiterated that while wikis have proven invaluable for curating data, the original purpose was to foster a more active approach beyond mere consumption of information and "to allow collaboration between many people as they evolve better collective solutions to shared problems."[55]

The "design pattern" paradigm introduced by Alexander has also had an enormous impact on the development of computer software itself, which was an initial goal of the wiki program. Alexander in *Notes on the Synthesis of Form* is himself skeptical of the computer's capacity to synthesize and create form based on his methodology, seeing computers as another extension of the mechanistic paradigm,[56] but computers have evolved considerably since the 1960s, in part as a response to the very objections raised by Alexander, and in part inspired by his work and his methodology. An example of this can be seen in the emergence of the paradigm of "object-oriented programming" which has become a dominant methodology of developing software in recent years, also directly inspired by Alexander's work.[57] [58] A fundamental text advocating this paradigm is Gamma et. al.'s *Design Patterns: Elements of Reusable Object-Oriented Software* (1994), which presents twenty-three tried and tested algorithmic patterns—organized around themes of creation, structure, and behavior—which are intended to be adapted to specific programming problems.[59] Like Alexander, *Design Patterns* argues that the value of developing software patterns is not primarily in their capacity to make future iterations of the problem easier or to save time—often they do nothing of the sort—but are instead fundamental to *good design.* Also like Alexander, they reiterate that the patterns should not be seen as "building blocks" (static objects), but are "descriptions of *communicating objects* and classes that are customized to solve a general design problem in a particular context."[60] These "objects" communicate with each other and with the outside world through data inputs and outputs, and as such form a network of strong and weak interdependencies. The aim is that by "abstracting the relationships within a recurrent problem, and [treating] them as objects within a generative design system, such a system can … allow a much more efficient development of design solutions for a wide range of problems."[61]

5.10. Global and Local – Alexander's Light Bulbs

Returning to the designed landscape, at first blush it seems difficult to compare a von Neumann inspired and an Alexandrian approach to this subject. Despite his detractors, Alexander has had a marked and continuing influence on the design of landscape spaces and many of his patterns could serve as a starting point for an entire monograph. Von Neumann, on the other hand, was never involved in any general work of architecture, let alone landscape architecture, and never expressed any inclinations or attitudes towards the design of the physical environment outside of his musings on the possibilities of climate engineering. Because of his involvement with large, impactful projects and his mathematic formalisms, it might be tempting to ascribe a top-down attitude to von Neumann, while Alexander's rejection of architectural authority and his insistence on including stakeholders in his projects implies he would represent a more bottom-up approach to design. The reality again is much more complicated than this.

A good starting point for a comparison of the two approaches would be with von Neumann's notion of the cellular automaton contrasted with a curious passage in *Notes on the Synthesis of Form,* where Alexander describes an emergence of order from a hypothetical array of 100 flashing lights. In the model he describes, each light has an even chance of turning "off" at each time step ("off" = 0), or of being reactivated ("on" = 1) only if a connected neighbor is also "on." Adaptation is achieved when each light is "off" (0). With no relations between them, the flashing will synchronize in the "off" state almost immediately. This represents an "order", but a very low grade one. If the lights are richly connected, say each light to every other one, they will likely synchronize only after an average of 10^{22} years, so for all intents and purposes never. But if the relations are localized into smaller subsystems, adaptation will take place within a reasonable time scale. He concludes self-organization or adaptation, "apart from chance…depends only on the pattern of interconnections between the lights."[62] These patterns of interconnections will be further explored in Chapter 8, but a key takeaway for Alexander is that adaptations in complex systems only takes place with a certain degree of heterogeneity and isolation of the system's parts, or as Alexander observes: "no complex adaptive system will succeed in adapting in a reasonable amount of time unless the adaptation can proceed subsystem by subsystem, each subsystem relatively independent of the others."[63]

Several problems with Alexander's model are immediately evident. As previously described, he describes adaptation as the lack of misfits, or in his light bulb array, the lack of "on" (1) states. Alexander has here introduced the idea that adaptation has a fixed *teleology* or preferred end state, and this teleology is something the designer can judge. This is questionable; while Alexander might want all the lightbulbs off, someone else might want them all on, and yet another might prefer them to be in a state of oscillating synchronization. Furthermore, his model involves a strict binary. Something is either a "fit" (0) or a "misfit" (1), and there are no gradients between the two states. Another problem with this model is Alexander's concept of isolation. In *A Pattern Language*, his wish to isolate problems led to his patterns of "Independent Regions" and "Mosaic of Subcultures" for example, suggesting cultures with barriers to contact with other cultures can develop "new ways of life" only when they are "spatially separated."[64] He proposes that there should be free movement of peoples between these subcultures and regions to prevent ghettoization, but history has shown that top-down attempts to spatially segregate and define communities has led to significant human misery. And a degree of top-down control is evident in many of his other patterns, and those with dissenting views from the broader community, those who don't speak the "language," or "misfits" in other ways in Alexander's paradigm would have to find new homes. Also unclear is how Alexander's atomized communities would come together to address global problems. In short, while his approach espouses the virtues of bottom-up processes, the thinking is still essentially top down. In reflecting upon the computational approach to design patterns, Gamma finds their approach to have evolved in a somewhat different direction from what Alexander proposed. Gamma explains how "rather than coming up with a set of interwoven patterns top-down, micro-architectures are more independent patterns that eventually relate to each other bottom-up. A pattern language guides you through the whole design, whereas we have these little pieces, bites of engineering knowledge."[65]

5.11. Global and Local – Von Neumann Cellular Landscapes

Von Neumann's paradigm, on the other hand, recognized that the world has become so interconnected that isolation of innovation, thought, and community is no longer possible. He recognized that contemporary society faced global problems, which in turn required global solutions. At the same time, he was skeptical of state-planning or fascist attempts to regulate this, offering truly bottom-up solutions at the level of individual human interactions and decisions. Von Neumann also recognized the difficulties with a *teleological* approach. Technology *could* allow us to do truly great things, but *should* we do them? His cellular automaton gives his answer. Evolution will decide what we *should* do. And if humans cannot solve the globe's crises through *adaptation*, perhaps the human legacy of artificial intelligence will make something out of the universe in the end. Von Neumann, to rephrase, believed evolution and adaptation in contemporary society act in the same way they had always acted in traditional societies, and if we were to "do

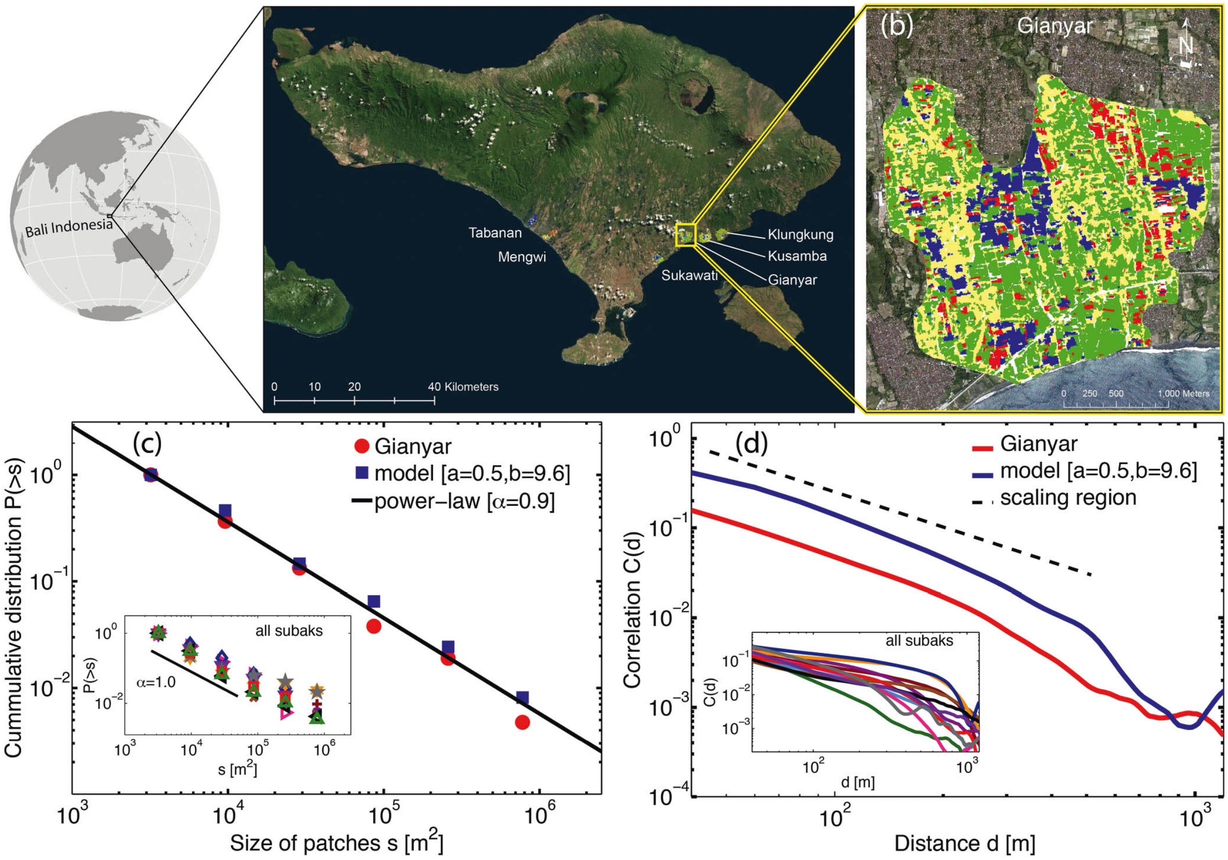

Figure 5.7: Diagrams derived from the computer simulation of landscapes in Bali where an optimized model for planting rice and the distribution of water *emerges* through purely local interactions.
Lansing et. al, “Adaptive self-organization of Bali’s ancient rice terraces.“, 2017. PNAS.

better than nature” and keep up with the changes technology offers, perhaps evolution could be carried out in digital space as part of a “new nature.”

What this means can perhaps be best illustrated by an example, showing how von Neumann’s ideas of simulated natures correspond to what is actually observed in traditionally evolved landscapes. A fascinating line of research carried out by anthropologist Stephen Lansing on the island of Bali since the 1970s gives a hint as to how the von Neumann inspired cellular automata and the use of his game theory can be used to describe the self-organizing processes of a landscape, and in turn how the use of such processes can inspire future generations of landscape planners to create the landscapes of tomorrow through an evolutionary process. Lansing’s research into the traditional management of rice terraces in Bali starts with a careful analysis of the balances present in the traditionally evolved landscape, where groups of farmers in a single watershed need to balance water consumption since the hydraulic network does not have the capacity for every family to flood its fields at the same time. Along with balancing water consumption, the farmers must also allow for their fields to be fallow for a certain amount of time each year so that rice infesting pests will die off, and to some extent, the fallow periods must be coordinated with neighbors so that all the pests in a region die all at once, preventing them from later jumping to and infesting nearby fields afterwards. Achieving a balance between patterns of water consumption and patterns of fallow periods for planting, then, is critical to this particular landscape.[66] [67]

Lansing then describes how the traditional agricultural pattern broke down after agricultural planners in a top-down fashion sought to increase the efficiency of the traditional paradigm by introducing a combination of pesticides and improved, fast-growing rice strains which would allow for more rice harvests in a single year. The top-down engineered system failed and crop yields plummeted along with a collapse of rural societies. Lansing and his team upon analyzing this, developed a series of digital models based on cellular grids and using principles derived from game theory to demonstrate to the Indonesian government how the traditional agricultural system represented not only an ideal model for long-term agricultural productivity, they also demonstrated *how* this pattern emerged based only on the interactions of actors with their neighbors. In this context, local self-interest and global optimization were able to correlate based on only a few parameters, with the model the researchers had developed showing "how feedbacks between human decisions and ecosystem processes can evolve toward an optimal state in which total harvests are maximized and the system approaches … optimality." The model also demonstrated "how multiscale cooperation from the community to the watershed scale could persist for centuries."[68] (Fig. 5.7)

5.12. Computationally Evolved Landscapes

The Lansing research suggests that the vernacular cultural landscape represents a generally "optimized" form and that interventions in such contexts need to be undertaken with care. The research also suggests that these processes are open to computational scrutiny, and that evolutionary scenarios which play out over years to centuries in the real world can be tested in a much more compressed timescale with computational methods. Cunningham and Mahaffey suggest the limited scope of Alexander's impact on the architectural profession in comparison with that on computer programming may be because the validity of Alexander's patterns could not be tested in the slow timescales of the real world, while digital patterns can be tested almost immediately. They go on to suggest that Alexander's approach may gain increasing relevance if his patterns are coded and tested in software environments: "While the time cycle of urban projects may not be shortened significantly, effective modeling approaches may be able to predict, with reasonable accuracy, the results of various patterns."[69] To make a truly "evolutionary" and "agile" pattern language which can have both an important local and global impact, such an approach may be the best way forward.

This is what was suggested by Thom Mayne in his book *Combinatory Urbanism* (2012). Mayne, like Alexander, Leibniz, and many others also rejects the "Cartesian" paradigm, but finds designers seem stuck in this paradigm for a variety of reasons. Mayne writes:

> "despite such advances in the understanding of complexity in general and an ever-sharper understanding that surface order does not necessarily reveal the existence of the deep systemic order that forms complex organisms, singular systems of organization continue to prevail…most urban architecture today…dangerously accepts Cartesian planning as the default means—as the only means—of demarcating land and organizing citizens. This overreliance on a gridiron infrastructure that negates contextual distinctions such as topography and cultural differentiation has proven largely ineffective at producing new and intricate places of urban value."[70]

Drawing from Stan Allen (see chapter 9) and Fumihiko Maki's text *Collective Form* (1964), Mayne comes to similar conclusions as Alexander and von

Neumann, that in modern society, we need to perform in a compressed time scale what was once done over the course of generations. Mayne then asks:

> "is it possible to collapse the time required for urban evolution, to achieve in one year what once took a hundred?... How can we combine the best qualities of traditional place making (character, quality, and sense of place) with the latest technological and scientific advances to yield a complex yet coherent urbanism that is neither random nor simplistic? How can we multiply urban effectiveness to create meaningful spaces that deal with initial realities along with additional agents. Lastly, how can we accommodate the unpredictable nature of space over the extended time span of a project's life cycle, leaving room for provisional changes, spontaneous experiences, and adhoc formations?"[71]

After making these observations and posing these questions, Mayne presents his thesis that the computer is the best tool at our disposal to create within our lifetimes cities with the positive qualities of traditional urbanism, but which can also address the needs and realities of the present, with adaptability for the future.

5.13. Summary Conclusion

The digital computer emerged in a century characterized by world-shaking societal and environmental change, and there is no expectation that the next century will see a deceleration of these processes. As evident in the life and work of John von Neumann, technological progress can advance and improve societies, but can also unleash immense and destructive forces. In all cases, instability increases with increasing complexity, and more energy and resources are required to maintain it. The need for societies to evolve and adapt with increasing speed also becomes paramount. This evolution and adaptation cannot be managed from a top down perspective, but requires harnessing the bottom-up and self-organizing potentials of complex systems and of societies.[72]

Both von Neumann and architect Christopher Alexander provide hints as to how this is to be done. Alexander advocates a position where small segments of society break problems down into manageable parts of the overall, larger system, and identify patterns of relationships between elements, and how these patterns can be changed or reconfigured. Patterns are identified, curated, and evolved through a cooperative, community process focused on local change. The adoption of Alexander's methodology by computer scientists has led to the emergence of powerful computing paradigms and online communities, whose methods can in turn be re-appropriated by designers looking to intervene in increasingly complex contexts. Von Neumann's model spanning the local to the global, in contrast, sees an approach of isolating problems and systems as unrealistic with the amount of interconnection in society and nature. His model more closely parallels the non-teleological nature of Darwinian natural selection, and his approach seems to advocate for artificial means of evolving machines and society by fostering conditions for a competitive "ecology." His game theory and cellular automaton models prefigure the emergence of agent-based computer models for mathematizing and predicting the behavior of rational actors. Such models can be used to decipher and in the end redirect the energies and flows of hybrid cultural-natural systems.

Endnotes

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13 John von Neumann and Oskar Morgenstern. *Theory of Games and Economic Behavior.* 3rd ed. (Princeton: Princeton University Press, 1953), 154

14 *Ibid*, 4-6.

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16 *Ibid*, 241.

17 *Ibid*, 241-244.

18 Von Neumann, *Theory of Self Reproducing Automata,* 36-41, 81.

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20 *Ibid*, 130.

21 *Ibid*, 86-87.

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23 *Ibid*, 131.

24 Konrad Zuse, "Rechnender Raum" (1967), 337-341.

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26 *Ibid*, 107.

27 *Ibid.*

28 as paraphrased by Ulam, 5.

29 Von Neumann, "Can We Survive Technology?", 108.

30 *Ibid.*

31 *Ibid*, 108-109.

32 *Ibid*, 109.

33 Macrae, 20.

34 *Ibid,* 88.

35 *Ibid*, 20.

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37 Christopher Alexander, *Notes on the Synthesis of Form.* (Cambridge, MA: Harvard University Press, 1964), 38.

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40 Christopher Alexander, *The Nature of Order. Book 1: The Phenomenon of Life* (Berkeley: The Center for Environmental Structure, 2002), 352.

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51 Helmut Leitner, *Mustertheorie: Einführung und Perspektiven auf den Spuren von Christopher Alexander, 2*nd ed. (Graz: Nausner & Nausner, 2016), 88-90.

52 Cunningham and Mahaffey.

53 *Ibid*, 5.

54 *Ibid*, 6-7.

55 *Ibid.*

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60 *Ibid,* 3. Emphasis added.

61 Cunningham and Mahaffey, 3.

62 Christopher Alexander, *Notes on the Synthesis of Form,* 40.

63 *Ibid,* 41.

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Summary Part I

The goal of Part I was to provide an introduction to a number of historical topics related to the development of algorithmic thinking on the one hand and systems thinking on the other. The nature of the research in Part I is characterized as "research *about* design" in contrast to "research *for* design" or "research *by* design" which are the goals of Parts II and III of this thesis respectively. (§0.4) In the introduction, three key questions that came to structure the thesis into these three general parts were introduced. This first part sought to deliver an answer to the question: "How do *algorithmic model*s relate to broader questions concerning the *emergence* and *creation* of form in natural and in human *systems*?" (§0.2) This question was addressed by first introducing key concepts relating to algorithms and *algorithmic models* (§1.2-1.5) followed by key concepts related to *systems* and systems thinking. (§1.8-§1.10) Out of this grew a larger account surrounding the development of formal systems on the one hand –a formalist narrative—and relational systems on the other—a structuralist narrative. The intentional, "discursive" *creation* of form through design and planning was contrasted in many instances with the unplanned, "non-discursive" *emergence* of form as a product of natural and cultural evolution. As landscape architecture incorporates elements of both deliberately created and planned form as well as emergent, spontaneous, and evolutionary form, a productive synthesis between these two types of form from an algorithmic perspective is proposed.

Accordingly, in the first two chapters of Part I, the research introduced the topic of algorithmic design and sought to contextualize this in the realm of landscape architecture. In the following Chapters 3-5, examples of attitudes and methods concerning designed and emergent landscapes were presented. These are presented in light of the development of formal logic and mathematics in the West, the systems upon which the fundamentals of computation would ultimately be based. Throughout, the text seeks to contextualize computational design not as a recent fad, but as the current manifestation of an extensive philosophical project with roots deep in human history. This philosophical tradition, at least in the West, has been closely tied to mathematics and especially spatial mathematics since the time of Euclid, and as such, computation's reliance on mathematical models and descriptions of the universe inevitably raises associations with these philosophical and existential themes. At the same time the research proposed that while computation is heavily invested in questions of form, how knowledge is structured, and as such represents a continuation of the development of formal systems and the formalist tradition, a potential hybrid practice between formalist logics and the scientific understanding of nature as an organic, evolved whole, can be envisioned through the mediation of computation. Whereas computers are machines, computational design does not need to be seen as "mechanistic" in nature, at least in the 19th century sense of the word growing out of the Industrial Revolution. Instead, computation has potentially more in common with processes of biology, evolution, and emergence than with the machines of industry. (§1.5) But this is not all. Algorithmic methods have already changed the way we receive and process information, the way we build, design and shape the environment around us, and this process seems to be accelerating. They also continue to change our understanding and even perception of what is natural, and the commonalities between algorithmic logic and biological logic have gone a long way towards fostering the currently fashionable attitude

Formal System	Euclidean Geometry Trigonometry Algebra Cartesian Coordinates Calculus Boolean Logic Topology Cellular Automata Fractal Geometry
Informational Tools	Stakes and Ropes Mapping Surveying Tools GPS - Satellite Aerial Photographs Lidar Open source mapping
Construction System	Manual Labor Stakes and Ropes Heavy Machinery Robots
Design Tools	Ruler | Compass | Protractor French Curve Computers
Understanding of Natural Behaviors	Experience | Tradition Sense | Reason Newton‘s Laws Natural Selection Quantum Theory Ecology
Cultural Worldviews	Tradition Determinism - Free Will Platonism Positivism Romanticism Modernism Structuralism Post Modernism

Table I: (*above*) Milestones in the development of formal systems along with corresponding advances in other fields.
Timeline left / ancient, right / modern

in the discipline that nature and culture are one and the same. A very rough timeline of key concepts and developments discussed in Part I with linkages to computational design is provided in Table I. The thesis will return to the larger question of the relationship between algorithmic design and the discipline of landscape architecture in the general conclusion at the end of this thesis, but several key concepts should be highlighted here before entering Part II.

A major underlying goal of this section was also to introduce a model for conceiving and designing algorithms themselves in order to address design problems on a continuum that spans between the ill-defined, but nevertheless useful categories of "form" on the one hand, "information" on the other, with "performance" being a category activated by the productive interaction or *isomorphism* between the two. (§2.6) Again, many of the topics which are associated with these three categories and which were discussed in Part I of the thesis are summarized in Table II. The argument is made here that pure formalism or pure *interiority*—or in the context of computation a focus only on the internal logic of an algorithm—is just as sterile as pure structuralism, relation, and *exteriority*—or a focus only on gathering information and data. Instead, a special focus needs to be placed on finding strategies to foster linkages and communication between the two realms. On the one hand, in a computational context, this means codes for generating forms at least in the context of landscape design need to be designed specifically to interact with layers of information, moving beyond mere digital experiments on the screen. On the other hand, the argument is proposed, a focus only on gathering and cataloguing information without attempting to develop methods to systematize and process it with a *formal* structure is equally unproductive. As this thesis moves into Part II, it will explore this idea further, with the scale tilted more towards the side of form, leaving for a moment aside the equally important question of how computation is changing the way we obtain and process information. Algorithms will be categorized into a series of families with several "patterns" or "objects" in each category touched upon in more detail. The reader should bear in mind, however, that the patterns do not need to operate in isolation; they are not slaves to context and relation, and much like living organisms or Leibniz's monads, have internal rules and logics all their own. In Part III, then, an attempt will be made to combine the formal logics of algorithmic patterns developed in Part II with layers of information to see how this *performative* narrative develops.

In addition to the tripartite construct of form, information, and performance, a more ambitious project relating to algorithmic design is explored—the goal of using computation to "evolve" new patterns in a world changing faster than the rate at which societies and nature can adapt to changing conditions. This ambition stems from the proposition put forth in Part I that form in human societies emerges in a manner not much different from the manner in which it emerges in natural systems. In both cases, it is largely the product of an unconscious, non-discursive process. This emerges by an interaction of fundamentally simple and basic rules combined with an extended period of natural or cultural selection. (§2.3 Hillier, §5.7Alexander, §3.6-§3.13) Computational algorithms also interact in terms of very basic and simple rules, (§1.3) and numerous thinkers have put forth the proposition that computational paradigms and strategies can be evolved much like other complex systems. (§1.5 Dennett, §5.5 Von Neumann) The need for this stems from the observation that human society in the last centuries has sped up its evolution to the point where the emergent properties of systems are changing before selection can optimize them. Non-discursive strategies for optimizing forms and systems are generally no longer viable. At the same time, deliberate manipulations of the system are

Table II: (*below*)Themes, ideas, and author's discussed in Part I of the thesis arranged in terms of Picon's three categories of Form, Performance, and Information.

Picon	**Form**	**Performance**	**Information**	§2.4
Linguistics	**Formalism**	**Functionalism**	**Structuralism**	§1.8
Steinitz	**Details**	**Tactics**	**Strategy**	§2.6
Deleuze	**Codes**	**Folding**	**Territories**	§2.3, 2.4
Ancient Writers	**Euclid**	**Julian of Ascalon**	**Lucretius**	§3.3, 3.6, 3.12
Cultural Landscapes	**Agriculture/Irrigation**	**Movement**	**Territory**	§3.11.
Leibniz	**Monads**	**Assemblages**	**Totalities**	§4.5
Von Humboldt	**Measures**	**Forces**	**Relationships**	§4.8
Goethe	**Inner Essence**	**Morphogenesis**	**Field**	§4.10.
Von Neumann	**Neurons / CPU**	**Speed**	**Memory**	§5.3, 5.5, 5.6
Alexander	**Patterns**	**Designs**	**Context (Field)**	§5.8
Biology	**Genetic Code**	**Natural Selection**	**Environment**	§5.5

often more detrimental than helpful. Alternative strategies need to be found to test forms and patterns which don't rely on the flawed genius of a single individual. (§2.3 Hillier, §5.6 Von Neumann, §5.7 Alexander) Computational methods may be of assistance in filling this gap, evolving new formal systems and patterns in their informational contexts, creating systems that are well adapted, demonstrate fitness, and that are ultimately performative. (§5.12 Mayne, §2.3 Hillier)

This question will also be addressed again in the general conclusion, but it should be noted here that this strategy is difficult to execute in practice as several fundamental differences exist between natural or cultural systems and computational systems. The physical world has rich layers of memory that often cannot be described algorithmically and they are hence excluded from the process or are often axiomatized out of the equation. (§5.6 Von Neumann) Both individuals, described by Leibniz as monads with individual layers of complexity and unique properties (§4.5 Leibniz) as well as broader ecosystems with countless layers of immeasurable relation between organism (§4.12 von Humboldt) have layers of complexity that are incredibly difficult if not impossible to axiomatize. Furthermore, unlike natural systems, computational algorithms often lack systems of redundancy, which in the end may be of critical importance to the long-term survival of any complex, adaptive system. (§5.5 Von Neumann) A final consideration, especially relevant in the context of landscape architecture, is the fact that computational systems follow a binary logic, which does not well reflect the unique qualities of landscape with its ambiguities. (§2.9 Meyer) Strategies need to be found to address this ambiguity or shifting relational topologies if computational design is to reach its full potential in the context of landscape design.

A practical approach in the here and now, in light of these potentials and problems, is to adopt a mixture of bottom up and top down approaches—both conceptually and algorithmically. Top down approaches, however, should still seek to harness the power of self-organization in systems and not impose an artificial order as far as possible. (§Meadows, §2.12. Barnett, *Emergence in Landscape Architecture,* 225.) Furthermore, an *isomorphism* or congruence needs to exist between forms and their informational context. When this congruence exists, the system can be said to perform. (§2.4) The poet Goethe (§4.10) with his concept of forms unfolding in fields provides a metaphor as to how this can be done. In the end, however, the need to engage the physical environment and the pressing problems it faces are critical. Landscape architects can be part of the broader project to make "the entire environment a work of art" (§1.8 Burnham) Algorithmic systems can help accomplish this, but the designer needs to surrender a degree of control. (§1.13 Carpo)

Part II

Algorithmic Patterns for Landscape Architectural Design

Chapter 6 – Introduction to Algorithmic Systems

Clockwork logic-the logic of the machines-will only build simple contraptions. Truly complex systems such as a cell, a meadow, an economy, or a brain (natural or artificial) require a rigorous non-technical logic. We now see that no logic except bio-logic can assemble a thinking device, or even a workable system of any magnitude.[1]

6.1. Introduction to Part II

In chapter 1, the notion of an algorithm as an effective, definite, and finite procedure was presented, along with some key milestones in the history of algorithmic design in art, architecture, and in landscape design. In chapters 3 through 5, some key milestones in the history of the development of the western formal system were introduced, which comprise the fundamentals of computation's logical operation. The formal system was paired with a structuralist argument that emphasized the importance of relations, connectivity, information, and memory. The space where the formal codes and the substance of memory meet is a performative space of growth, evolution, and emergence. Modern computation is often seen as predominately mechanistic paradigm, with an emphasis on its logical operations. The argument will continue to be made that these cannot be seen in isolation, and that the information (memory) and evolutionary (performance) aspects of computation need to be considered as well.

Part II of this thesis is organized into nine brief chapters, Chapters 6 – 14, which provide an overview of several algorithmic systems or *design patterns* grouped by topic. Each chapter presents a theme important in contemporary design discourse and supports that topic with three algorithmic examples. While each chapter could be read as an independent essay, the chapters refer back to each other and the algorithms in particular describe concepts of increasing difficulty as the chapters progress. The next chapter in this sequence, Chapter 7, deals with issues of randomness, indeterminacy, and probability, concepts essential to a contemporary understanding of matter. Chapter 8 then introduces the concept of networks and mathematical topology, essential structures for the description of relational systems that organize matter into coherent structures. Chapter 9 contrasts the scientific concept of highly articulated networks with highly connected networks in light of the philosophical thought of Gilles Deleuze and Felix Guattari and their concept of striated and smooth spaces. Chapter 10 can be seen as an exploration about how striated spaces and systems grow and develop in increasing levels of articulation. The following two chapters (Chapters 11 and 12) return to the question of modeling smooth spaces, which are more difficult to describe algorithmically than striated spaces but which perhaps offer greater potential for creative outcomes. The qualities of smooth, vector-dominated spaces are discussed in the Chapter 11 while strategies for studying the emergence of pattern in such spaces through the interactions of intelligent agents and automata is the focus of Chapter 12. Chapter 13 then recombines the strains of the previous chapters on smooth and striated spaces into a topic of particular interest to landscape design,

Figure 6.0: (*page opposite*) Aerial Image of a "Tiger Bush" ecosystem. The pattern in nature emerges through a binary process of interactions, which can be compared to an algorithmic process. (See §7.3)

geomorphology and the genesis of landform. The final chapter of Part II, Chapter 14, brings together many ideas and also looks forward to emerging methodologies in algorithmic design with a discussion of digital ecologies and evolution.

The present chapter serves as an introduction to some of the key aspects of algorithmic systems in the context of this thesis. Of all the chapters, this one gets closest to the discipline of computer science and no attempt is made to introduce concepts from landscape design. For computer scientists, it might appear very basic in its details and for landscape architects, it may at times veer towards the abstract—it is hoped a reasonable balance is achieved. While the chapter can be skipped for those who either find it too basic or too technical, several key terms and algorithmic paradigms are introduced towards the end of the chapter which may prove helpful for understanding concepts in later chapters.

6.2. Programming languages

The language spoken by computer processors is at the most basic level the binary code of 0s and 1s which correspond to certain circuits being switched "off" (0) or "on"(1). These 0s and 1s are in turn grouped together into small chunks of data (bits) which in turn correspond to specific instructions that the CPU can carry out. Various patterns in the bits of data comprise one of many "machine languages." Machine languages are generally totally unreadable to most humans, with only specialist computer hardware engineers able to begin to make sense of what the instructions mean. Above the level of machine languages are "assembly languages" which abstract the chunks of 0s and 1s of machine language into identifiable instructions or words. The machine language instruction "0101111000" for example, becomes ADD which means "add one number to another."[2] Assembly language still operates on a level much more abstract than what most programmers today would use, although before the advent of higher level paradigms in the 1950s, most programming work was done in these very basic languages.[3]

Today, most computer coding is done in one of many "higher-level languages" which are composed of precise instructions comprehensible by humans with some training in the nuances of a particular language. These languages in turn need to be translated by a compiler to communicate with the computer's CPU, and the languages have structural limitations imposed upon them by the underlying computer architecture (the machine language instruction set). Higher-level languages in turn are often based around one of several programming language paradigms that help the human user structure thought and programs in a logical, comprehensible, and perhaps reusable way. Each paradigm and language has its advantages and disadvantages, and most professional programmers will know several different languages, and may switch languages depending on the specific task. Achieving the level of proficiency demanded by software engineering is a rigorous and demanding task requiring countless hours of effort and years of experience.

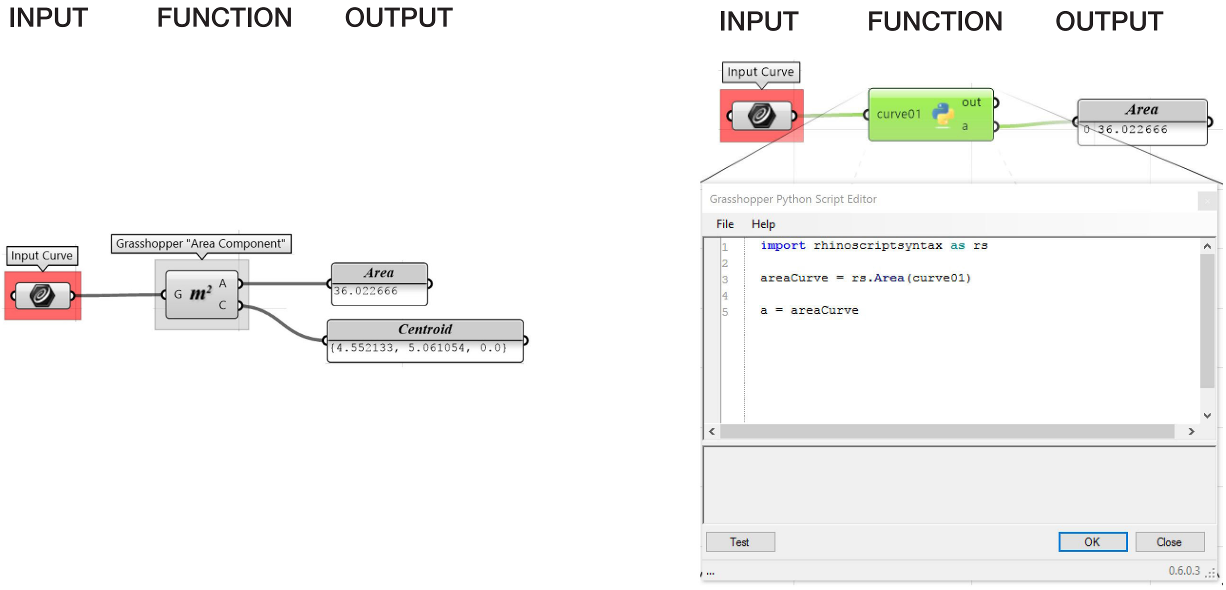
6.3. Programming Paradigms, Patterns, and Monads

In most cases, those wishing to explore an algorithmic approach to design in architecture or landscape architecture do not have the time nor inclination to master the intricacies of software development and to become completely fluent in a programming language. In recent years, however, many software packages used by designers, such as CADD programs, 3D modelling suites, GIS programs, and gaming engines have developed interfaces to allow the inclusion of much simpler scripting operations—small chunks of larger programs—into current workflows. Two general approaches exist. The first is to use a modified version of a popular programming language which is tailored to communicate with a specific software, linking "objects" in a 3D model, for example, to objects in a short program. Commonly used languages for this task include C#, Python, and Visual Basic. The second approach is to use one of a number of native graphical algorithm editors that have been incorporated into many popular software environments used by designers in recent years. Here the "programs" are comprised of a network of nodes and wires diagramming an algorithmic process, with wires representing the flow of information, and nodes representing specific operations or functions. ArcGIS has such a system, as does the 3D modeling program Rhino with its interface Grasshopper. The CADD program Vectorworks has recently developed a graphical algorithm editor known as "Marionette."

The algorithms shown in this thesis make use primarily of the Grasshopper algorithm editor in Rhino, with more complex routines scripted in an adapted version of Python script. Although the basic Rhino-Grasshopper environment does not tend to favor the "object-oriented" approach introduced in the previous chapter, which has played a dominant role in recent years and which has its legacy in the design patterns of Christopher Alexander, certain custom plugins and techniques allow users to build reusable "objects" which operate based on the input of certain attributes. Trevor Patt obliquely referenced a link between the object-oriented paradigm, specifically notions from object-oriented philosophy, and Leibniz's concept of the Monad in his doctoral thesis *Assemblage Form*.[4] In the "functional programming paradigm" the term "monad" is used to denote certain connective structures. In object-oriented programming, " the "monad pattern" is a design pattern for types, and a "monad" is a type that uses that pattern."[5] This thesis will not explore these notions from computer science in any detail, but the concepts of patterns vs. monads in the chapters which follow is a helpful concept. The thesis will also depart somewhat from the definition of a monad in functional programming.

"Objects" in a scripting context can be seen as associations of related functions grouped together to perform a specific task. The objects are in turn related to other objects in complex relational networks, which

Figure 6.1: (below) A "simple" area function scripted in Grasshopper (left) and Grasshopper with Python scripting (right).



```
import rhinoscriptsyntax as rs

areaCurve = rs.Area(curve01)

a = areaCurve
```

form a “design pattern.” These patterns can in turn be grouped together to create a new object. This nested series of connected operations, much like the picture of nature described by Leibniz, form a nested hierarchy of logical interrelations. The objects, when opaque and non-decomposable—a “computational black box”—can be seen as a type of monad. Monads assemble into patterns, which assemble into monads, which in turn assemble into more complex patterns, and so on. Figure 6.1 shows examples of very simple functions, constructed in Grasshopper and in Python, for calculating the area of a complex curve. For the average user, this is the lowest fundamental level which they will want to access, and the inner workings of these “monadic black boxes” are not important. If we opened the “black box,” however, we would see a whole new web of interactions being performed. The “black box” first needs to determine what kind of shape is drawn to see if a simple algebraic or Euclidean method can be used for calculating area, or if more complex methods based in calculus need to be used. If the shape is a NURBS curve, equations using for example, anti-derivatives can be used to integrate the curve. Otherwise it needs to go through the Archimedean process of exhaustion to integrate the form. (Fig. 6.2) While we do not have to open all of the black boxes, it is helpful to understand something of what is going on, much like a study of molecules and cells can help a doctor better understand the body. As such, the next couple of sections will delve a little deeper into the black boxes.

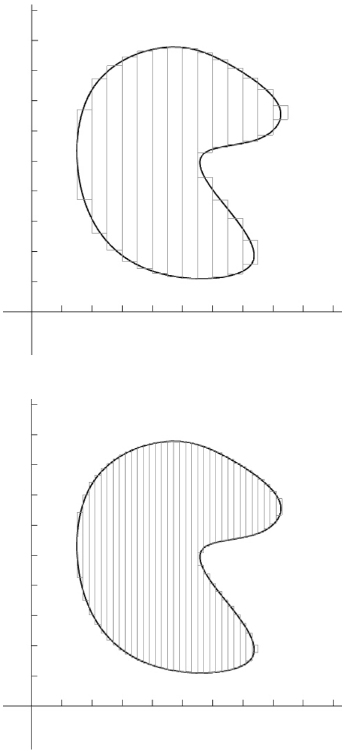


Figure 6.2: The area of an irregular piece of geometry was traditionally calculated through the time-consuming process of integration. An “area function” seems to make this process easier, but a complex series of decisions have to be made by the computer in the background to accomplish this seemingly simple task.

6.4. Functions and Basic Operators

An analysis of a typical processor’s instruction set points to very limited amount of basic operations a computer actually performs.[6] The power and flexibility of the computer is achieved by taking this limited number of operations and combining them to compose functions, which range from very simple to highly complex. A function is a series of operations that take one or more ‘inputs,’ and return, after performing the operations, one or more ‘outputs.’ (Fig. 6.3) The operations of interest for composing functions exist in one of three groups: operators of basic arithmetic, logical operators, and “jump” or “loop” statements.

Before 1980, the only arithmetic operations processors performed were basic integer mathematics in the four familiar categories of addition, subtraction, multiplication, and division. There are specific “increment” and “decrement” instructions as well, but these in effect are simple additions or subtractions of 1. After Intel released a “math coprocessor” in 1980, floating point mathematics began to be performed directly by the processor, speeding up the calculation of functions such as square roots and tangents, but such floating point mathematical functions can be decomposed into more primitive functions and as such are not required for programming.[7] At a fundamental level, addition, subtraction, multiplication, and division can also be decomposed into more fundamental operations, as shown by Alonso Church’s lambda calculus (see §1.3), which is demonstrated in section §6.7 below. For novice programmers or those who are not inclined towards higher mathematics, however, the realization that algorithms can be composed with only these basic mathematic operators (+, -, *, /) is a powerful realization.

6.5. Logical Operators

The second critical component of computing functions is the system of propositional logic, also known as conditionals, which direct programs based on whether certain criteria have been met. The tests are binary yes/no questions, which ascertain the truth or falseness of a particular statement. Truth values are ascertained by comparing two values (through the machine language instruction CMP compare). This comparison is combined with a operator such as greater than, less than, equal to, or not equal to. The CPU then returns a value of '0' if the comparison is false, or a '1' if true. If a statement is deemed true, the computer is then usually instructed to perform a certain operation. To this can be added an else statement for an alternate operation to be performed if the statement is not true. The basic pattern is:

If *(this is true)* then *(do this)* else *(do this)*

In modern computation, the relatively simple system of propositional logic traces its roots back to the mathematician George Boole, who defined algebraic logic in *The Laws of Thought* (1854), reinvigorating the development of mathematical logic, which had been moribund since the time of Aristotle.[8] In this logic, if-then statements are combined with additional operands known as "Boolean operators," named for Boole in honor of his work defining them. The most common ones are: AND (conjunction), OR (disjunction), and NOT (negation). Less frequently used, but ingrained in the core instruction set is XOR ("either/or but not both"). NOT takes only one value and always returns the opposite, i.e. NOT 1 = 0. The other ones also follow predictable patterns. Below are a few examples showing the values these operators return with various true (1) and false (0) values:

0 AND 0 – 0	0 OR 0 – 0	0 XOR 0 – 0
0 AND 1 – 0	0 OR 1 – 1	0 XOR 1 – 1
1 AND 1 – 1	1 OR 1 – 1	1 XOR 1 – 0

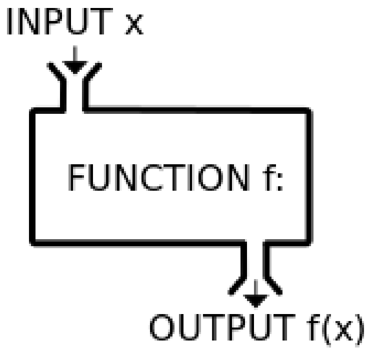


Figure 6.3: General Schematic of a Function.

The system of logic while deceptively simple was perhaps the most important breakthrough allowing modern computation. As articulated by Zuse, "of particular importance is the realization that all information can be broken up into yes-no values (bits). The "truth" values of statement calculus assume only two ratings (true and false)." The connecting operations and the rules of statement calculus can therefore be viewed as the elementary operations of information processing."[9]

While Boole is credited with the mid-19th century rebirth of mathematical logic, as alluded to early Leibniz had worked extensively on developing a logical calculus which some deem more advanced than Boole's.[10] By 1686, just two years after introducing his infinitesimal calculus in *A New Method for Finding Maxima and Minima,* Leibniz completed the manuscript *Generales Inquisitiones* which had developed a complete set of symbolic logic. Like much of Leibniz's work, it was not published until 1903, perhaps as Russell speculates because of Leibniz's concern that he could not fully recognize his logical system with Aristotle's.[11] We see hints of Leibniz's logical system in "The Monadology," where he discusses principles of truth, contradiction, and identity, linking them to mathematical axioms or postulates, but unfortunately this work remained buried for more than two centuries.

6.6. Recursion and Iteration

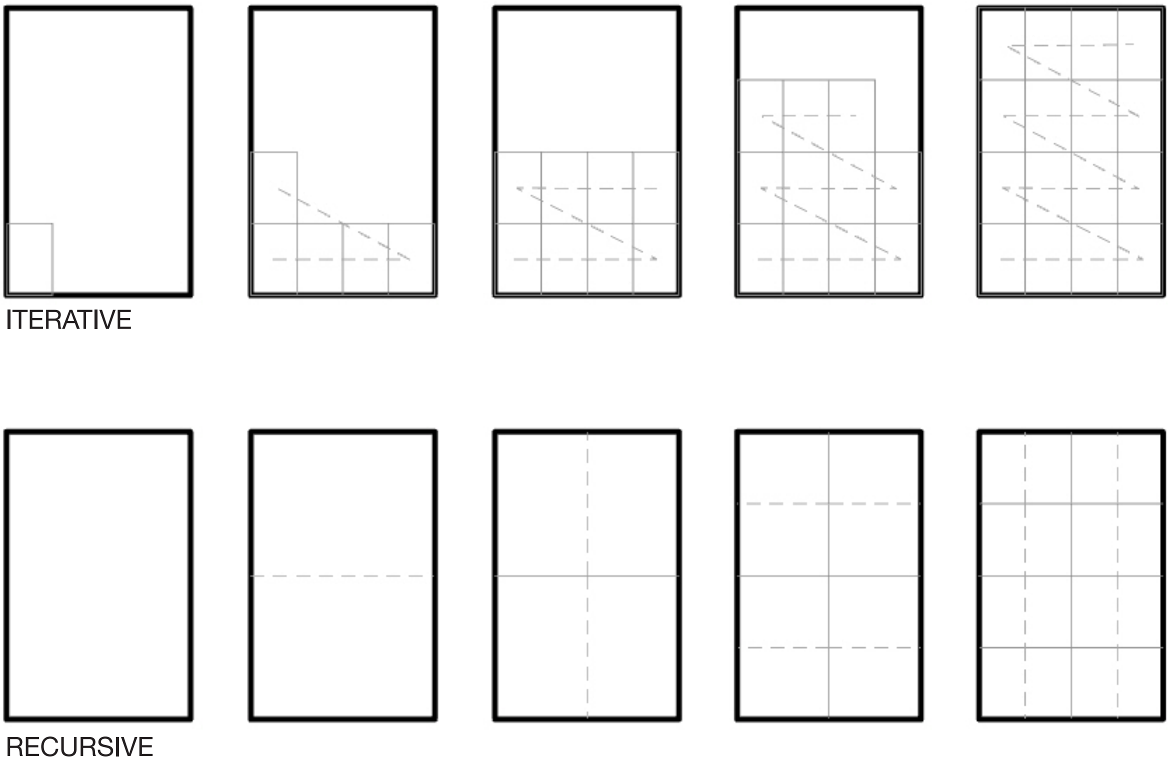
The third critical component necessary for composing functions are "jump" or "loop" types of statements. These are necessary to repeatedly perform a similar task a certain number of times. Two related paradigms for repetition exist in computation, *recursion* and *iteration.*[12] The difference is often merely a structural one, and similar or identical results can be used with one or the other, but from a practical and a philosophical standpoint, it is important to make a difference between the two. Below are two paraphrases of the concepts developed by the author in the context of this thesis based on several definitions from computer science, but with the author's own interpretation:

> An iterative process repeats an action or set of instructions in much the same way that a factory churns out products. Widgets are assembled, but the factory itself remains unchanged by the iterative process. Iteration then can generally be seen as a *mechanistic* process.
>
> A recursive process *calls itself* and the initial input is changed at each time step. Recursion is then an *evolutionary* or *organic* process. Just as an individual today is an incremental variant of who they were yesterday, recursive processes are the current iteration of a series of prior states.

A simple example might help clarify the difference between the two perspectives. Imagine we want to construct a window with a grid of sixteen rectangles. This can be done iteratively by a machine that outputs window panes in a row of 4 panels, after which a second row of 4 panels is placed above this, and so on. (Fig. 6.4, *top*). A similar result can be achieved recursively by taking a single window opening, and at each time step dividing each rectangle from the prior time step along its shortest axis. If this process is recursively performed 4 times, the same result is achieved as with the iterative process. (Fig. 6.4, *bottom*)

With more complex problems, an iterative or a recursive approach might be favored. The window show in Figure 6.5 for example, can be described fairly easily with an iterative approach, but is not well-described by a recursive rule set. The opposite is true of the window in Figure 6.6.

Figure 6.4: (below) Iterative vs. Recursive division of a window.



In computer science, iterative approaches are generally preferred for all simple problems as they tend to be faster and make fewer demands on the computer's memory. Recursive approaches, however, tend to be more compact in computer code and better at dealing with complexity.[13]

6.7. The Nature of Recursion

At a very basic level, it is interesting to note that all of the computer's operations could be described in terms of recursive statements combined with the logical operators and "goto" statements. The operation of addition for example, *could* be rewritten as a *recursive* loop—this is in fact the essence of the model of computation proposed by Alan Turing and Alonso Church's lambda calculus. Take the following pseudo program which attempts to rewrite the program 3 + 5 = 8 as a recursive loop:

```
Input X → 3
Input Y → 5

LOOP Y Number of Times
        X=X+1 (This is the "increment" instruction – it is
        performed 5 Times (the value of Y) per the previous
        instruction)

Output X → 8
```

If all operations were performed in such a way, with repeated incremental processes performed at each timestep, computation would be *much* slower, but it is theoretically possible to do it in this way. Since most people are familiar and comfortable with the formalization x+y = z, however, and this is also computationally much faster, there is little reason in practical application to go with the non-recursive approach.

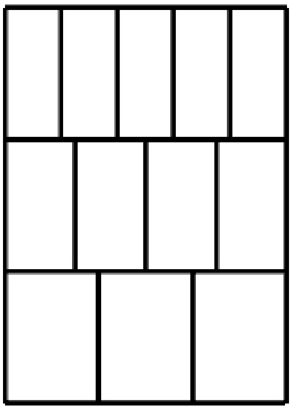


Figure 6.5: The window above could be scripted with an iterative process, but a recursive approach would not be possible.

The process of recursion, so fundamental to computation, but also of nature, introduces a number of interesting philosophical questions, dilemmas, and paradoxes. One of the fundamental premises of western thought is that a thing cannot be its own cause. Circular reasoning is anathema to clean, rational thought, and arguments based on such loops are readily dismissed. One of the consequences of systems thinking, postmodern thought, and computation, however, is the realization that things *can*, to a degree, be their own cause. As mentioned in Chapter 1, in Gödel, Escher, Bach, Hofstadter introduces the notion of the "strange loop" as vital to the emergence of complexity both in the natural world and in artificial intelligences. Several examples he offers of strange loops are some of the many process which can be observed in cells. In one process, he observes that ribosomes are required for the manufacture of proteins, but proteins can only be manufactured by ribosomes.[14] On a larger scale, DNA requires the cell's machinery to replicate and propagate itself, but the cell's machinery cannot be constructed without DNA.[15] How increasing levels of complexity are obtained through recursive feedback loops is an important question for scientific inquiry in all fields dealing with complex system; Hofstadter uses the term "bootstrapping" for this process, referencing the English paradoxical saying "to lift oneself up by her bootstraps."[16] The processes which allow "bootstrapping" in nature are often only temporary scaffoldings which cease to exist once a thing reaches its "final" form, or are no longer operational. Having served their evolutionary purpose early in the earth's history, they often fade away once they are no longer needed or once conditions change.[17] While it may be impossible to rediscover the early processes that made the production of proteins and ribosomes possible in

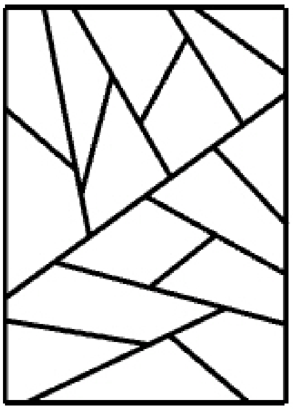


Figure 6.6: Recursive subdivision of a window using the "Chinese Ice-Ray Lattice" method. While possible to achieve the same form iteratively, it would be needelesly complex.

the first place, the well-documented history of computation gives us some insights into *how* complexity can emerge from the interaction of simple fundamental components through time. These innumerable circular feedback loops, hard to process with linear logic, can be processed in the space of recursion and computation.

6.8. Data Structures

The previous sections attempted to give a very basic overview the computer's logical operation. Most programming languages follow similar paradigms for constructing functions using a combination of processor instructions, logical operators, and repetitive loops. An area where most languages diverge is the question of how information, or data, is structured in the computer's memory. The types of data upon which the computer can operate and which it can store include integers, fractional (float) numbers, strings i.e. characters or words, and vectors.[18] These data in turn need to be organized in a logical and consistent way so that operations between multiple data sets can be executed properly and so that specific pieces of information can be retrieved. Aho and Ullman's *Foundations of Computer Science* (1992) devotes five chapters, representing more than a third of their book, to the topic of various models for structuring data. Several data structures can be derived from each model. These models include the:

> *Tree Data Model*, which as the name suggests has a hierarchical structure where data are stored in a nodes which are connected to successive nodes along non-redundant paths.[19] (see Chapter 8)
> *List Data Model*- a simplified tree. Conceptually very simple, lists are expressed as a sequence of elements enclosed by parentheses. (1, 2, 3, 4, …).[20]
> Additional operations not able to be performed with a tree can be performed on a list.
> *Set Data Model*- According to Aho and Ullman, "the set is the most fundamental data model of mathematics. Every concept in mathematics, from trees to real numbers, is expressible as a special kind of set."[21] Sets are especially appropriate for performing Boolean operations of intersection (AND), union (OR), and difference (NOT).[22]
> *Relational Data Model* This model stores data in database-like tables, where a series of attributes are associated or related together.[23]
> *Graph Data Model,* shares properties with the tree in that it deals with topological relations between nodes, but it can express much more complex relationships between data and can also incorporate directed (half) edges.[24]

The listed data structures cannot be described in any extensive detail at this point, but anyone attempting to learn algorithmic design will have to engage several of these structures early on, and conceptualizing them and learning methods to work with them present a significant early roadblock to developing new and innovative algorithms. Probably the most important thing to recognize is that interacting sets of data should in most cases be structured in a similar or identical way. Examples of the "Tree" and "List" data structure types are presented in this chapter's second example. (Fig. 6.16)

6.9. Ontogenetic vs. Teleological Algorithms

In the following chapters, the text will frequently reference two general classifications of algorithms, *ontogenetic* vs. *teleological*. The two terms are not in common use in computer science, borrowed from discussions in the procedural content generation community, with the two approaches referencing two terms frequently used terms in philosophical discourse, teleology and ontology. The two approaches are discussed in a short text by Bjarki Guðlaugsson, "Procedural Context Generation" (2006). He describes how:

> "Teleological modeling…is a technique for modeling phenomena using true physical rules. This is an incredibly data-intensive approach, and it's probably the correct one for scientific applications where the end result must accurately reflect reality…Ontogenetic modeling…is a technique for modeling phenomena based on properties of their appearance, …focus[ing] mainly on the end results rather than looking at how we actually got there."[25]

To clarify this distinction, compare the image of the paths of quantum particles as observed in a bubble chamber image vs. the results of Eno Henze's *Subjektbeschleuniger*. (Fig. 6.7) While superficially similar, the processes for deriving the form in Henze's work are fundamentally different from the fundamental behavior of quantum particles. Henze himself explains that the mimicry of the paths of the bubble chamber seen not as "a scientific evidence, but rather an aesthetic evidence for our search for the absolute."[26] A *teleological* approach to the same problem would require a much more thorough understanding of the problem, and even then the approach might not yield the intended results. As explained by Mick West, "the real world operates at a much finer grained level than is possible to simulate on a computer. The "real world" operates at molecular, atomic, and subatomic levels. The so-called "rigid bodies" that modern physics engines simulate are in reality composed of septillions (1 septillion = 1 billion billion billion billion) of molecules"[27] He concludes that even when a generally *teleological* approach is used, "realism must begin to take a back seat to another type of realism—the reality of our limited resources."[28] This is also the conclusion of Sanford Kwinter as cited in §1.14, that the challenge of computation is in "learning how to make a simple organization (the computer) model what is intrinsic about a more complex, infinitely entailed organization."[29] Total simulation is an impossible goal, but that does not mean it is not possible to create abstractions of reality that then operate parallel to processes in reality. The approach used, however, must relate to an algorithm's ultimate goals.

This introduces the problem of reductionism in algorithms and simulations, especially when a *teleological* or process based approach is desired. For performance reasons, they need to be kept as simple as possible, but they also need to determine the right variables to include, as well as the right boundary conditions. Alexander addressed this problem as a critical early step in his pattern language (see §5.8). Von Neumann, however, points out many of the difficulties in this method. When describing the "axiomatic method," the method for reducing a problem into elementary parts, he makes a number of important observations, noting that "by choosing the parts too large, by attributing too many and too complex functions to them, you lose the problem at the moment of defining it. One also loses the problem by defining it too small."[30] He goes on to note that "even if one chooses the parts in the right order of magnitude" it is nearly impossible to order the parts property as there "are no rigorous rules on how axioms should be chosen, just common sense rules…Even if the axioms are chosen within the common sense area, it is usually very difficult to achieve an agreement between two people who have done this independently…. by axiomatizing [a problem] in this manner, one has thrown half of the

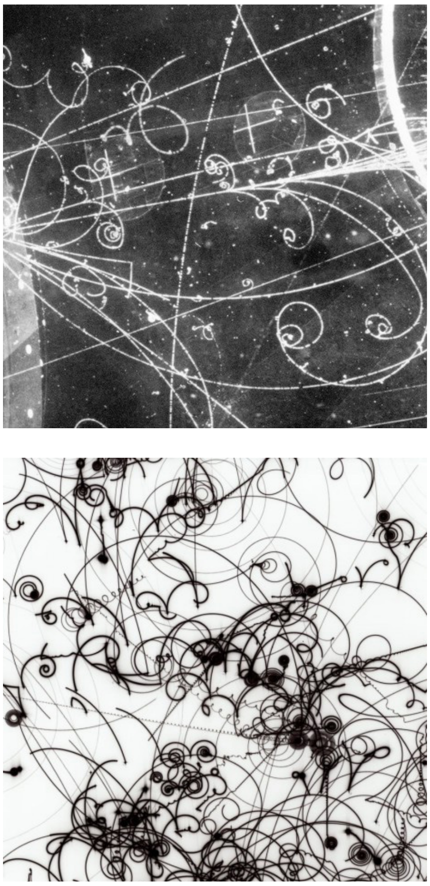


Figure 6.7: An image from a bubble chamber (source: Fermilab) and an algorithmic work of art by Eno Henze attempting to mimic the bubble chamber's aesthetic, but not its internal logic. This would be an example of an "ontogenetic" algorithm.

Image courtesy of Fermilab
Image courtesy of Eno Henze

problem out the window, and it may be the more important half."[31] This point will be revisited in the conclusion to this thesis, but is a critical point to keep in mind while defining algorithms, their parameters and parts, as well as their boundary conditions.

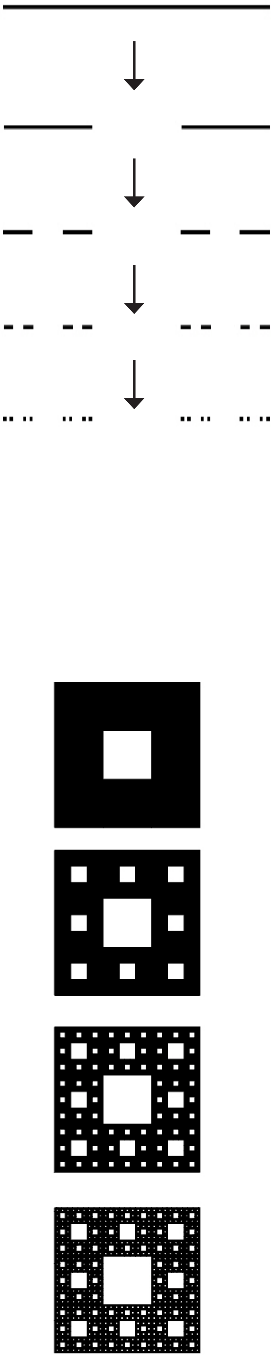


Figure 6.8: Cantor Set (*above*) and the Sierpinski Carpet (*below*)--two early fractal descriptions.

6.10. Algorithmic Methods

The next eight chapters will present a mix of algorithms of an *ontogenetic* and *teleological* character that may prove useful in landscape design projects. Some will again be referenced in the design applications in Part III of this thesis, but the overall aim is to create a series of "design patterns" inspired in a sense from Gamma's computational design patterns and Alexander's *Pattern Language*. Two examples of common algorithmic patterns or methods, however, are presented here to demonstrate the general structure and a comparison between the two scripting approaches used in this thesis, i.e. a hybrid between Rhino-Grasshopper and Grasshopper-Python.

6.11. Fractals

In the mid 1970s, a researcher at IBM, French mathematician Benoit Mandelbrot, began publishing a series of papers introducing a new paradigm for geometry, which he termed "fractal geometry." His findings were synthesized into a landmark volume published in 1982, *The Fractal Geometry of Nature,* where he proposed that classical geometric approaches were ill-suited for describing natural form, eloquently expressed by a famous quote from the book's introduction, where he observes that: "Clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lighting travel in a straight line."[32]

Mandelbrot can be credited with inventing the term "fractals," but the curious phenomena he had been observing with dimensions of the infinite had fascinated and puzzled mathematicians for centuries. Leibniz, who Mandelbrot cites as a major source of inspiration, had already begun to develop his philosophy surrounding observation of such forms as discussed in chapter 4, imbedding his observation of the infinitely nested hierarchy of nature into "The Monadology", for example, and defining the principle of self-similarity.[33] The systematic study of what Mandelbrot would later call fractal forms experienced a sort of golden age in the late 19th and early twentieth century, with notable fractal examples cited by Mandelbrot having already been part of the mathematical lexicon for almost a century before fractal geometry exploded onto the scene in the late 1970s and 1980s. Specific example include those developed by Georg Cantor,[34] Giuseppe Peano,[35] Helge von Koch,[36] and Waclaw Sierpinski.[37] (Fig. 6.8) In Kepes' *The New Landscape* some of the principles of fractal geometry were already intimated a few decades before Mandelbrot (see §6.8), and this is seen again in the work of Peter Stevens in the early 1970s. (see §8.3) The recognition and use of fractal patterns can be considered much older, as argued by Ron Eglash in his book *African Fractals: Modern Computing and Indigenous Design* (1999), who gives numerous examples of their use by indigenous cultures in the art, architecture, design, and even in the arrangement of their settlements.[38]

6.12. The Koch Curve and Related Fractal Methods

The algorithmic examples in the following chapters will make numerous references to methods for generating fractal patterns, but here is presented one of the most famous early fractal descriptions, the Koch Curve, identified by Swedish mathematician Helge von Koch in 1904. The curve was an early recognition of the paradoxical properties of fractals, as the area, after a number of iterations, converges to a finite number, around 8/5 the area of the original triangle, while the length of the perimeter diverges to infinity. The curve is constructed through a simple recursive process.[39] (Figs. 6.9a)

> -each segment is divided into three equal parts. The middle part is then removed.
> -in place of the middle segment, a partial equilateral triangle pointing outwards is added.

Each of the resulting segments goes through this recursive process multiple times, adding length to the perimeter at each step. (Fig. 6.9b) Since the overall length of the form increases by 4/3 after each recursion, the length can become theoretically infinite. After a few steps in the computer, however, the changes become increasingly fine-scaled and are not noticeable, but the computational time increases exponentially. If this is allowed to run in the computer for too long, like most fractals using recursive processes, it will quickly overwhelm the system's resources.

In *Algorithmic Architecture,* Terzidis adapts the logic of the Koch curve to make an easy to adapt, but nevertheless productive exercise for beginners in scripting methods. He presents a method whereby a "base" is paired with a "generator," a form which replaces each segment from the base in the first recursion. In subsequent recursions, the generators from the previous step are in turn decomposed into their constituent segments, becoming the base for the next generation.[40] In the Koch curve, the "base"

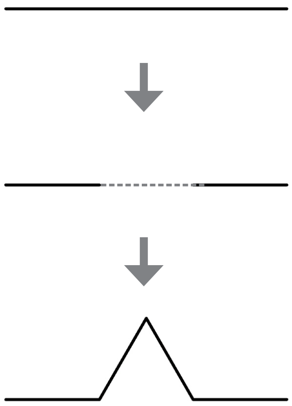


Figure 6.9a: The Koch Curve's Axiom

Figure 6.9b: *(below)* The Koch Curve's Evolution from the base condition through four recursions.

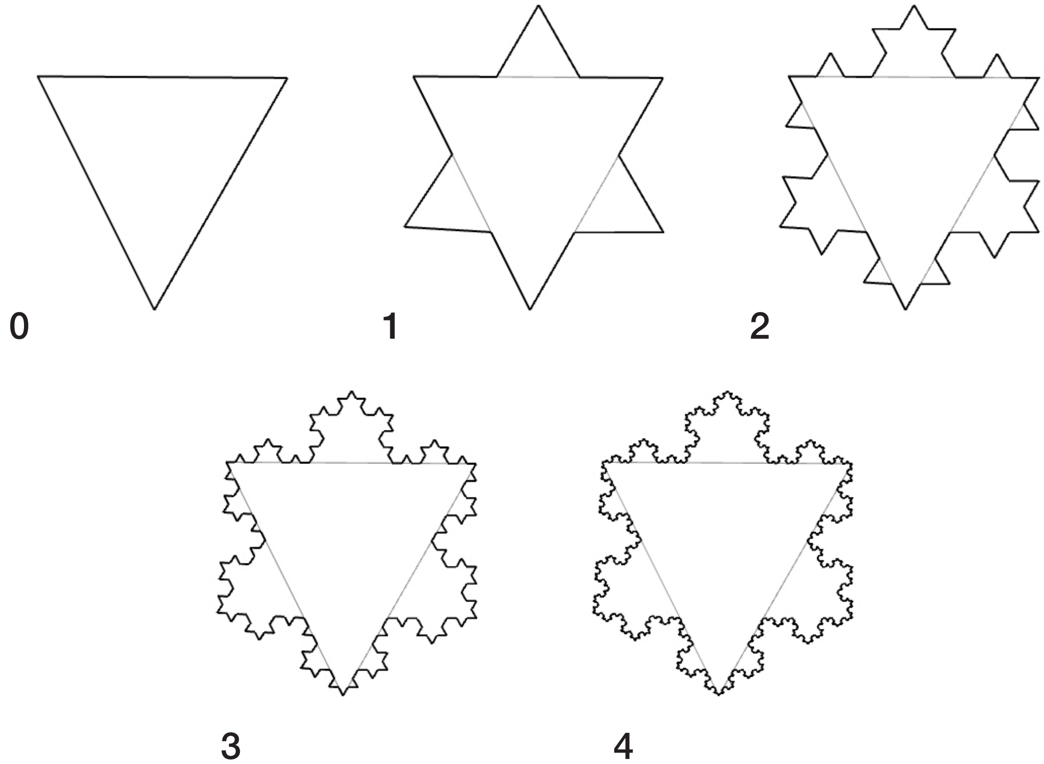
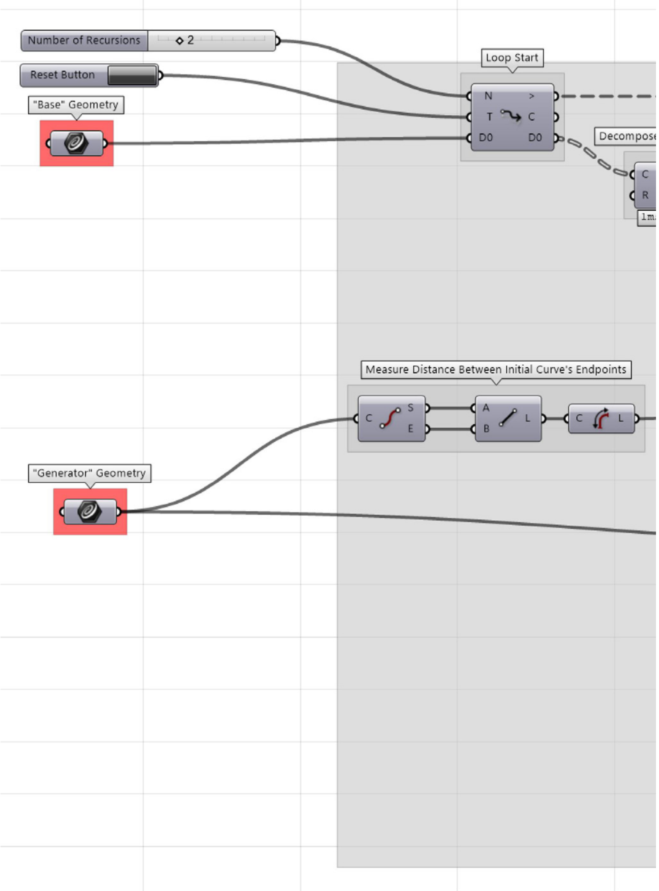


Figure 6.10: Grasshopper script for creating fractals from a base and generator drawn in Rhino. The two pieces are input into the the script through two parameter containers marked in red, with a single output marked in blue.



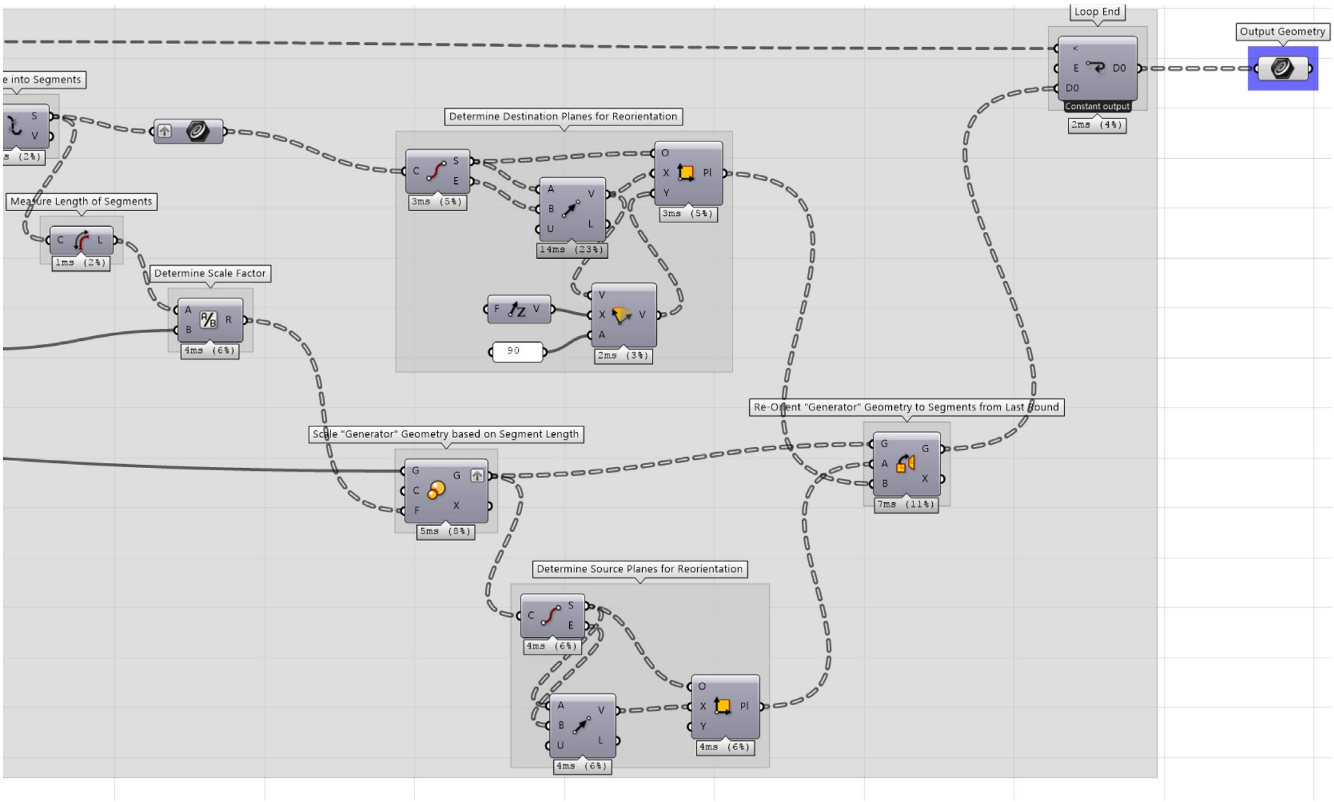
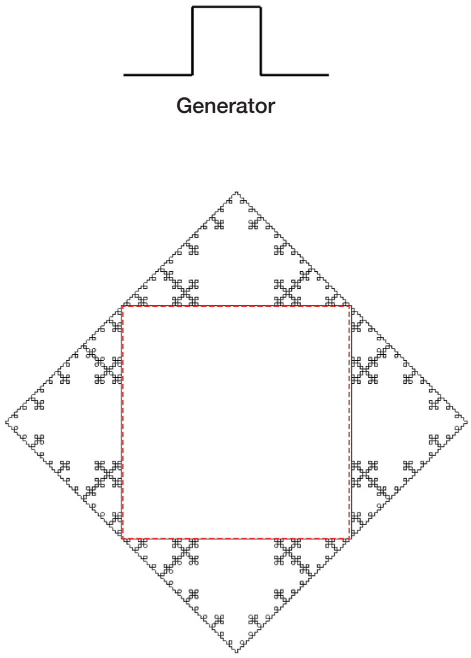
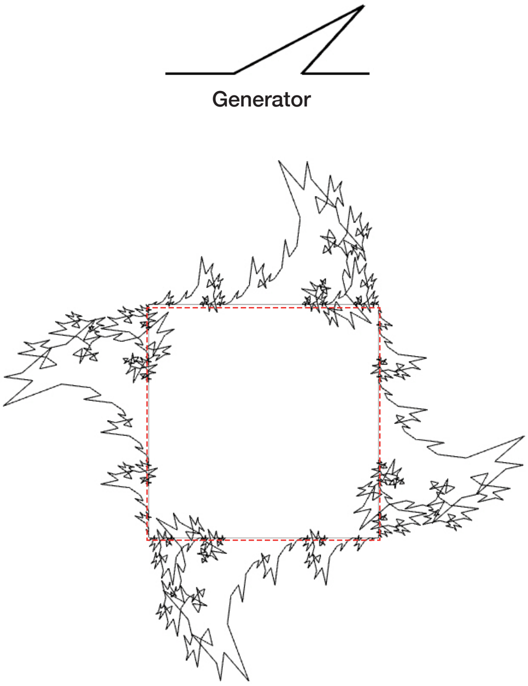
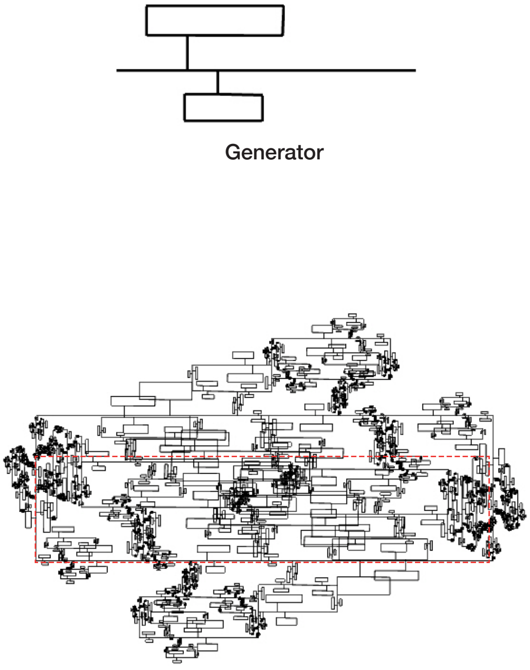


Figure 6.11: Various generators are drawn in Rhino are applied to a base. (dashed red shape) After a few iterations, the algorithm produces complex fractal forms.

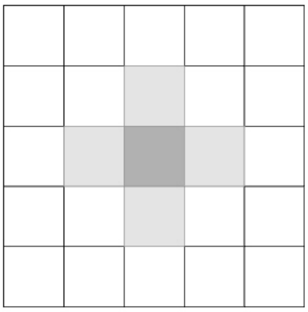






is the initial triangle, and the "generator" is the segment with the added equilateral triangle. Figure 6.11 shows a few examples of this methodology, based on similar studies performed by Terzidis' students.[41]

The algorithm as presented here imports the "base" and "generator" from geometry drawn directly in Rhino. The geometry needs to be drawn with the functionality of the algorithm in mind, but quick changes can be made in Rhino, quickly producing many different pleasant and unpleasant results. The basic Grasshopper component used to scale and reorient the geometry at each step are supplemented by the very helpful plugin Anemone, developed by Mateusz Zwierzycki, and critical to the functionality of many of the algorithms presented in this thesis.[42] Without this plugin, designers would have to resort to using a programming language such as Python, which can be overly intimidating for most novice users. Notes on the algorithm's functionality are included in the image, but more in-depth explanations cannot be presented in this thesis. See the "Note on the Technical Description of Algorithms in this Thesis" (§6.15) below.



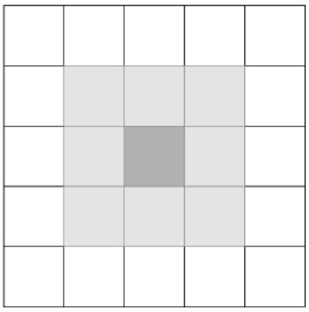


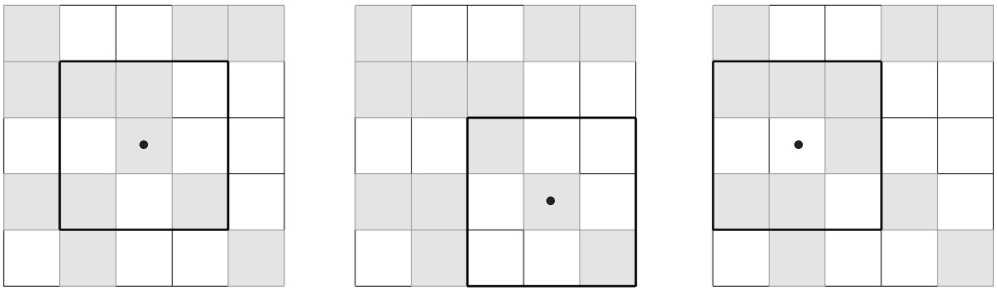
Figure 6.12: Von Neumann Neighborhood (top) and Moore neighborhood (bottom) often used in cellular automata.

6.13. Cave Cellular Automaton

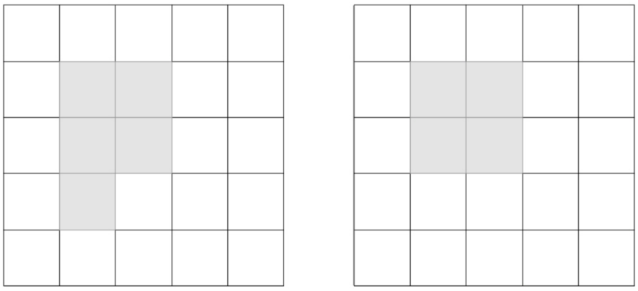
The last chapter introduced an algorithmic paradigm known as the cellular automaton. Cellular automata are often used to study how global patterns emerge from local interactions. An outside observer can see this global pattern, but each individual cell is only concerned with the state of its neighbors. This particular example is known as the "Cave Cellular Automaton" since it has been frequently used by procedural game developers as a starting point for designing procedural levels or "dungeons". It aims to create a mostly connected interior "cave-like" structure which a player can explore, and which can be quickly updated into a new variation multiple times, theoretically extending the game's re-playability. While several good descriptions of this algorithm exist, this example references the one by Jeremy Kun.[43] This cellular automaton is the first of several which will be presented since it is relatively simple and since it evolves quickly to a "stable" structure, unlike some cellular automata, which can continue to evolve almost indefinitely.

The first decision when creating such a model is to decide on a cell structure. Regular rectangular grids are the most common, but other possibilities such as hexagonal grids or irregular structures exist as well. In this example, a simple grid is used. In the grid, individual cells only interact with other cells in their defined "neighborhood." The two most commonly used neighborhood types in a gridded structure are the "Von Neumann neighborhood," where the neighbors are the 4 cells in the immediate left/right/up/down directions (N,S,E,W). The "Moore neighborhood" adds four more cells in the NE, NW, SE, and SW compass directions for a total of eight neighbors. (Fig. 6.12)

Once the neighborhood is determined, a ruleset for *how* the cells interact needs to be defined. A common ruleset defines which cells will be "born," which ones will "survive," and which ones will "die" with each time step. Important considerations are the current state of each cell and the current state of the neighbors. In this binary cellular automaton, cells are described as being either "dead" or "alive" corresponding to a 0 or 1 respectively. With each time step, the cells then look at their neighbors and will update their state based on the automaton's rules. Here the ruleset is:



cell “survives” **cell “dies”** **cell is “born”**



updated states - round 1 **updated states - round 2 -**

Figure 6.13: Changes in cell states based on the ruleset described in §6.13.

Born rule: If the current cell has 6 or more neighbors which are alive, the cell will become (or remain alive regardless of its current state.

Survive rule: If the current cell has 3 or more neighbors which are alive, the cell will remain alive,
but if the current cell is already dead, it will remain dead.

Death rule: If the current cell has 2 or fewer neighbors which are alive, the cell will die, or remain
dead if already dead.

In Figure 6.13, these principles are illustrated. The central cell in this 25 cell structure is currently alive, and has four neighbors which are also alive. This means its state remains unchanged—it has “survived.” In the second diagram, the cell immediately to the southeast of the central cell has only two neighbors which are alive. The cell which is currently alive will “die” in the next time step. Finally, the third diagram shows the condition of the cell immediately to the west of the central cell. This cell is currently dead, but it has six neighbors who are alive, so the cell will become alive, or be “born” in the next time step.

Figure 6.14 shows how this particular cellular automaton will evolve. Since the cells at the borders have few neighbors, they all die in the first round. Special considerations are usually taken for border conditions to avoid such problems, but for now we will ignore this. One can see that after the

Figure 6.14: *(opposite page)*
Changes in cellular automaton through 6 rounds using the cave ruleset described in §6.13.
Initial population - 45% alive
cell born with 6,7,8 neighbors
cell survives with 3,4,5,6,7,8 neighbors
cell dies with 0,1,2 neighbors.

first time step, a small patch towards the west has consolidated. In the next round, the "panhandle" of this patch dies since it doesn't have enough neighbors to stay alive. The four remaining cells, however, each have three neighbors, so as long as the simulation continues, they will remain as a stable structure. If any one of these remaining cells were to "die" however, the structure would disappear entirely, but this is not a risk in this very small example. As described previously, this particular cellular automaton is designed with a rule set where it will quickly evolve into stable structures, since in a computer game a stable variant needs to be presented to the player, but in other automata which will be presented later, this is not always the case.

6.14. Description of Alternate Methods for Coding the "Cave" Algorithm

In contrast to the previous example which is developed using base geometry from Rhino, and which in turn is algorithmically manipulated with Grasshopper, this example does not use Rhino geometry at all. It begins with Grasshopper functions for the initial setup, (Fig. 6.16) but the algorithmic process is advanced with a Python script. (Fig. 6.17) Cellular automata can be very resource intensive, and the Rhino-Grasshopper interface will have trouble maintaining an acceptable speed. As a comparison, a second version using only grasshopper was also developed. (Fig. 6.18) While probably simpler to setup for an intermediate user, the calculation time is around 16 times slower. Below are some calculation times for this particular setup, with an initial grid 50 x 50 cells (2500 cells total)

Initial Setup with Grasshopper	42.15 seconds (41.2 seconds just for drawing the surfaces to be colored!)
Python Calculation – 10 steps	77 milliseconds
Grasshopper alternate – 10 steps	1268 milliseconds (16x slower)

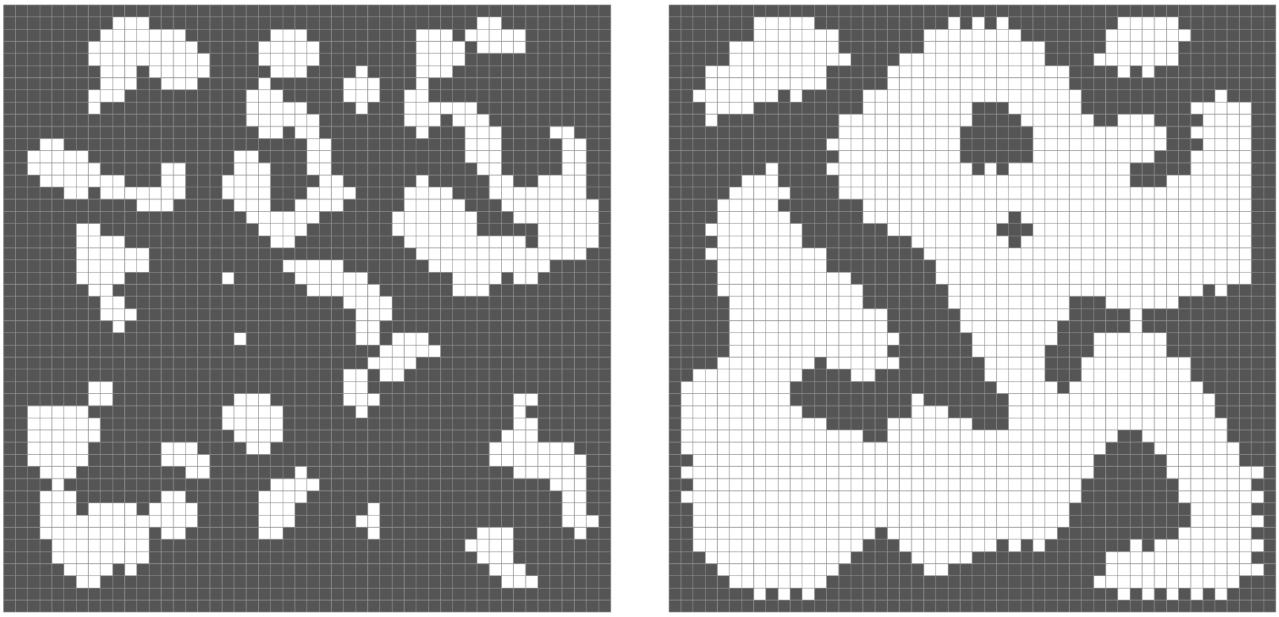
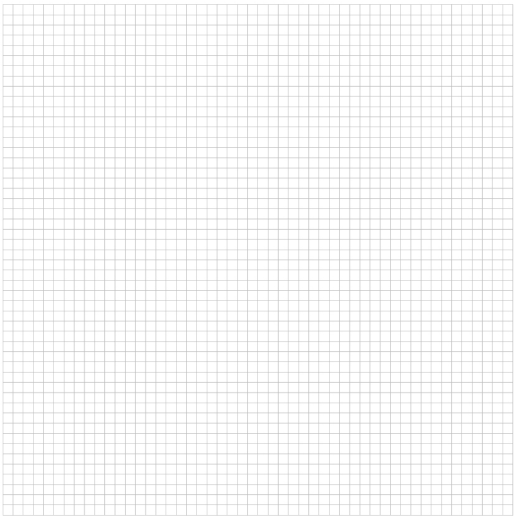


Figure 6.15: *(below)* Results after 10 rounds with modified parameters.

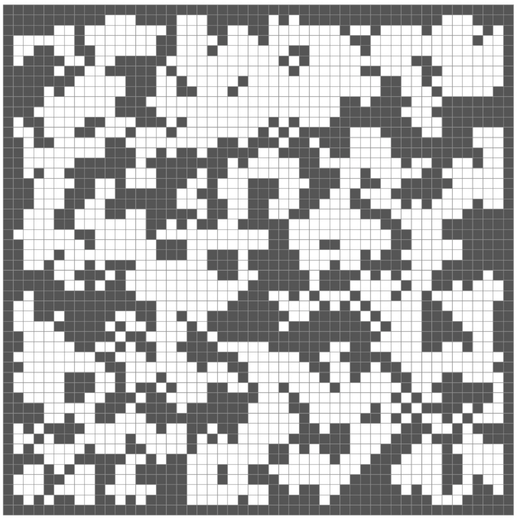
Parameters image left:
initial- 40% alive
born, 5,6,7,8 neighbors
survive with 2,3,4,5,6,7,8 neighbors
die with 0,1 neighbors

Parameters image right:
initial 57% alive
born or survive with 5,6,7,8 neighbors
die with 0,1,2,3,4 neighbors

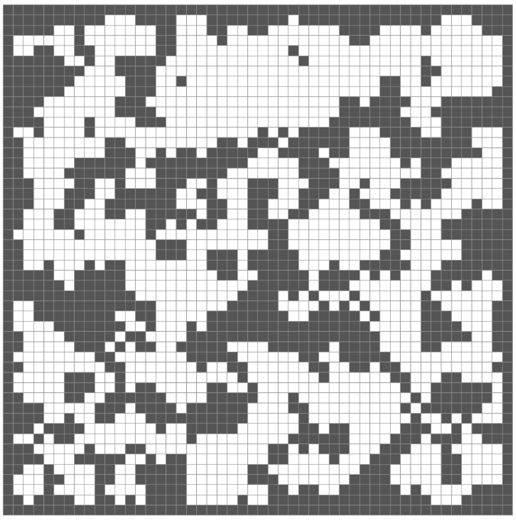


0 - unpopulated grid

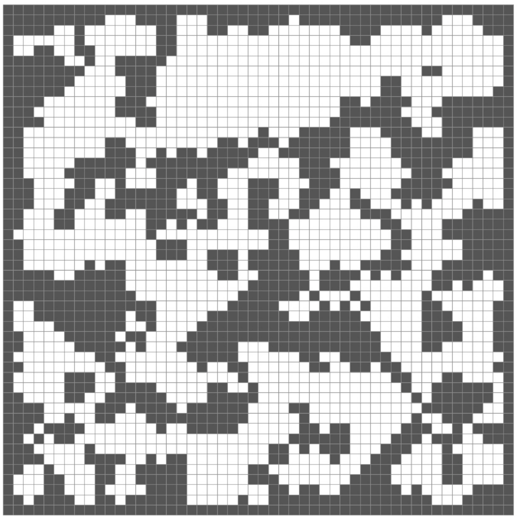
0 - initial random setup



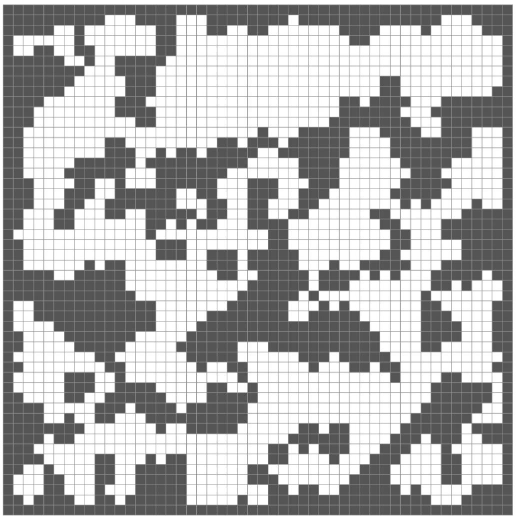
1st round



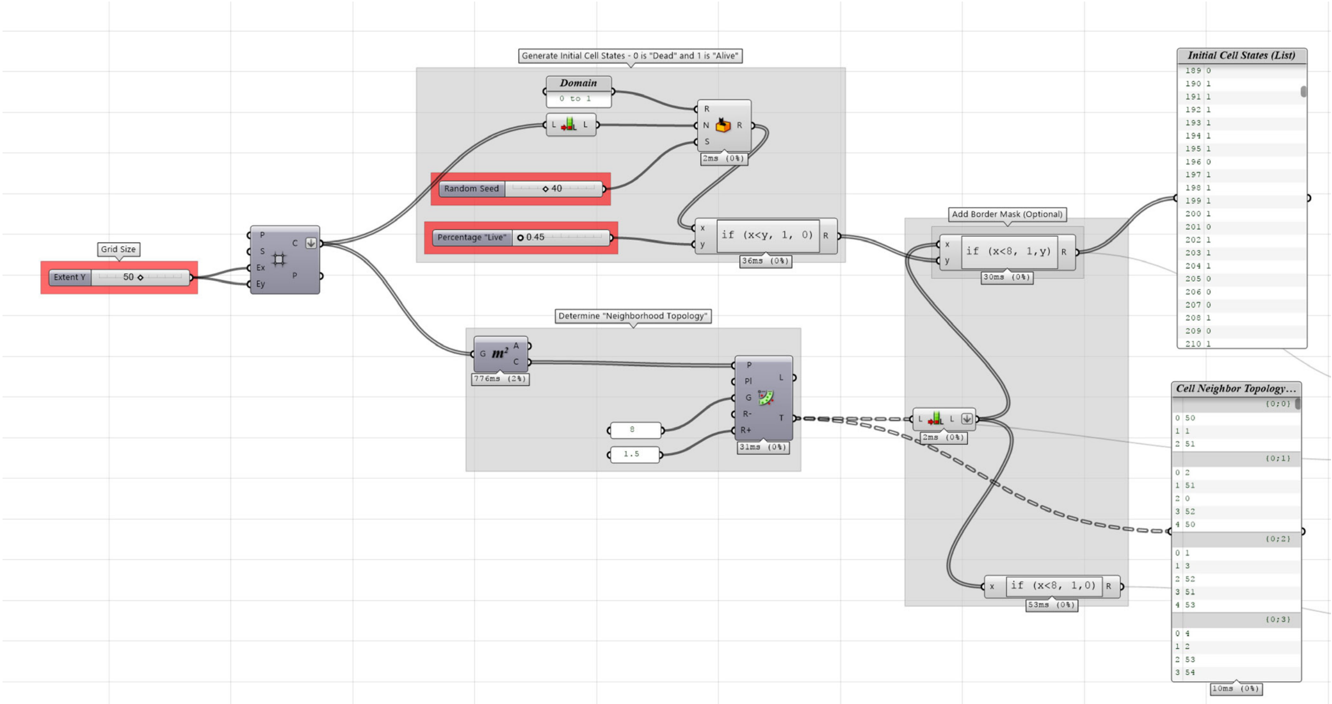
2nd round



3rd round



6th round



```
Initial Cell States (List)
189 0
190 1
191 1
192 1
193 1
194 1
195 1
196 0
197 1
198 1
199 1
200 1
201 0
202 1
203 1
204 1
205 0
206 0
207 0
208 1
209 0
210 1
```

```
Cell Neighbor Topology...
{0;0}
0 50
1 1
2 51
{0;1}
0 2
1 51
2 0
3 52
4 50
{0;2}
0 1
1 3
2 52
3 51
4 53
{0;3}
0 4
1 2
2 53
3 54
```

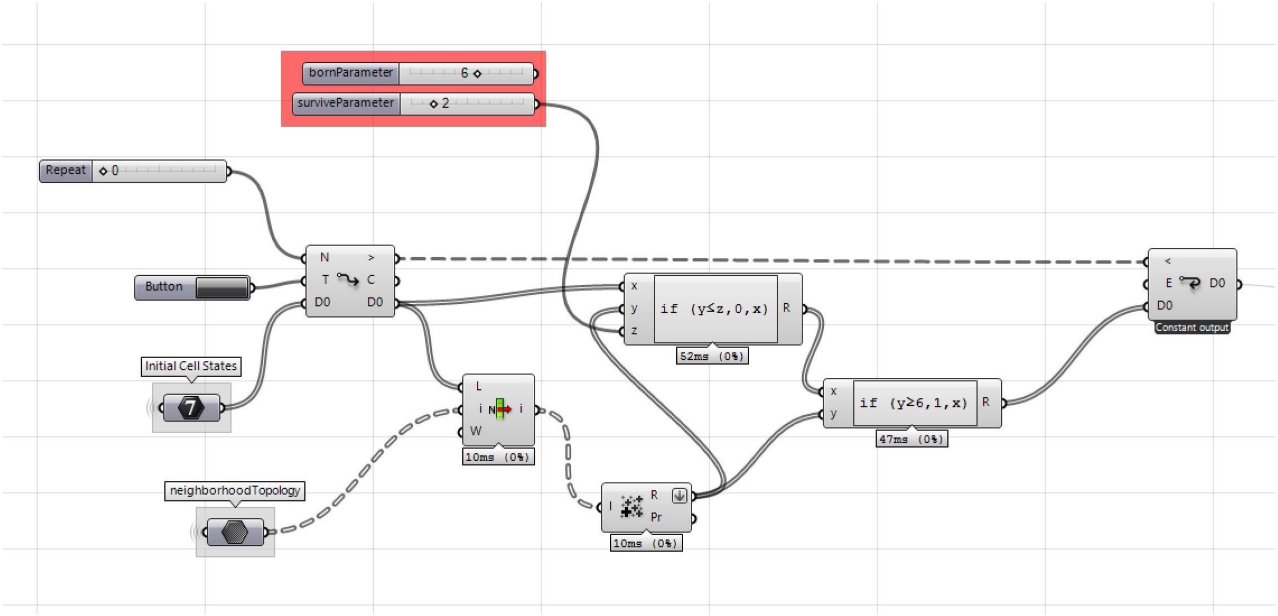
Figure 6.16: *(above)* Grasshopper script for initial setup of cave algorithm. The panels at the right show the list of cell states using the List Data Structure Type, while the neighbor typology makes use of the Tree Data Structure Type

Figure 6.17: *(below)* Grasshopper script for the calculation of the cave algorithm.

Figure 6.18: *(opposite page)* Python script for the calculation of the cave algorithm.

A function to determine the state sum of the neighbors is defined in lines 16-33, a function to update states in lines 36-52, and one to add the border mask in lines 54-63. The actual execution happens in lines 69-73.

Text in green is not required for functionality, being comments for the programmer to aid in debugging.



```
#Information imported from Rhino

#numRounds                 -  integer parameter
#cellStates                -  integer list either "0" or "1"
#neighborhoodTopology      -  integer tree with 3 - 8 branches
#born                      -  integer parameter
#survive                   -  integer parameter
#borderMask                -  integer list either "0" or "1"


#define additional variables
currentCellStates = cellStates
numCells = len(cellStates)

#returns a List summing up the total number of live cells in each cell's neighborhood
def getStateSum(numCellsF, neighborhoodTopologyF, currentCellStatesF):
    #create empty stateSum list
    stateSum = []
    for i in range(numCellsF):
        stateCount = 0
        #extract number of neighbors for each cell
        currentNeighbors = neighborhoodTopologyF.Branch(i)
        len1 = len(currentNeighbors)
        #loop runs for the total number of neighbors
        for i in range(len1):
            #iteratively go through the list of neighbors
            getState = currentNeighbors[i]
            #get the state of the current neighbor
            state = currentCellStatesF[getState]
            #running tally of cell states
            stateCount = stateCount + state
        stateSum.append(stateCount);
    return stateSum;
        
#updates the currentCellStaes list based on Born / Survive / Die criteria
def updateState(bornF, surviveF, stateSumF, numCellsF, currentCellStatesF):
    updatedStateList = []
    bornSurviveDie = 0
    for i in range(numCellsF):
        currentSum = stateSumF[i]
        #print "Current State",currentCellStatesF[i]
        #print "Current 'On' Neighbors", currentSum
        if currentSum >= bornF:
            bornSurviveDie = 1
        elif currentSum >= surviveF:
            bornSurviveDie = currentCellStatesF[i]
        else:
            bornSurviveDie = 0
        #print "Updated State", bornSurviveDie
        #print ""
        updatedStateList.append(bornSurviveDie);
    return updatedStateList;
        
def addBorderMask(borderMaskF, currentCellStatesF, numCellsF):
    stateWithMask = []
    addMask = 0
    for i in range (numCellsF):
        if borderMask[i] == 1:
            addMask = 1
        else:
            addMask = currentCellStatesF[i]
        stateWithMask.append(addMask);
    return stateWithMask
        
    

print borderMask

for i in range(numRounds):
    b = getStateSum(numCells, neighborhoodTopology, currentCellStates)
    currentCellStates = updateState(born, survive, b, numCells, currentCellStates)
    currentCellStates = addBorderMask(borderMask, currentCellStates,numCells)
a = currentCellStates
```

This is primarily because of the speed at which the Anemone plugin in Grasshopper executes loops. Here the difference between 0.08 seconds and 1.3 seconds is not dramatic, but some scripts with, for example 500 iterations or more can see significant performance differences. Also, other scripts are so complex that Grasshopper becomes more burdensome than helpful, and moving into a more conventional coding environment is recommended or even required.

6.15. Note on the Technical Description of Algorithms in this Thesis

Like in the previous example, images of the scripts themselves are presented here only as a reference for those already familiar with the programs in question, and to give the inexperienced reader a general idea of the mechanics behind the algorithms. The images have notes explaining the logic of the operations, but no additional explanation can be offered here. Also, similar images will not be shown for the algorithms in the coming chapters. Tutorials and explanations, however, are available online as of the time of publication at the author's website: generativelandscapes.wordpress.com. The website was developed in conjunction with this thesis, and includes many additional examples of algorithms not included here.

6.16. Chapter Summary

This chapter introduced several key concepts related to the structuring of algorithms as a series of interconnected patterns. While most programming today takes place with "higher" level languages, at a fundamental level, the computer executes its task by executing an interconnected series of rudimentary functions, comprised only of basic arithmetic operations, logical operators, and recursive or looping statements. The recursive nature of computing—its iterative progression through states, is one of the reasons why it is so powerful at paralleling natural systems.

Functions in turn, through an emergent process, become interconnected into ever more complex functions known as "objects." Objects form the basis for algorithmic design patterns in the programming paradigm known as object oriented computing. Algorithms themselves, incorporating a series of interconnected objects, can be categorized as *ontogenetic* or *teleological* in nature. *Ontogenetic* algorithms seek to convey the formal essence of a thing or object through computational methods which do not necessarily parallel the processes which would create the object it represents in nature. *Teleological* algorithms, in contrast, seek to mimic the logics of process, often at the cost of greater computational complexity and demand on computing resources. It is particularly important in these types of problems to reduce or *axiomatize* the problem in an intelligent way, defining elementary parts at the proper scale, with the proper magnitude, and in the proper order. Since there is no rigorous logic to carrying out this process, numerous methods, both good and bad, handle similar problems in very different ways.

Finally, this chapter presents two examples of algorithms developed using a visual scripting editor on the one hand and the python programming language on the other. Such tools, especially in the design context, make the process of coding easier much, but also can lead to repetitive design solutions as beginning users especially, tend to gravitate towards the most simple tools. Developing innovative and new solutions requires more experience and a grounding in methods developed in other disciplines.

Endnotes

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4 Trevor Patt, *Assemblage Form: An ontology of the urban generic with regard to architecture, computation, and design.* (EPFL Laussane, 2016), 33-41.

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A full description of the instruction set is available in each processor's manual. See for example: Intel. *Intel 65 and IA-32 Architectures Software Developer's Manual. Vol. 2 (2A, 2B, 2C &2D): Instruction Set Reference A-Z.* (Dec. 2017), 3.2, 4.2, 5.3.

7 Jack Woehr. "A Conversation with William Kahan: How Important is Numerical Accuracy." *Dr. Dobbs Journal.* (1997), www.drdobbs.com/architecture-and-design/a-conversation-with-william-kahan/184410314. Accessed 26 Feb 2018.

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9 Konrad Zuse, "Rechnender Raum," as published in *A Computable Univers: Understanding & Exploring Nature as Computation.* trans. Adrian German and Hector Zenil. (World Scientific, 2012), 3.

10 Marko Malink and Anubav Vaudevan, "The Logic of Leibniz's *Generales Inquisitiones de Analysi Notionum et Veritatum.*" *The Review of Symbolic Logic* (April 2016), 3-4.

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12 Alfred Aho and Jeffrey Ullman. *Foundations of Computer Science.* (Computer Science Press, 1992), 25. See p. 27-34 for a description of iterative functions, p. 59-75 for a description of recursive programming.

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14 Hofstadter, 528.

15 *Ibid*, 530.

16 *Ibid*, 293-294.

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18 Kostas Terzidis, *Algorithmic Architecture.* (Amsterdam: Elsevier, 2006), 68.

19 Aho and Ullman, 223-224.

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21 *Ibid*, 337.

22 *Ibid*, 342.

23 *Ibid*, 403-406.

24 *Ibid*, 451.

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28 *Ibid,* 35.

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30 John von Neumann, *Theory of Self Reproducing Automata,* ed. and completed by Arthur Banks (Urbana: University of Illinois Press, 1966), 76.

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33 *Ibid,* 19.

34 *Ibid,* 74-82.

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Chapter 07 – Chance & Order

"Anyone who considers arithmetical methods of producing random digits is, of course, in a state of sin." – John von Neumann[1]

7.1. Introduction

Design has traditionally been seen, at least in the western tradition, as an art bringing order and structure to a seemingly disorganized and at times random universe. This notion of design and the role of the designer is being increasingly challenged as scientific discovery advances the notion that much of the order and structure we perceive in the universe comes through the capacity of matter and of societies to self-organize and evolve through time. The engine that drives this process towards greater perceived order and optimized form consists of two elements—energy flows into the system and somewhat paradoxically, random and at times senseless variation. At the same time, as scientific theories asserting the fundamental indeterminacy of matter at the microscopic scale and of the non-linear behavior of human and natural systems at macroscopic scales become widespread, designers are increasingly looking for new tools to understand the emergence of form from complex and chaotic systems. One such tool is the use of random number generators to simulate conditions of randomness and indeterminacy in a computational environment. While such tools have powerful uses, caution should be exercised for several fundamental reasons. First, computational randomness is derived in a process fundamentally different from that observed in material systems. Second, pure randomness is rarely observable at macroscopic scales because of the complex relationships which govern processes, and as a corollary, too strong of a reliance on artificially generated randomness may mask rational and deterministic processes which instead are critical to understanding and intervening in the behavior of a system. What follows is a brief overview of some of issues associated with randomness in nature and design, as well as examples of algorithms which explore the nature of randomness and the emergence of form from chaotic systems.

Figure 7.0: (*page opposite*) Circles form near small cracks in the ice made in an apparently random pattern by birds on the River Leine near Hannover. Water emerging from the cracks melts the snow in circles with a near perfect radius.

7.2. Laplace's Demon

In his 1814 text *A Philosophical Essay on Probabilities*, the French Philosopher Pierre-Simon Laplace posited that if an intelligence existed which could comprehend "all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes."[2] Laplace's omniscient "intellect", now commonly referred to as "Laplace's Demon," reflects the optimistic attitude present at the beginning of the 19th century that sprang from the great advances in science, engineering, and mathematics in the wake of the Enlightenment and the ever-increasing discovery of linear formulas that seemed to explain the movement and the interactions between bodies at all scales. This view of nature as essentially knowable, mechanistic, and linear—

the deterministic clockwork universe—posits that there are no chance or random events, only inadequate understanding of the series of actions which produce a seemingly random outcome. If one were to precisely gauge the exact mass of a coin, the exact velocity with which it is tossed, the friction of each particle of air, and so forth, according to Laplace, one should be able to know with certainty whether heads or tails would come up. In the wake of the mass computerization of our society, a sort of Neo-Laplacian dream has emerged in some circles—a faith that computers, Laplace's demon made flesh—or rather made silicon—and supplied with massive amounts of data and with the right equations, will be able to predict future states based on precise observations of present phenomena.

7.3. Fundamental Indeterminacy of Matter

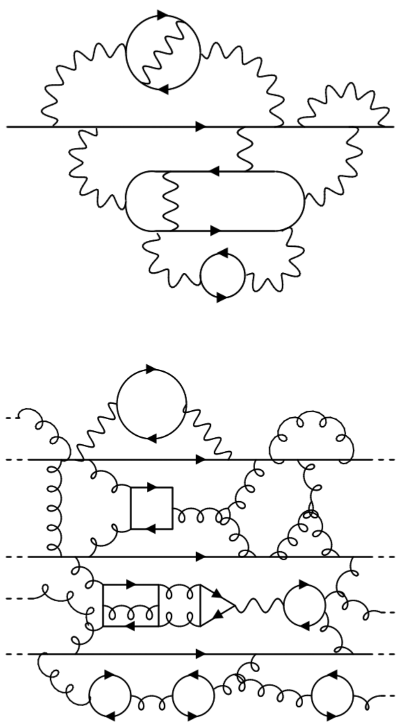


Figure 7.1: A "Feynmann Diagrams" showing the path of quantum particles through space and time, in an electron (*top*) and in a proton (*bottom*). Arrows moving to the left represent anti-particles moving "backward" through time, affecting the particle's overall trajectory. Squiggly lines represent new types of particles "created" which are in turn destroyed upon another interaction. The overall impression is that even in this model of the simplest particle, a "Rube Goldberg" like series of interactions is taking place (see Fig. 7.2)

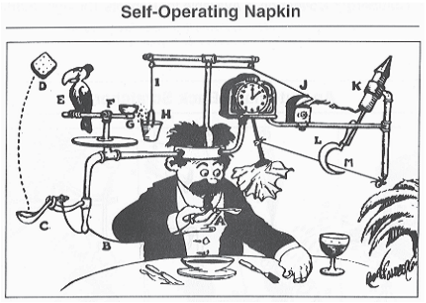


Figure 7.2: A "Rube Goldberg Machine," named for the cartoonist who became famous for designing contraptions that would perform the simplest tasks in the most complex way possible. This particular machine is called "Self-Operating Napkin"

Long before the invention of the first computer, however, the model of a deterministic universe characterized by Laplace's thinking was quickly upended with later scientific developments in the 19th and early 20th centuries, first by the discoveries of the laws of thermodynamics, which stipulated the irreversibility of certain processes along with the accompanying understanding that past states cannot be determined based on knowledge of current states,[3] and secondly by the advances of quantum mechanics. At a fundamental level, quantum mechanical systems do not act like tiny billiard balls colliding and bouncing off of each other in ways which could be expressed with Newtonian formulas, but in ways that are indeterministic and ultimately random.[4] The mechanisms that determine this perceived randomness defy easy conceptualization and can seem magical in nature, with particles spontaneously appearing, disappearing, colliding with other vagrant particles moving backwards through time, and seemingly defying all laws of causality. (Fig. 7.1) Even if one were to map all of the interactions governing the simple change of a particle's vector, the process can seem like a massive Rube Goldberg machine of endless layers of complexity. (Fig. 7.2) Additionally, as a consequence of the particle-wave duality of matter, where particles interact with each other as objects, but travel between each other as waves, the information required to perform a Laplacian calculation for a particle—that is its precise position and its precise momentum—cannot be simultaneously determined as expressed in the work of Werner Heisenberg and his "Uncertainty Principle".[5] This is not a result of a technological deficiency, but seems to be a *fundamental property of matter*. Quantum systems, therefore, cannot be seen in the light of classical mechanics, where variables are fixed and underlying, even if unobserved, but as a fields of probabilistic distributions of variables, where values cannot be assigned without destroying the functional relationships between particles.[6] Only by using the laws of probability and laws of averages, do deterministic properties of matter begin to emerge from what Warren Weaver called *disorganized complex systems*, subject to scientific scrutiny and calculation.[7]

7.4. Further considerations introduced by Chaos Theory

A further complication to the Laplacian dream is introduced through the implications of chaos theory. Grounded in mathematical models and simulations of natural phenomena, chaos theory observes that even in a strictly deterministic system, which quantum mechanics refutes, even very small variations in initial conditions can lead to radically different end states. As explained by Edward Lorenz, an early pioneer in chaos theory, "two states differing by imperceptible amounts may eventually evolve into two considerably different end states. If, then, there is any error whatever in observing the present state—and in any real system such errors seem inevitable—an acceptable prediction of an instantaneous state in the distant future may well be impossible.”[8] (Fig. 7.3) Lorenz’s observations entered the mainstream public consciousness with the publication nearly ten years later with a presentation entitled “Predictability: Does the Flap of a Butterfly’s wings in Brazil Set Off a Tornado in Texas?”, with the presentation’s premise becoming known as the “Butterfly Effect.” The point of the paper was not that blame could be assigned to a single butterfly in Brazil for a specific event in Texas, but that the number and position of butterflies could never be known, along with all the non-butterfly actors which factor into the behavior of a system.[9] Combined with the principles of quantum uncertainty, the flap or non-flap of a certain butterfly’s wing could just be the result of a quantum fluctuation in a single butterfly brain neuron.

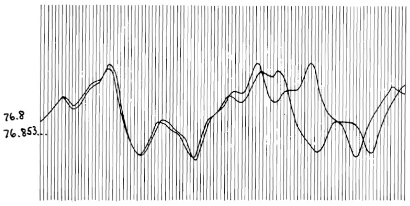


Figure 7.3: Lorenz Patterns. Two curves with miniscule differences in starting conditions diverge signficantly through time.

A similar finding was graphically presented in a 1976 paper by the biologist Robert May, who analyzed a non-linear equation first introduced by Pierre François Verhulst that has become known as the logistic map. Verhulst’s equation represents the 19th century tendency to try and reduce natural phenomena to simple equations; May’s analysis points to an inherent flaw in the equation even if it were accepted as a valid mathematical representation of a natural phenomenon. The equation itself pretended to model demographic growth, accounting for variables such as reproduction and starvation, and attempts to show how the ratio of population to overall carrying capacity (*x*) changes with various rates of growth (*r*). The graph of this known as the “logistic map,” (Fig. 7.4) shows that up to around the value of *r*=3 (Figure xx, point B), the population stabilizes at a specific *x* value. As r increases, however, the value of *x* first fluctuates between two values (a periodic attractor), then 4 values, 8, 16, 32, etc. At a certain point, no discernable relationship or period can be observed and the system is said to be “chaotic.” The point at which this happens (Fig. 7.4, around point D) is said to be at the “onset of chaos,” a point after which the equation becomes essentially useless with no discernable pattern.

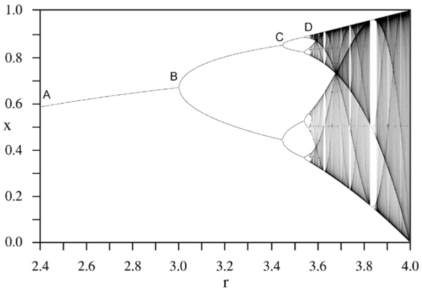


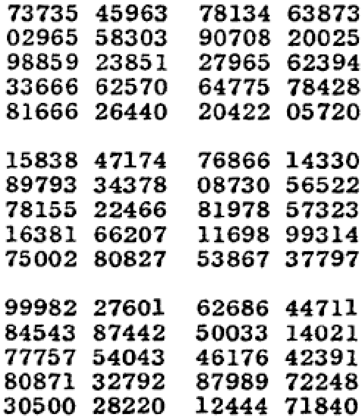
Figure 7.4: Graph of the logistic map. The function between A and B has a *fixed-point attractor*. At B there is a *bifurcation* or *state change* and the system is goverened by a *periodic two-point attractor*. At C another bifurcation changes the system to a period 4 point attractor, and so on. After roughly point D, no period can be deduced, and the system becomes chaotic. The region after point D represents “*the onset of chaos*.”

Many more such mathematical demonstrations came out of the period of chaos research which reached a high point in the 1970s and 1980s. One legacy of this period was that mathematicians demonstrated mathematically, and in a way that captured the public imagination, the difficulties inherent in mathematical approaches to describing or simulating nature by presenting extreme scenarios, and questioned, probably rightfully so, the validity of the megalomaniacal dream of exercising control through rational calculation. On the other hand, in many ways these were provocations that did not necessarily show the way forward, with pure chaos being just as unhelpful a theoretical construct as pure order.[10] According to landscape theorist Martin Prominski, the legacy of this period, however, may be best seen in the corollary questions which they posed: “*Wie kommt es trotz der Möglichkeit zum deterministischen Chaos zu der relative stabilen Formen- und Strukturvielfalt in der Natur? Wie ensteht Ordnung in nichtlinearen Prozessen?*”[11] Quantum mechanics and chaos theory do not presuppose an anything goes universe, and the difficulty or impossibility of predicting *exact* futures does not mean that trends and probabilities cannot be predicted in certain settings. Paraphrasing James Gleick’s work on chaos studies, Tom Mayne declares that “perhaps the most important revelation from chaos studies is not that order appears out of chaos, but that some systems that appear chaotic are really just complex.[12]

7.5. Random heterogeneity leads to structure

The answer to the question of “how does order emerge from chaos?”, of course, depends on how order is defined in the first place. According to the Big Bang theory, a little over 13 billion years ago, the universe was a singularity of infinitely dense matter compressed into an infinitely dense space. By most definitions, this singularity would be considered much more "ordered" than the current state of the universe. Likewise, an eventual end-case scenario for the universe, billions of years into the future, would be a homogenous, even distribution of atoms, deplete of all energy at a temperature just above absolute zero. This also, by most definitions, would also be considered an ordered state, although it presents a very low-grade order.[13] Both states, however, at least to our eyes, seem entirely devoid of *structure*. Structure is born of relationships between objects; a branch is a structure in a tree so long as it is tied to a trunk, a smaller branch, a twig, or a leaf. Once this relationship is severed, structure could no longer be said to exist.

Rudolf Arnheim in *Entropy and Art* correlates order with this "structural theme," which he associates with the term "*anabolic tendency*… the *shape-building cosmic principle* that accounts for the structure of atoms and molecules, the power to bind and loose…and this theme *creates orderly form through interaction*…"[14] It is through interaction that structure emerges from random variation. An easy to analyze example of an interactive force intrinsic to structure is gravitation. Since the time of Newton, a fundamental scientific premise explains that all particles in the universe are somehow gravitationally bound to all others. Random variation in the distribution of matter is, at the same time, key to the emergence of structure through gravitational forces. If matter were homogenously distributed through space, gravitational relationships would not lead to the condensation of matter into super-clusters, galaxies, stars, and planets.[15] Somewhat more difficult to analyze, but also recognized as a key generator of order, at least in the biological world, is the random variation of genes coupled with the non-random filter of natural selection, a process driven by a series of competitive and cooperative relationships. This is key to the emergence of structural relationships in all life forms as first proposed by Charles Darwin, but hinted at by many others centuries earlier. The importance of random mutation and the phenomenon of genetic drift are well-understood as the raw material upon which evolution acts to create the amazing variety of life now living on earth, with innumerable forms long lost when blind chance such as the impact of an asteroid rendered them unfit to pass their genes onto the next generation.



73735	45963	78134	63873
02965	58303	90708	20025
98859	23851	27965	62394
33666	62570	64775	78428
81666	26440	20422	05720
15838	47174	76866	14330
89793	34378	08730	56522
78155	22466	81978	57323
16381	66207	11698	99314
75002	80827	53867	37797
99982	27601	62686	44711
84543	87442	50033	14021
77757	54043	46176	42391
80871	32792	87989	72248
30500	28220	12444	71840

Figure 7.5: 300 of the million random digits from the RAND corporation book *A Million Random Digits with 100,000 Normal Deviates.*

In Chapter 5, the two protagonists von Neumann and Alexander both proposed models for how structure emerges based on evolutionary processes with both concluding are essentially bottom up in nature. Alexander's model of the interconnected lights (§5.10) made some questionable conjectures, but his conclusion that adaptation, "apart from chance…depends only on the pattern of interconnections between the lights"[16] is sound. These patterns of interconnections will be the subject of the next chapter on topology and networks.

Von Neumann posits another model for the emergence of order, his cellular automaton, but he also recognized that another key factor needs to be brought into play, that as society becomes more complex, and as evolution speeds up, this system increases in instability and requires more and more inputs of energy. (§5.6) According to Delanda, "nonlinear models show that without an energy flow of a certain intensity, no system, whether natural or cultural, can gain access to the self-organization resources constituted by endogenously generated stable states…and transitions between those states."[17] The second law of thermodynamics states that in a closed system, matter will always tend to a state of greater entropy. The emergence of order on our planet seemingly defying the second law is the result of the enormous input of solar energy. Systems requiring more energy input than the sun can provide need to find new strategies or technologies to support their increasingly complex states—in other words they need to innovate. An early example in evolutionary history, for example, was the emergence of predation. More recently, human societies have tapped into fossilized solar energy and in the 20th century, nuclear energy itself. The emergence of the computer can also be seen as a type of "state change" allowing society to organize itself on a higher and more productive level, but this is not without cost, and instability always accompanies innovation. According to Kwinter, "the more ordered and differentiated, … the more unstable and expensive (in terms of energy required to sustain it) the system becomes. Instability, it turns out, is the precondition of creativity."[18]

7.6. Pseudo-randomness and Indeterminacy in Computation

In contrast to the physical universe, which quantum theory asserts is indeterministic in nature, computational space can be described as fundamentally deterministic. That is, if a standard algorithm or computer program is run with the exact same inputs, we can expect the same outputs or results every time. Often computer programs, in an attempt to simulate randomness, will use lists of random numbers to simulate a random process of some sort. An inherent problem is these lists themselves only offer *pseudo-random numbers*, since they are in turn generated by another deterministic algorithm. Von Neumann, intimately aware of this problem, offered his famous quip cited at the beginning of this section to light-heartedly communicate the seriousness of the problem before then going on to present some novel algorithms for generating pseudo-random numbers lists.[19] Such lists were very valuable for scientific, engineering, military, and especially statistical research, and in the years before the widespread use of computers by the general public, researchers would invest in a well-generated set of random digits. (Fig. 7.5)

For many purposes, using such lists presents no serious problems, but when running simulations to try and uncover hidden orders in sets of data, one must be aware of this problem as the method of generating random numbers could in turn produce a false pattern. An example is given in Figure 7.7, a failed test of an algorithm constructed by the author with an intended output similar to the random walks that will be described shortly. (§A7.1) Here, lines of movement were created where a walker's heading is rotated at each time step by a small random value. After each iteration of the algorithm, the random number "seed" is reset based on the current iteration. Starting with a regular point of grids, one can clearly see that each walker follows a discernably non-random path as the algorithm progresses through various random number lists. Unaware of this problem, an uninformed user might think some deep underlying order in nature has been uncovered; what has been uncovered here, however, is only the fault of the programmer.

In the previous section, the difference between *ontogenetic* and *teleological* algorithms was introduced, that is an algorithm that approximates a form, but not the processes that generate that form, vs. an algorithm that attempts to simulate the processes which lead to a certain outcome. In this context, nearly all random number algorithms are essentially ontogenetic, with little or no relationship to the underlying generative processes which might generate that quantity in nature. Because of the importance of introducing true indeterminacy into certain processes, various methods have been devised to bring randomness from the external world into the computational environment. Most notable is the use of various devices and methods to read indeterministic quantum states for this purpose. Paradoxically, such indeterminacy in the computational environment allows the computer to solve certain problems which are very difficult or even unsolvable in a traditional, deterministic computational environment.[20]

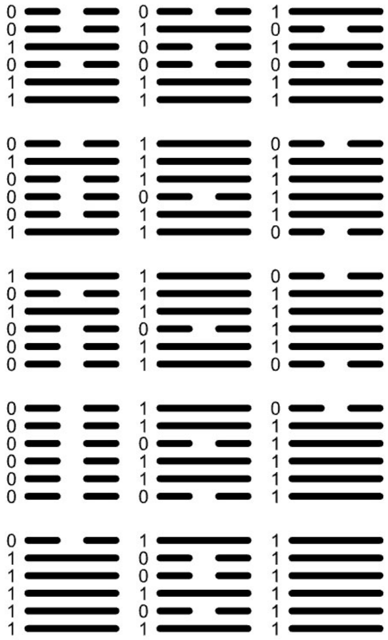


Figure 7.6: Random binary patterns have a long history. The 6 digit random binary of the *I-Ching* was used as an oracle device in China for at least 2000 years. Many think Leibniz's binary system was inspired by the *I-Ching,* with the sinophilic Leibniz himself commenting on the binary nature of the ancient Chinese text.

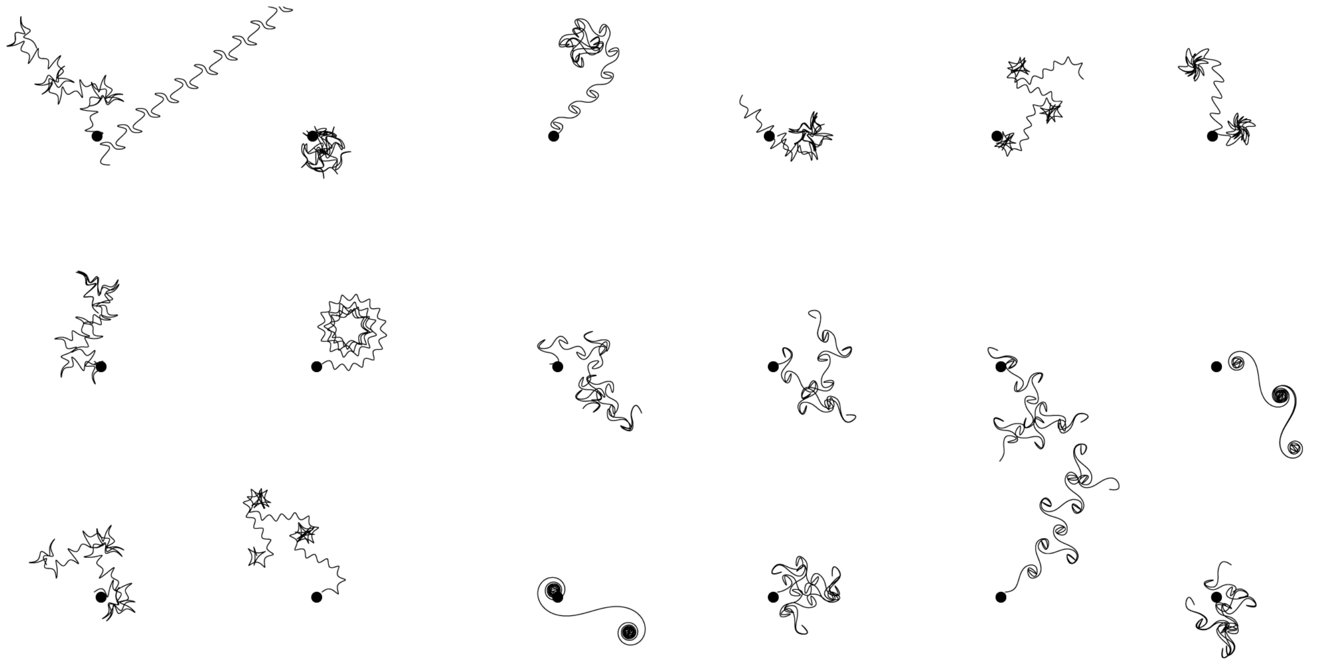


Figure 7.7: Paths generated with a faulty implementation of a random number generator. Although the forms look interesting, the patterns are anything but random. False patterns in random number generators can skew results in stochastic simulations.

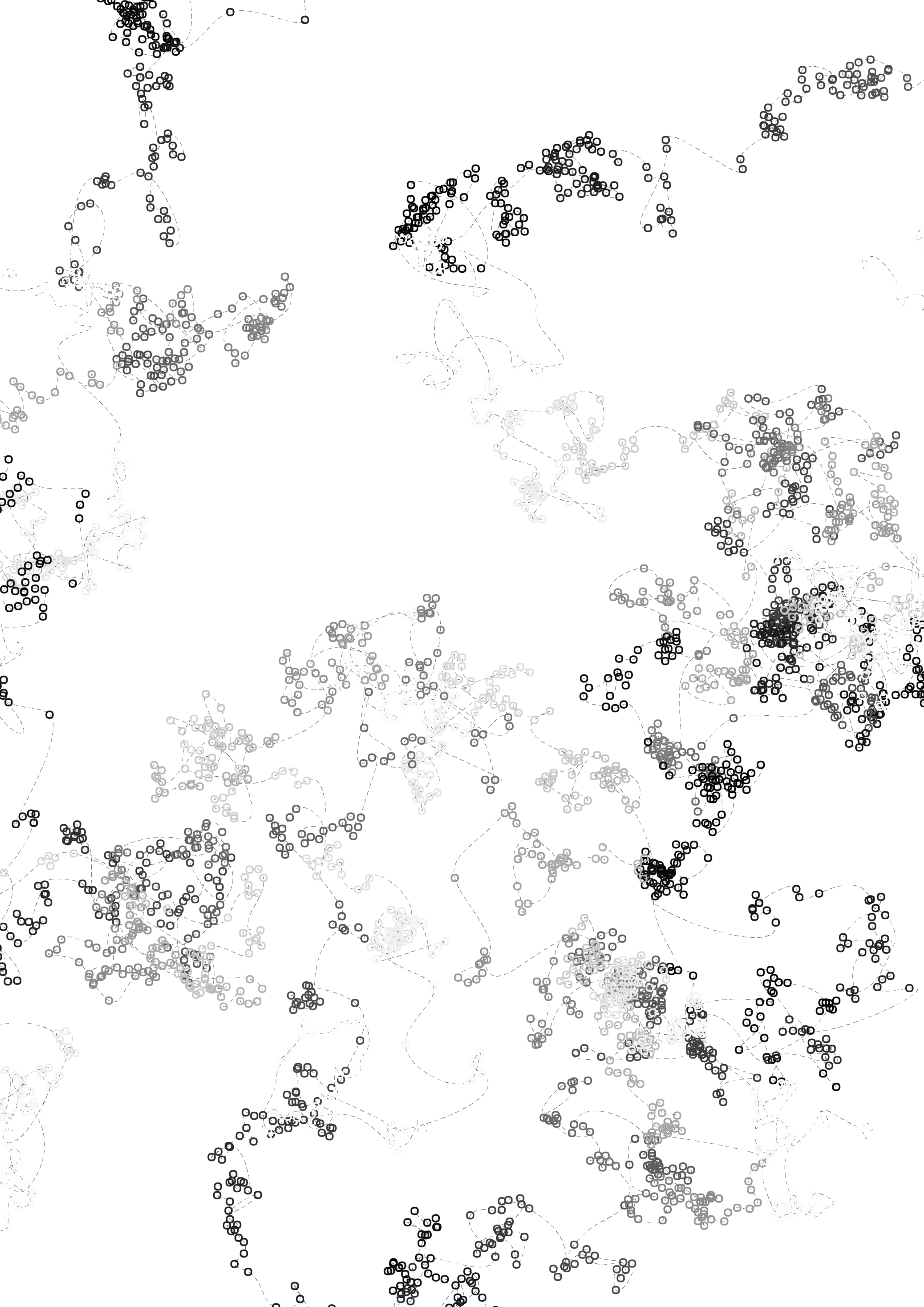
environment, which is perhaps of most interest to designers, is to take cues from the actual environment, through the use of sensors, for example, or to allow for inputs or interactions from a range of users. As argued by Mario Carpo, "all that is digital is variable, and all that is digitally variable is potentially open to interaction, communality, and participation."[21] Carpo goes on to lament the relatively slow relinquishing of authorship on the part of designers ostensibly concerned with indeterminate systems, but who slavishly adhere to a strictly deterministic process, and contrasts this with the open-sourced, collective authorship characteristic of much of the rest of contemporary digital culture. Here randomness is probably not a suitable term, but such processes open to *chance* often produce results surprisingly better or more interesting than those of the single author.

7.7. Summary Conclusion

The presence of random variation in natural and human systems is a key component in the generation of order, and indeterminacy is a fundamental property of matter on the quantum scale. Through structural relationships between pieces of matter, and through the input of energy, order emerges in systems through a process of evolution and adaptation, with random variation being the raw material these systems work upon. Finding ways to introduce chance and to work with indeterminacy in computational systems remains a fundamental concern that needs to be addressed by designers of algorithmic systems. While random number generators can prove helpful in some cases, such a solution might mistakenly ignore an underlying process, pattern, or logic that is important to the system's function. Furthermore, indeterminacy can be introduced into a system by the designer relinquishing some control over the process to involve outside actors, but this is best dealt with when strategies for accommodating indeterminate inputs are developed.

To conclude this chapter, three examples of algorithms demonstrating specific aspects of chance and the emergence of structure from chaotic systems are presented. Since most of the algorithmic examples in the following chapters also make use of aspects of chance, randomness, and indeterminacy, they provide an important foundation for later examples.

The three algorithms demonstrate a relationship between randomness and the fractal forms often observed in nature, (§A7.1) the emergence of differentiation through the gradual accumulation of minute changes, (§A7.2) and how interaction between distinct substances can lead to the emergence of pattern. (§A7.3)



Algorithm 7.1. Random Walks

A very basic but useful type of algorithm, which can be used either alone or in conjunction with more complex algorithms to simulate phenomena of randomness encountered in a diverse range of contexts, is the random walk. A few applications of simple or biased random walks include a 1-dimensional random walk simulating variations in stock prices,[22] a 2-dimensional one approximating the foraging behavior of an animal in open countryside,[23] or a 3-dimensional one tracing the movement of a particle of dust in the air. These last two are classic examples of the problem of *diffusion*, which the random walk is particularly well suited to modeling. It is important to note that the most useful random walks are not purely random in nature, and are largely ontological algorithms blind to the underlying fundamentals driving randomness. Simulations using random walks are often more interesting and informative when they are combined with other phenomena, such as the "correlated random walk" used to model animal movement and ecosystem diffusion. In this correlated random walk, a specific directional bias—that is one direction is chosen more often than the others—creates a model which more closely parallels observed behavior.[24]

Figure 7.8: *(opposite)* Results of a random walk using a random movement direction based on the "Levy Flight" principle.

The first description of this mathematical problem by Karl Pearson in 1905 serves as a good starting point for constructing the algorithm:

> "A man starts from a point O and walks *l* yards in a straight line; he then turns through any angle whatever and walks another *l* yards in a second straight line. He repeats this process *n* times."[25]

The algorithm as described consists of a series of discreet steps of movement. At each step, a random velocity is chosen from a list of random or pseudo-random numbers. This can be done in a continuous space (movement is possible in any direction), or to simplify matters further, along a grid with only four possible directions of movement. Pearson describes a fixed range of movement in the variable *l* but this can be varied as well. Interestingly, other authors have demonstrated that as the distance travelled *l* approaches zero, the random walk comes closer and closer to approximating the physical phenomenon known as Brownian motion,[26] a type of motion useful in many algorithmic simulations, some of which will be discussed in forthcoming chapters. Brownian Motion was first described by the Scottish biologist Robert Brown, who observed the random movement of dust particles, much as Lucretius did 2000 years earlier, with the additional observation that the movement was similar regardless of the scale at which it was observed—in other words, as concluded by Batty, it was fractal in nature.[27] Batty himself uses random walks as a part of his algorithms used to model the growth of cities, as populations grow and diffuse into a larger and larger spatial realm.

In the images shown here, two classic random walks are shown, along with a variation incorporating what has become known as "Lévy Flight." This is essentially similar to a classical random walk, except where values fall at an extreme, they are "heavily-tailed" to produce a movement known as a flight. The hypothesis is that a foraging animal's movements approximate Brownian motion until resources become scarce, when it then makes a sudden jump to a new area. This does not apply only to lower animals, but has also been used to model the diffusion of hunter-gatherer populations as well, where periods of local foraging are followed by sudden jumps representing directed migrations to a new camp, where the process repeats.[28] The algorithm, to reiterate, does not take into account fundamental drivers of behavior, but instead only approximates an observed phenomenon.

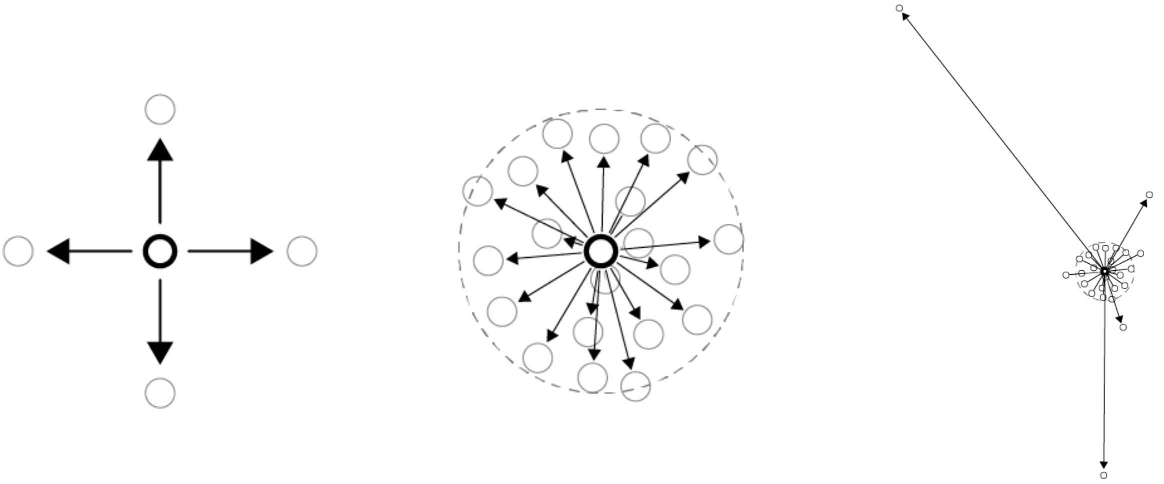
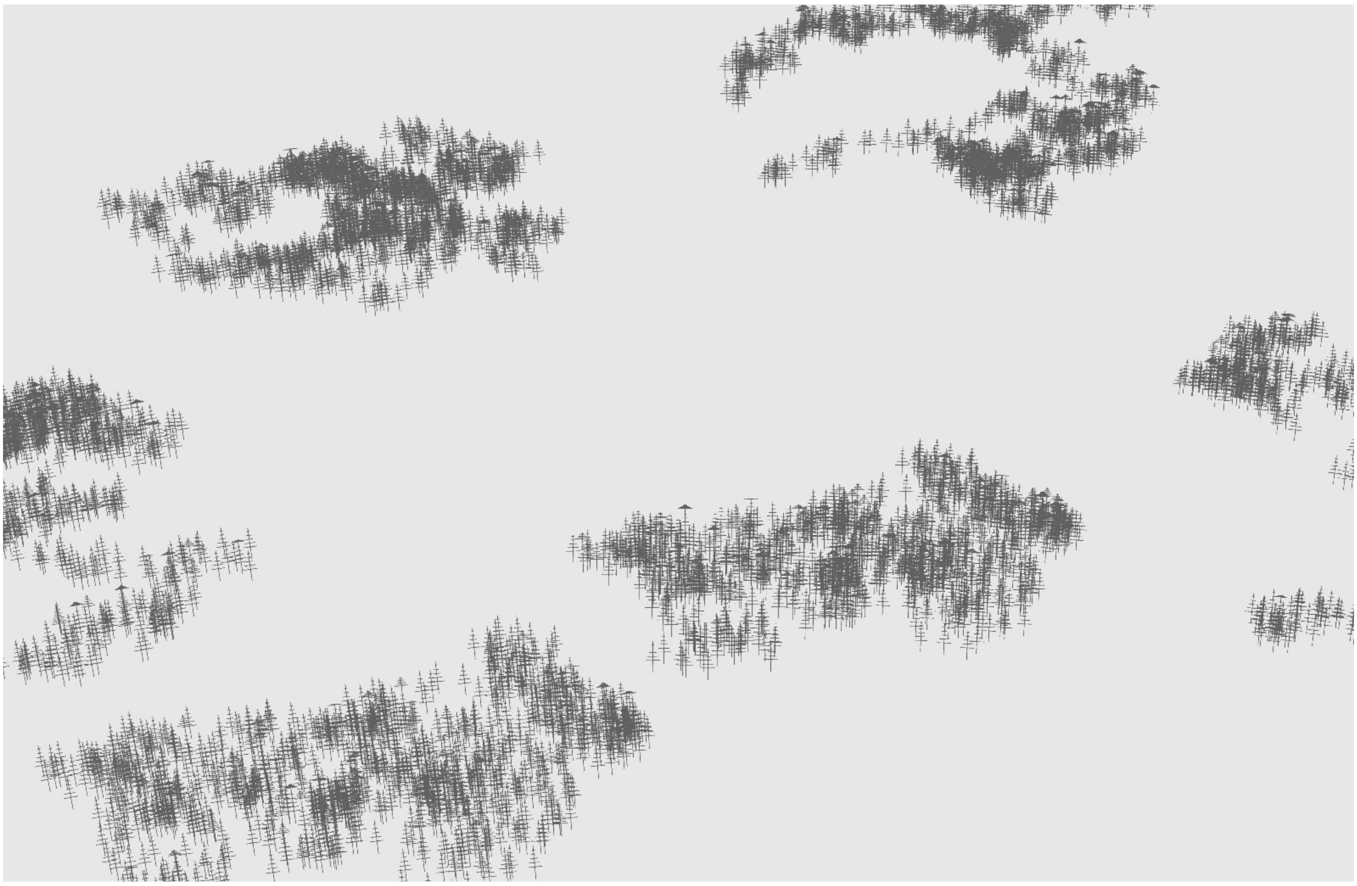
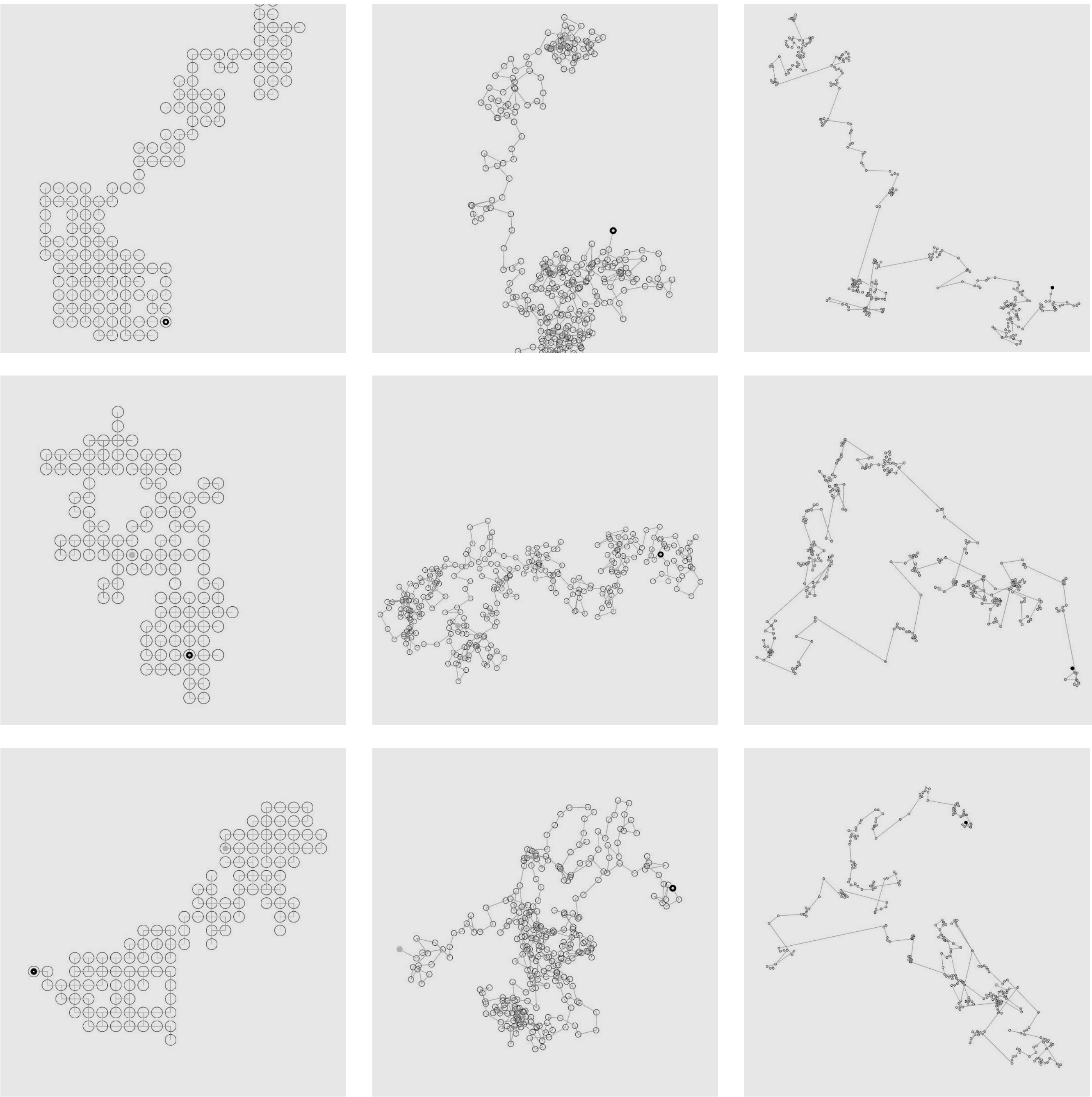


Figure 7.9: *(above)* Possible directions of movement in the various 2D random walk models. 1) In the simplest, movement is limited to 4 directions (N,S,E,W) with a uniform step size. 2) In the second example, movement can happen in any direction and in a random range of movement between 0 and 1. 3) The third diagram represents movement in a random walk exhibiting properties of Levy Flight.





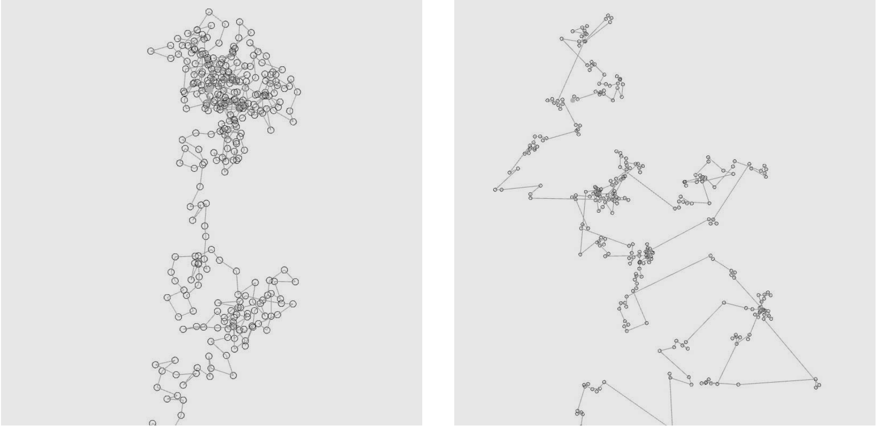
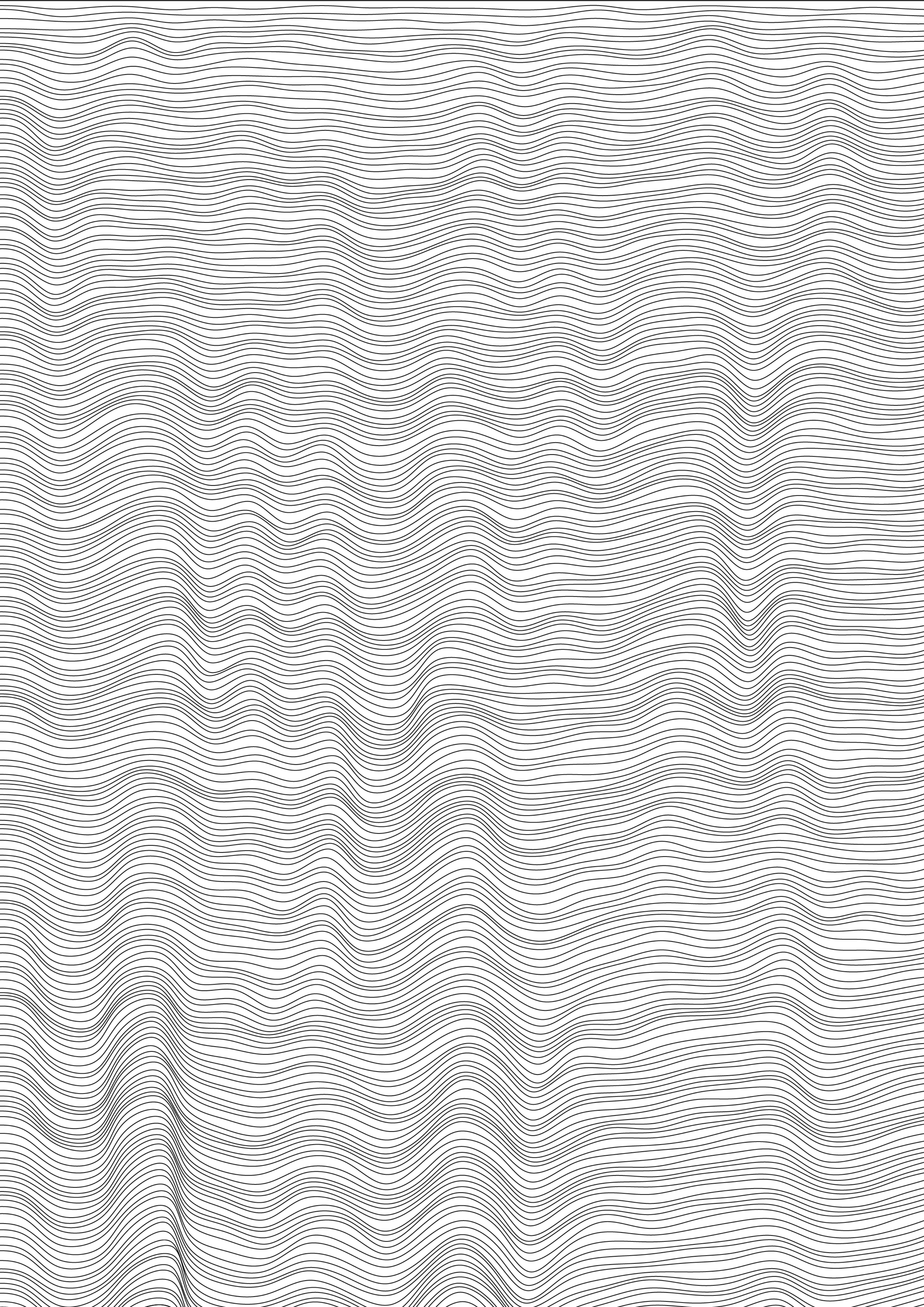


Figure 7.10: Random Walks using the three strategies presented on the previous page. The first colum represents strategy 1, the second column strategy 2, and the third, strategy 3 with Levy flight properies

Figure 7.11 *(page opposite, bottom)* Clusters of trees generated from six starting points. Random walks can give an ontogenetic impression of many classes of patterning in nature, but mask the complexity of underlying process.



Algorithm 7.2. Random Offset Algorithm

This simple algorithm illustrates a fundamental principle of chaos theory—that the accumulation of small variations through time can lead to fundamentally different end states. Inspired by the growth of rings on a tree, it can also be seen to show how the youthful homogeneity of an organism such as a tree gives way to the very divergent states of the organism in its old age.

The logic of the algorithm parallels closely the logic expressed in Georg Nees' Schotter (§1.6) where small variations in each time step accumulate through time to create divergence. In each iteration, the algorithm is provided with a curve, in this case an initially straight line, which is in turn divided many times to achieve an even distribution of equally spaced points. The points are then moved along a single vector a predetermined amount with a very small amount of random variation. One point may be moved 10.1 units, the next 10.15 units, the next 9.95 units, etc. From these points a new curve is constructed, which in turn becomes the initial curve for the next iteration or time step. Over time and with no predetermined pattern, much as in a random walk, small variations begin to accumulate to create gnarl-like structures. Eventually, two adjacent points may diverge sufficiently such that an interpolated curve cannot be drawn between them. In a second variation of the algorithm, when the curvature of a line gets too high, this breaks the line severing the structural relationship between two sets of points. Such ruptures also occur in diverging systems in nature.

Figure 7.12: *(opposite)* Results of the random offeset algorithm. The initial line is at the top of the page.

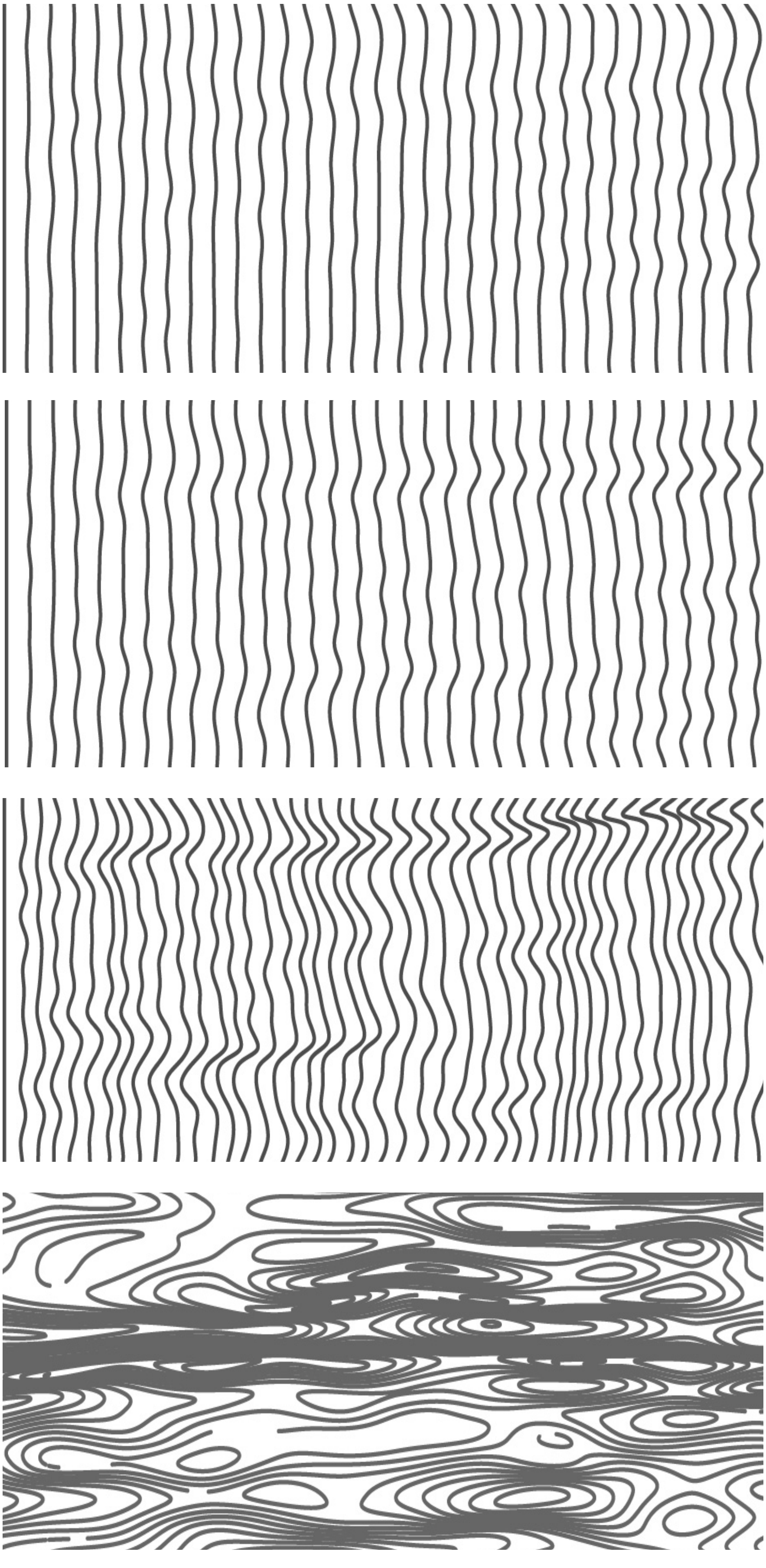
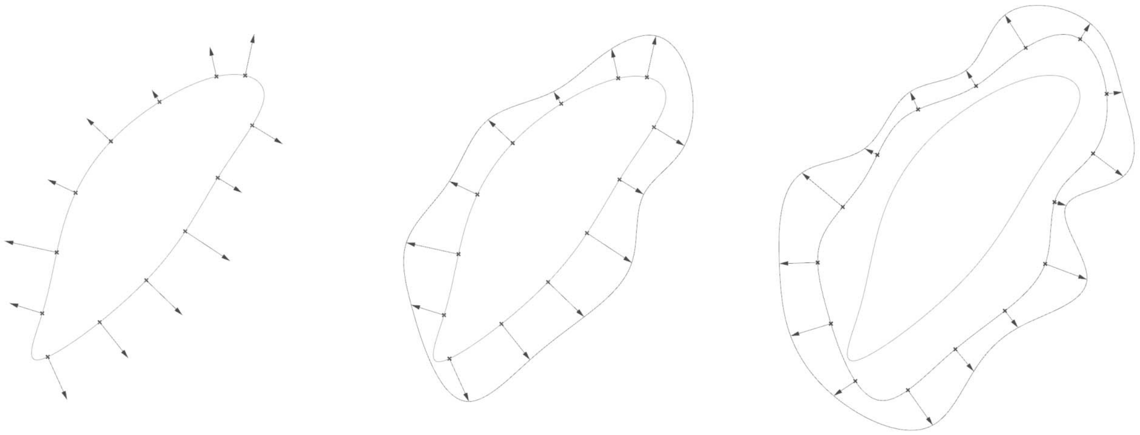
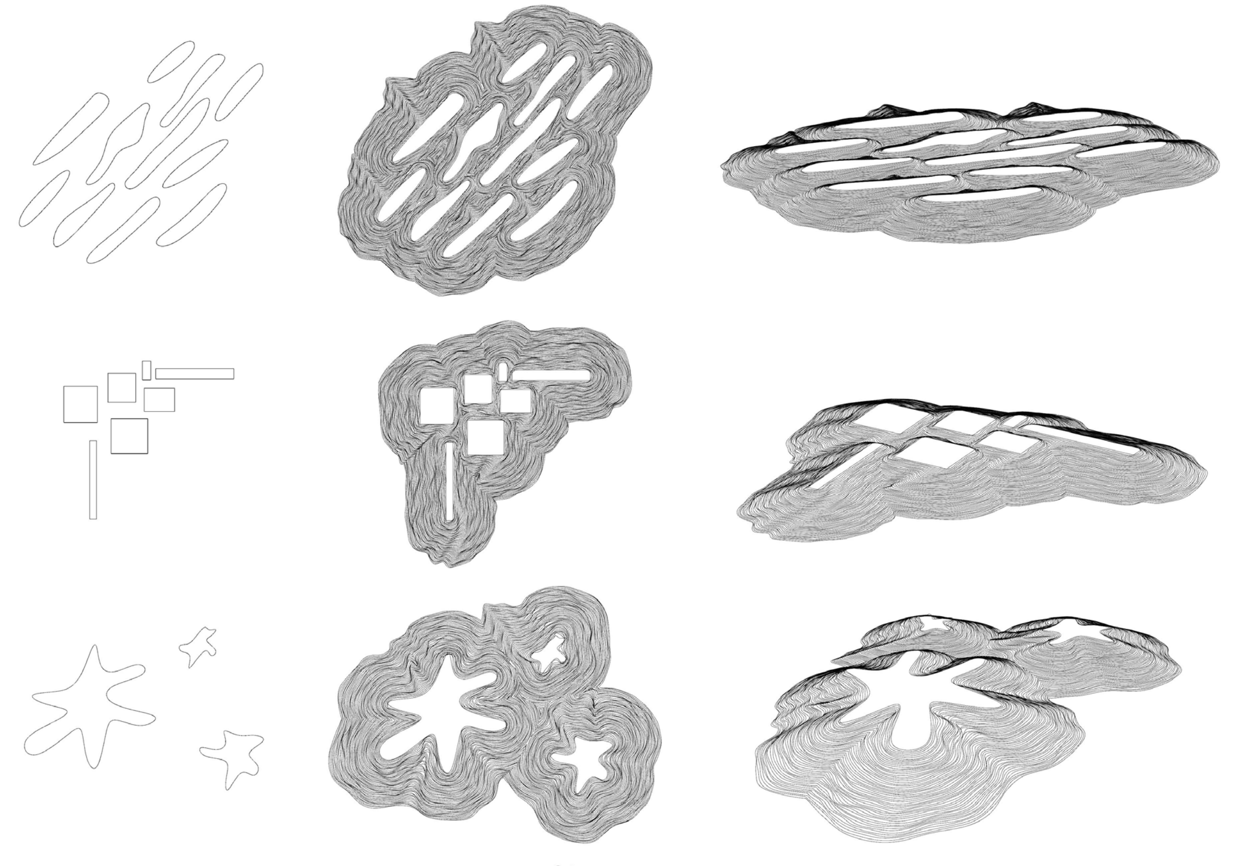
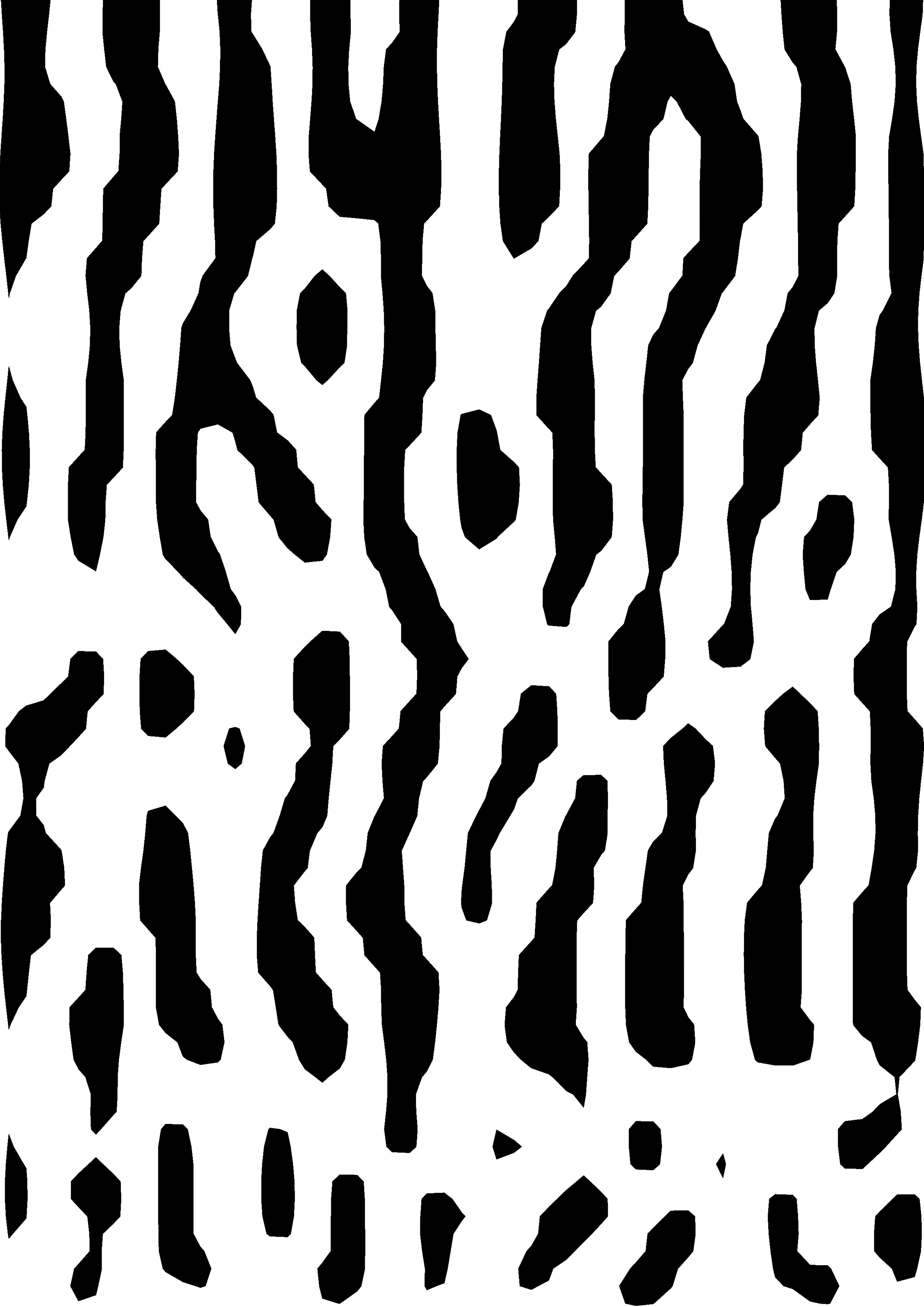


Figure 7.13: (*page left)* 1st image: Results of the algorithm with regular line offset, top. 2nd image, random seed changed. 3rd image, overall growth in each round has a second random domain added, corresponding to wet years or dry years in tree ring growth, for example. 4th image: When a topography is made with the lines forming a series of sections, when contour lines are then drawn the pattern looks like wood grain.

Figure 7.14: *(opposite page)* The process can also be applied to closed forms. Here each offset is also seen as a contour line, and moved down in the Z-axis, forming interesting landforms from a simple base.







Algorithm 7.3. Reaction-Diffusion System

This final algorithm attempts to give an impression of how discernible patterns and structures can emerge from random and chaotic environments. The algorithm is an adaptation of the NetLogo Fur model developed by Uri Wilensky,[29] which in turn was inspired by mathematical studies undertaken by Alan Turing to explain the emergence of certain forms and patterns in biological organisms. Science writer Philip Ball uses Turing's hypothesis along with various tests of the hypothesis as a key case-study to explain the emergence of form in nature in his landmark text *Shapes: Nature's Patterns: a Tapestry in Three Parts* which in turn has had a significant impact on the thinking of many digital designers.

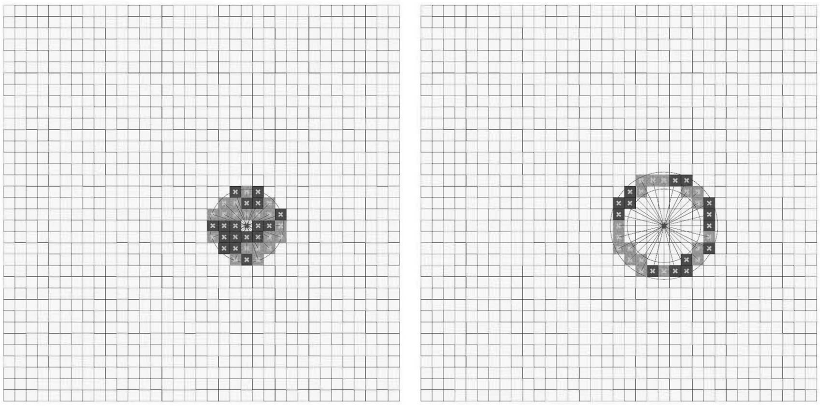
Turing proposed a mechanism whereby chemical reactions between two chemicals, combined with a process of chemical diffusion through cells, would lead to specific "wave-like" patterns observed in certain organisms.[30] While Turning was neither a biologist nor a chemist, experimental evidence has since shown that his mathematical musings were largely correct.[31] Also called an "activator-inhibitor" system, the logic in such algorithms has also been observed in the patterning of vegetation in certain ecosystems. This "self-organized patchiness" typically emerges in marginally arid ecosystems, where a "positive feedback between plant growth and availability of water" is established where the presence of existing vegetation reinforces the growth of neighbors, serving as an activator, and areas already devoid of vegetation reinforce conditions of aridity, acting in effect as an inhibitor to future plant growth.[32] These ecosystems often so closely parallel the patterning exhibited in animals that they have acquired names reflecting these associations, such as in the striped ecosystem of "tiger bush" or the spotty vegetation of "leopard bush".[33] Other ecosystems under conditions of significant stress, such as scarce availability of nutrients, may also exhibit such patterning, such as peat bogs.[34]

Figure 7.15: *(opposite page)* Pattern derived with a Reaction-diffusion cellular automaton with a subsequent smoothing algorithm applied to remove the blocky nature of such a process. The neighborhoods also move along a gradient, with neighborhoods towards the top having an oval shape, while neighborhoods towards the bottom are round.

The algorithm here uses a classic cellular automaton model (see §6.13) with two discreet states. It starts by dividing a space into a number of cells, and assigning a random value, either 0 or 1 (dead or live) to each cell. At each time-step, the algorithm then performs a series of computations for each cell. The first is a "fine-scale" calculation for the activators, which sums up the all of the values of the cells within a variable inner "neighborhood," defined by a parametrically variable radius representing an area of diffusion of activator chemicals in the case of the Turing model, or the presence of water in the case of the arid ecosystem models. Next a "coarse-scale" calculation is performed for the neighborhood of the inhibitors, a larger, peripheral neighborhood also defined by an adjustable radius. The sum of these two calculations is then compared to determine whether activators or inhibitors have a stronger effect at the cell, which then in turn is used to determine whether the cell "lives" or "dies" in the next iteration. In the case of an ecosystem, this would be the literal growth or death of a plant based on the presence of water, trapped by the roots of neighbors. Once understood, the logic of the computation is fairly easy to understand, but the algorithm can become very computationally intensive very quickly.

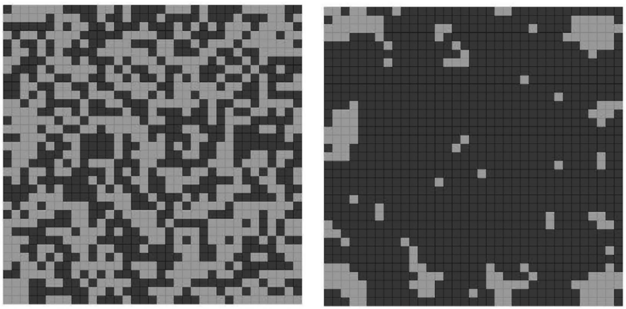
In an undifferentiated computational space, the various types of patterning can emerge from adjusting the relative strength of the activators vis-à-vis the inhibitors. The pattern of diffusion, reflected in the morphology of the underlying cells, can also influence the diffusion process, leading to either stripes or spots. More interesting patterns begin to emerge as the algorithm deals with the various morphological structures of the underlying substrate. This is observed in animals, where large spotty patterning in the body of an animal gives way to stripes in the narrow extremities.[35] Similarly, in ecosystems, the variation of the underlying substrate can effect the overall distribution and morphology of the patterning. The key to achieving interesting effects with this algorithm is in the careful development of a logic associated the various cells with their respective neighborhoods of interaction. The large image demonstrating this algorithm uses neighborhoods which gradually morph between essentially circular diffusion regions to elliptical ones, showing a transition from spotty to striped patterning systems. Further tests were done using spaces of varying topological and morphological complexity, and showed initial promise in incorporating such an algorithm into a design context.

Figure 7.16: (*top right*) This agorithm in contrast to the cave cellular in §6.13. uses a sophisticated neighborhood. Cells in an inner ring are influenced by activator chemicals, while cells in an outer ring are influenced by inhibitor chemicals. This corresponds to a simple chemical reaction observed in nature.

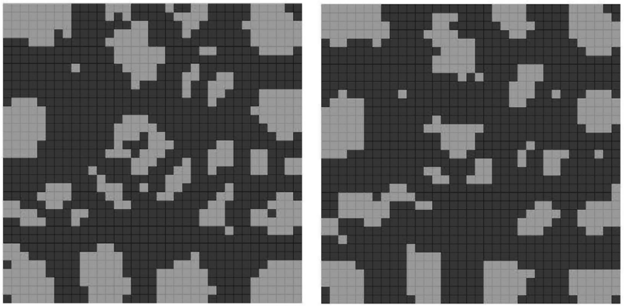


Inner Ring Neighborhood **Outer Ring Neighborhood**

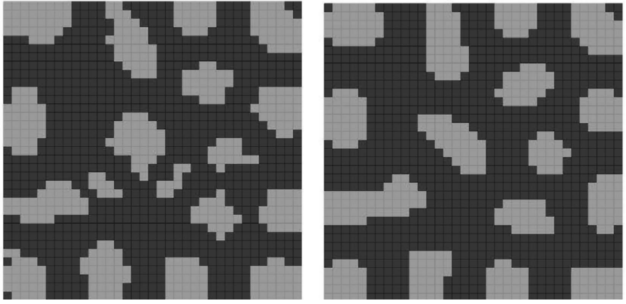
Figure 7.17: (*bottom right*) Results of the algorithm through the first 5 time steps. The initial randomness gives way after one time-step to a very different pattern. Where chemicals survive the first reaction, spots slowly form until reaching a steady state after a few recursions.



0 initial **1st recursion**



2nd recursion **3rd recursion**



4th recursion **5th recursion**

Figure 7.18 (*below*): A similar effect is seen in some ecosystems, for example in the so-called tiger bush in semi-arid climates in the top image or in grass under stress in droughts, pictured below.

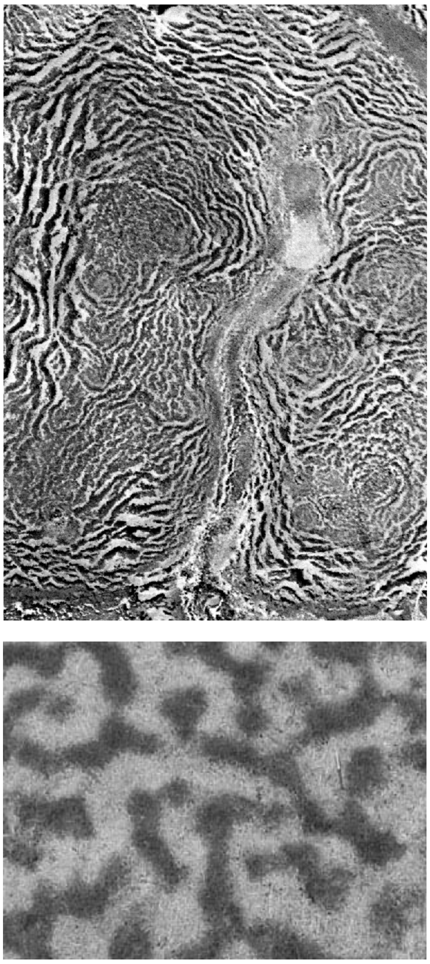


Figure 7.19: Variations achieved by altering the neighborhood definitions, the cell proportions (square vs. rectangular), and the relative strength of the activator vs. the inhibitor chemicals.

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Chapter 08 - Networks & Topology

"Mathematicians do not study objects, but the relations between objects; to them it is a matter of indifference if these objects are replaced by others, provided that the relations do not change. Matter does not engage their attention, they are interested by form alone." – Henri Poincaré[1]

8.1. Introduction

The previous chapter introduced the concept that while chance, randomness, indeterminacy, and variability are inherent to matter at a fundamental level, ordered, predictable, and stable structures emerge in a regular and largely predictable fashion in both nature and in culture. What we perceive as order and structure emerges not from the "object" properties of matter, but from their systemic interactions and relationships to other elements. This chapter explores the concept of structures and systems through the lens of relational networks and the mathematical concept of topology. Topological networks can be used to describe 2- and 3-dimensional form in a concrete sense as well as abstract configurations with ambiguous spatial-structural relationships such as infrastructural networks and dynamic natural and androgenic systems. It examines the properties of several network and topological structures and shows how a change in the topology of a system or structure can fundamentally alter its behavior and efficiency. It also introduces the concept of network redundancy, and how redundant structures can contribute to the overall efficiency and resiliency of a system. Likewise, algorithmic systems can be described in terms of their topology. As the topology of an algorithm exists in an abstract computational space and not in physical space, the computational topology of an algorithm may share little relation to the physical properties of the spatial structure it describes but is rather more closely related to the space of production for a certain form.

The importance of the mathematics of topology has already been touched upon several times in this thesis. For Hillier and Alexander, identifying topological relationships lies at the heart of their "discursive" method, to identify configurations and patterns in systems, and to in turn recommend alterations to the system of configuration (§2.3, §5.8). Kwinter finds the study of topological relationships closely linked with the studies of networks and infrastructure, which he believes this lies at the heart of the 21st century design task: "What is interesting today, and what matters is *infrastructure*…in a word, *grids* of any and all kinds."[2] At the same time, however, configurational networks in landscape space have a level of ambiguity and topological uncertainty which makes topological studies in landscape space quite different from how an architect might use these mathematics. This led the team led by Girot to reformulate the concept of topology in the context of landscape architecture as discussed in §2.11. We will return to this theme in the conclusion of the chapter, but first some of the fundamentals of the classic uses of topology should be presented.

Figure 8.0: (*page opposite*) An emergent network formed by voles in a meadow. The paths exhibit properties of both a branching and a meandered network.

8.2. Poincaré’s *Analysis situs*

In §2.11, the concept of mathematical topology was introduced as the study of the relational configurations between things—the mathematical discipline “concerned with those properties of geometric configurations which are unaltered by elastic deformations” and with the “organized spatial relationships and proximities within surface structures.”[3] The contributions of Leibniz and Euler to lay the foundations of the discipline were introduced as well. The study of mathematical topology in the modern sense, however, owes its greatest debt to Henri Poincaré as introduced in his 1895 paper “On *Analysis Situs.”*[4] In the paper, he introduces concepts that laid the foundation for the rapid developments in the discipline in the 20th century, contributing the fundamental basis of the mathematics of dynamical and chaotic systems which would be explored later in the century.[5] The subjects this paper introduced included “1.Definition of Manifolds; 2.Cycles and Homology; 3.Intersection Index and Duality; 4.Differential Forms and Cycles; 5.Extension of the Euler Characteristics for Polyhedra; 6.Fundamental Groups; and 7.Manifolds and Discrete Groups.”[6] While Poincaré did not complete definitive work on these subjects, what he did was open up many new avenues of related inquiry which would only really begin to bear fruit decades later. While it is beyond the scope of this chapter to explore all of these concepts in depth, Poincaré’s definitions on manifolds, or “n-dimensional” shapes is of particular interest to designers working with computational geometric structures. The concept of homology where forms with similar fundamental structures can be mathematically compared laid the basis for D’Arcy Thompson’s groundbreaking study of biological structures published in 1917, *On Growth and Form.* Thompson cites Poincaré a number of times, especially in respect to his mathematics of curves and surfaces, and their application to the mathematics of growth and the theory of transformations.[7]

8.2. Graphs, Mathematical Topology, and Networks

In mathematics, relationships between elements are often studied with a diagram known as a *graph*. A graph consists of two basic types of elements—nodes and edges. The node is a simplification representing an object, a category, a self-contained system, etc. The edges are lines or arcs connecting the nodes, representing a specific relationship or interaction. Edges can have directionality indicating a reciprocal relationship or a one-

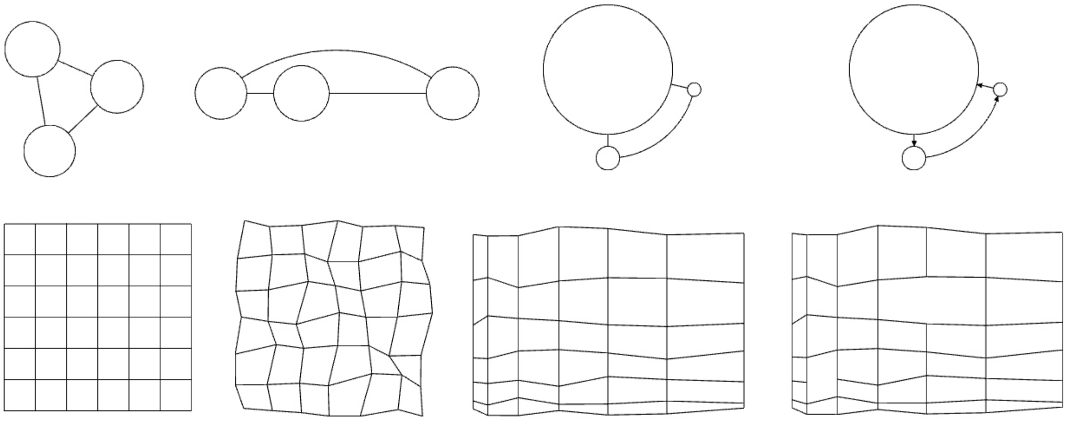


Figure 8.1: (*below*) The first three graphs in each row are topologically identical, while the final graph in each row is not identical to the prior ones.

way path and depending on what the graph is trying to show, such graphs usually have some graphic indication of the directionality of the edges. Graphs are important in the mathematical field of topology, which studies the continuous deformation of geometry in space. A topological relationship in a graph is preserved when the number of nodes and the configuration of the edges between them are unaltered. At the same time, the size of the nodes and the length of edges can be freely changed without altering the graph's underlying topology. In Figure 8.1, the first three diagrams in each row are topologically identical. Regardless of the size of the nodes, if the number, directionality, and degree of the edges is preserved, the topology remains unchanged. Only in the fourth graph in each sequence has the topology changed. The last diagram in the top sequence has added directionality and is thus topologically distinct, whereas the elimination of two of the edges in the deformed grid has changed its topology.

As relationships between elements are of fundamental importance, a graph does not necessarily show spatial relationships between elements. In Figure 8.2, the top graph is equivalent to the graph in the center since they have the same number of nodes and the edges between the nodes are equivalent. The center graph is not equivalent to the graph at the bottom even though spatially they appear similar, as the center graph is undirected, unlike the bottom graph, which is directed. Where a graph does show a spatial relationship, directionality, although not necessarily distance is preserved. In Figure 8.3, the top two graphs are equivalent, where a single line without arrowheads in the top left shows a mutual relationship. This is made more explicit in the graph at the top right, although no new information is added. The two graphs at the bottom are also equivalent to each other, although they are not equivalent to the graphs at the top. The nodes on graphs are often described in terms of degree, that is the number of connections to other nodes. The top and center graphs both have a degree sequence 2 – 3 – 2 – 4 – 1. In a directed graph, the degree is often described in terms of in-degree and out-degree, which are shown in the graph at the bottom.

The study of networks relies heavily on graphs and topological relationships, but the graphs used in network science may or may not relate to physical space. In a graph describing a social network or a scale-free network such as the world-wide web, space plays little role. On the contrary, in the well-known example of a subway network route map, the general configuration tends to correspond roughly to geographical landmarks, but distance and directionality is usually grossly simplified in the interest of overall legibility. In almost any other real-world network, nodes and edges have properties that vary through time which effect network behavior. Although relying on an underlying graph structure, network simulations account for factors such as travel time, distance, or overall capacity by 'weighting' the edges and nodes.

A clear example of this can be demonstrated by thinking about the development of software for a car's navigational GPS system, which will weight stretches of a highway differently than a back-road with a low speed limit, and will usually suggest travel on the highway even if this stretch is longer geographically. Additionally, nodes can have properties that affect overall system behavior. The nodes, in this case the intersections, also have a cost associated with them slowing down or stopping travel altogether. Better GPS systems today often gather real-time information about the properties of the edges and nodes in a travel network, such as average speed or carrying capacity, which effects how the system recommends a route, and recalculates network behavior constantly although topological relations remain static. We will return shortly to the systemic behavior of networks with their nodes

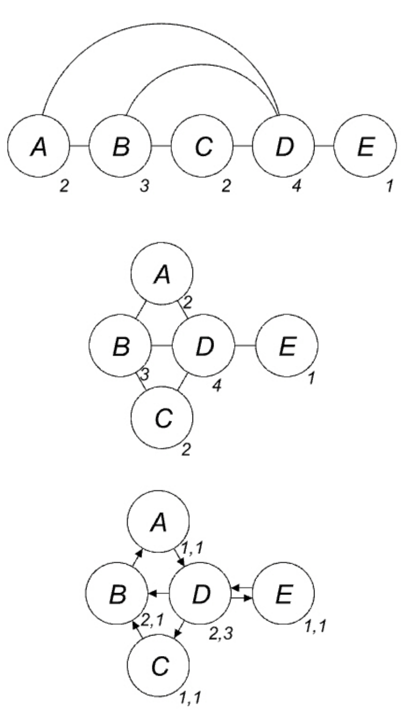


Figure 8.2: The graphs show in the first two images are identical, while the second and third images are not identical to each other, despite superficial similarities.

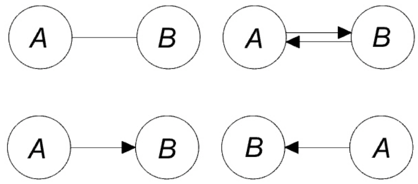


Figure 8.3: The top two graphs as well as the bottom two graphs are topologically identical to each other, but the top graphs are not identical to the bottom ones.

and edges, but first it is important to define some common topological structures.

8.3. Non-Redundant Graph Structures – "Trees"

In Harvard-trained architect Peter Steven's 1974 book *Patterns in Nature*, the author proposed that in 2- and 3-dimensional physical spaces, there are only a very limited number of possible configurations of elements, and that consequently nature is forced to reuse the same basic formal strategies in diverse contexts. The variety and diversity we perceive in nature comes not through innovative formal structures, but through topological deformations and hybrid configurations of the limited palette of possible spatial arrangements.[8] For example, according to Stevens, in 2D space there are only four strategies to connect a random group of points to each other without any overlap between points and without any redundant connections, i.e. where there is only one possible path between any two random points. (Fig. 8.4) It should be noted that such a non-redundant structure in mathematics is commonly known as a "tree" and tree-like structures are often used to structure computational data (§6.8). Returning to Stevens and his four graphs, he also proposed that these graphs corresponded to four archetypes for pattern formation in nature, each with certain efficiencies and drawbacks. Stevens four strategies are as follows:[9]

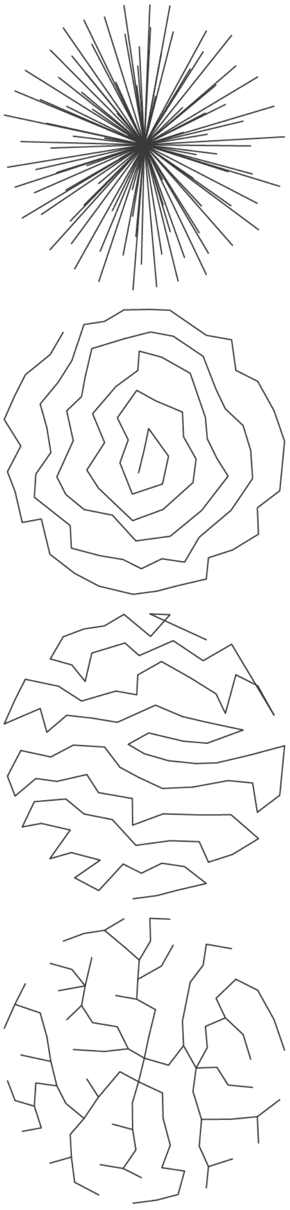


Figure 8.4: Algorithmically derived non-redundant graph structures based on basic patterns as described in Stevens' *Patterns in Nature,* 37-50. See also §A9.1

> Spirals: The spiral starts at a central point, and progressing in one of two directions, connects points in a rotating fashion. There is no branching in a spiral, with each point connected to only two other points, possessing a degree of 2, except for the start- and end-points, which have a degree of 1.

> Meanders: A meander is similar to a spiral having an identical degree structure, but connects points in a much more flexible manner, with frequent changes of the direction of connections. Meanders and spirals share many similar properties.

Explosions: An explosion connects a single point directly to each other point in the set.

> Branching Structures: In a branching structure, nodes can have a degree higher than 2, and points are typically connected to their nearest neighbor regardless of whether other connections come into this point already. Branching structures usually start at a single point, and "grow" from this single point incrementally, adding connections to the nearest neighboring point in an iterative manner.

Stevens recognized that the limitations of space would cause similar organizational structures to appear even when different processes of formation where in play, but like Kepes had in *The New Landscape*, he observed general trends and commonalities in the behavior of these four networks, and proposed that processes of formation and function were closely related to the associated form.[10]

The simplest of the four is the explosion, which also has the shortest average distance between any two points. This network prioritizes speed, but the cost of the network is extremely high in terms of overall length. The spiral, on the other hand, is generally very compact having a low overall length and can develop in a very ordered fashion, but as overall size increases, the distance between any two random points increases as a function of its length. The spiral can be seen as an orderly transfer of energy or material from one point to another. The meander is similar to the spiral in its properties, but in contrast to an ordered development, it can develop in a number of dynamic and chaotic ways. Depending on how it is formed, the meander can in some instances be even more compact than the spiral, but in others it has a far longer length. This network forms in spaces with energy transfer from one point to another, but where flows of matter or energy are highly variable. The last of the networks has perhaps the most surprising properties. The structure of a branching network, like the explosion, connects one point to every other point in the network in a fairly direct path. It is generally only slightly less efficient than the explosion in this way. It does this, however, in a very economical way, with a low overall length, even compared with spirals or meanders. Because of its economy and efficiency, it is no surprise that this type of network is the basis of the body plan of many organisms, including all vertebrates, some invertebrates (the others having a fundamentally spiral body plan), as well as most plants. Most networks are not purely of one type or another, and hybrids exist between them. River basins, for example, generally follow a branching pattern connecting all points in the river basin to a single river mouth, but between nodes in the overall branching structure, meander patterns tend to form. Likewise, plants might have an overall branching structure, but this is deployed in a spiral fashion.[11] [12]

8.4. Redundant Graph Structures

The four non-redundant graph structures, or typological "trees" proposed by Stevens, do not account for the structure of all or even most natural systems. All contain a fundamental flaw; if one node in the network fails, the network loses overall connectivity and depending on *where* the failure of the node is, the network itself might completely fail. We see this in living things, where the loss of a small branch in a tree, or a finger in a person, while injuring the organism, generally is not detrimental to the entity's long-term survival. A loss of a central node, however, usually leads to death. Networks with additional edges connecting nodes, however, can often overcome this fundamental defect and in the case of loss of one or more nodes, alternative pathways for transferring energy or material can be used. Von Neumann comments on the importance of redundancy, noting:

> If you look at automata which have been built by men or which exist in nature you will very frequently notice that their structure is controlled only partly by rigorous requirements and is controlled to a much larger extent by the manner in which they might fail … Rather than precautions against failure, they are arrangements by which it is attempted to achieve a state where at least a majority of all failures will not be lethal.[13]

In addition to building precautions against failure, the presence of redundant pathways, such as in the human brain, give the system much greater flexibility to adapt to changing conditions.[14] Redundant nodes can also lead to increased network performance by reducing the overall distance between nodes, outperforming all of the non-redundant networks with only a marginal increase in length. A network with many redundant connections, in contrast to a "tree," is often referred to as a "meshwork."

Like non-redundant networks, redundant ones can be described in terms of their degree structure. Networks with a regular degree structure as well as regular edge length form regular patterns and tessellations. For example, the three regular tessellations of the Euclidean plane, a triangular tessellation, the square grid, and the hexagonal honeycomb structure, have

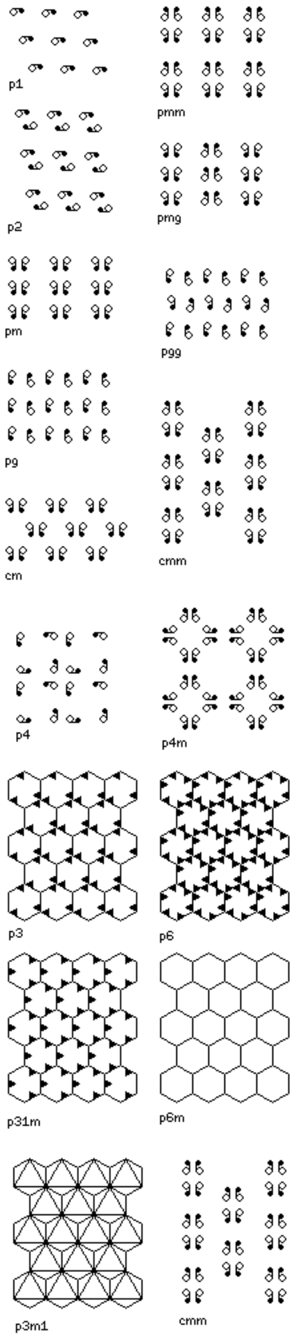


Figure 8.5: Wallpaper Groups. Topology of 2-dimensional patterns can be related to relationships based on translations, reflections, or rotations of geometry.

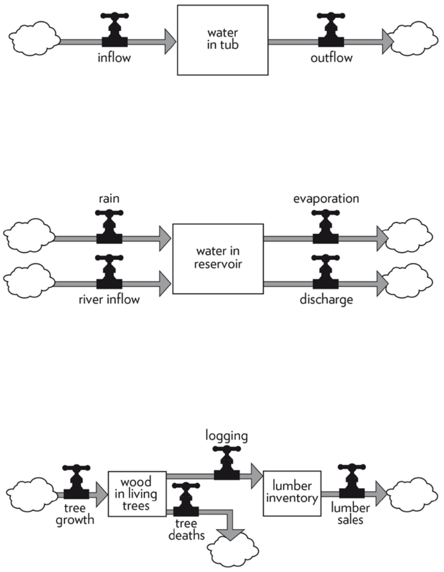


Figure 8.6: Diagrams for three simple systems: a bathtub, a reservoir, and a forest/lumberyard. from Donella Meadows, *Thinking in Systems,* p. 19.

Figure 8.7: *(above)* Adding nodes (up to a certain point) can make the total network length shorter.

uniform edge length and a uniform degree structure (except at the edges) of 6, 4, and 3 respectively.[15] While such networks—especially the grid—are often associated with man-made or planned systems, in many ways such networks emerge naturally under uniform conditions or processes. The formation of such structures will be revisited in Chapter 10. In general, however, in the 2-dimensional plane, nature tends to favor the formation of tessellations with a degree structure of 3 and 120° angles, while degree structures of 4 with 90° angles are often a characteristic of human designed networks or grids. Furthermore, of the regular polyhedral structures described by Euclid, only the cube, with a degree structure of 6 and 90° angles can form a regular tessellation in 3-dimensional space, leading to its associations by the Greeks with solidity and the element of earth. More irregular configurations, however, lend many more possibilities. In the 2D plane, tessellated patterns have been identified to fall into 17 distinct groupings, known as *wallpaper groups*, (Fig. 8.5) while in 3-dimensional space, 219 distinct types of *space groups* are present. An early advocate of computational methods in architecture, George Stiny, coined the term “shape grammars” to study configurational structures and their transformations, and this remains an active field of research. In studying larger networks, where configuration becomes more hybridized and even ambiguous and fluid, such studies begin to lose applicability. As such, they may be of limited interest to landscape architects looking to work with larger systems.

8.5. Systemic Graphs

The networks described up to now have a strong spatial component, which is important in design for determining how elements in space can be organized to achieve certain efficiencies. Not all networks useful by designers, however, should be read as graphs with a physical dimension. Graphs are also useful for the analysis of more abstract systems. Alexander, in fact, finds topological studies to be of limited use when describing mere formal properties, finding topology “may be a poor tool if used to prescribe the physical nature of forms, it can become a very powerful tool indeed if it is used to explore the conceptual order and pattern which a problem presents to its designer.”[16] In describing such systems with a graph, however, the meaning of connections and nodes could take on additional measures and dimensions. Donella Meadows describes in *Thinking in Systems* two important concepts for most networks’ behavior, the *flows* in edges and the *stock* in nodes, both of which can vary over time. In real world networks, physical dimensions or properties usually limit both flows and stocks. Meadows presents the simple analogy of a bathtub to demonstrate this concept. (Fig. 8.6) The bathtub itself is a node that can carry up to a certain amount of water. The pipe leading to the bathtub’s faucet is a directed edge that can have variable *flow*, but only up to a certain point. Likewise, the drain and sewer pipe also represent a directed edge with an upper capacity on its *flow*. The *stock* is the total amount of water in the bathtub, which Meadows defines as “the memory of the history of changing flows within the system.”[17] All other systems also have stocks and flows. The amount of ore in a mine, of lumber in a forest, or of electricity in a capacitor, can all be described in terms of a node with a quantifiable stock. In these cases, the limit on stock size is limited to a physical quantity of the node—the size of a mine, forest, or capacitor respectively, but some stocks, such as the population of brown bears in Romania, or humans in Asia, are related to abstract agglomerations based on arbitrary geographical units.

This introduces another very important consideration in drawing systemic graphs. *All* of them are abstractions, but their utility depends on determining useful boundary conditions for the nodes and useful measures of material and energy flows through the edges of the system. Systemic interactions within a node also need to be simplified. A fairly simple graph could be made where the earth is single node with inputs of solar energy and cosmic dust, and outputs of heat and gases such as oxygen—less useful would be a graph with eastern hemisphere and western hemisphere as two nodes of a graph and then mapping the material exchanges between the two halves of the earth. Likewise, it often doesn't make sense to approach problems of design with the abstract boundaries of a project, of a municipality, or worse, of a sheet of paper, without considering the open nature of the systems at play. In computational space, ill- or well-chosen boundaries can also have a significant impact on final results.

8.6. Network Logic

An additional consideration when working with relational systems is that network logic is not always intuitive. It does not conform to the logical constraints of 3-dimensional physical space, to the quantification rules of mathematical space, or to the linear nature of western logic. Adding nodes to a network in physical space, for example, can *subtract* length. (Fig. 8.7). Sometimes length matters, sometimes, such as in networks with fractal qualities, it is altogether unhelpful in apprehending network behavior—a single rye plant, for example, grows 387 miles of root in four months—when root hairs are accounted for this length exceeds 7000 miles.[18] Important implications for the performance, speed, and resiliency of a network are derived from its relational structure and whether it tends to the *treelike* model or exhibits properties of a *meshwork*. (Fig. 8.8)

Networks also tend to be dynamic and evolutionary. Cycles and non-linear interactions, in the form of recycling of energy and material and feedback mechanisms, can fundamentally change how stocks and flows behave, and even induce what are called *state changes* or *bifurcations,* mathematically defined as a sudden change in topology observed in dynamic systems,[19] but recently also extensively applied to the philosophy of science and societies as well.[20] As an example of this phenomenon, consider that the ecosystem carrying capacity or maximum population stock of Britain in the Mesolithic age, for example, seems to have been little more than 5000 people.[21] It is impossible to point to any one cause as to why Britain now supports 12,000 times that population, but numerous state changes induced by factors such as a warming climate, technological advances in agriculture and industry, and the advent of networks of global trade, have made possible through complex self-reinforcing feedback cycles a space which far exceeds the "natural" limits on human population. These state changes are difficult or even impossible to model before the fact, since, as argued by nonlinear thinkers, it is impossible to predict precisely how changes to feedback mechanisms will affect complex system behavior over longer time scales.

What is clear, however, is that networks can fundamentally change the nature of space and this is of fundamental importance to the spatial design disciplines. The concept of "the five-minute walk" is familiar to most all designers, but most planning documents still draw these walks as circles with a fixed radius as if it were a "five-minute" trip "as the crow flies." In reality, the complex topology of urban space can speed up or slow down certain walks, a phenomenon that is accounted for in the computational analyses of urban space used by, for example, GoogleMaps. A similar concept is deployed on the fascinating website Rome2Rio, where the user inputs any two points on the globe and an algorithm returns the time for trip between the two points using a combination of flights, buses, driving, and walking. (Fig. 8.9) Thousands of years ago, before the development of

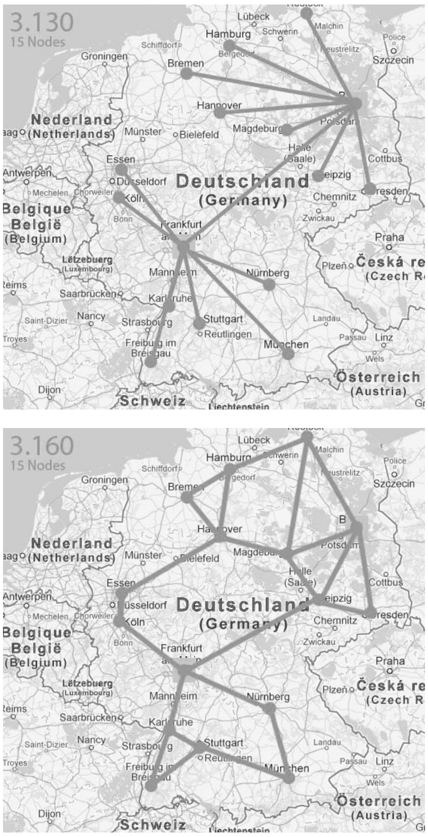


Figure 8.8: *(above)* Two hypothetical networks connecting 15 cities in Germany of approximately equal length. The network at top is a tree while the bottom network is generally a meshwork with redundant connections (every node has at least 2 paths to every other node). The top network characterized as a "double explosion" (see §A8.1), prioritizes speed and might be used, for example, by an airline, but a failure in a central node will have disastrous implications for the network.

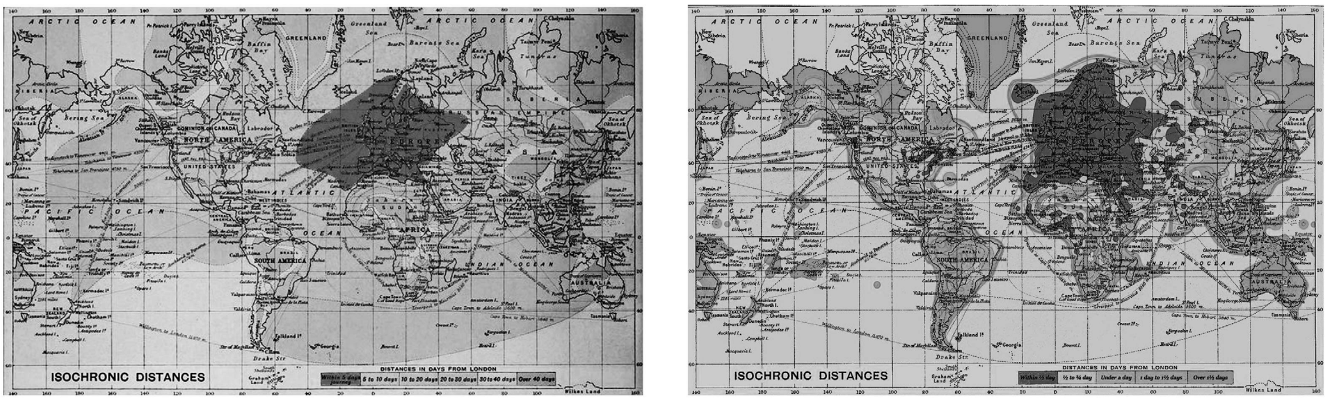


Figure 8.9: *(above)* These two world *isochronic* maps from 1914 and 2014 show travel times from London to other points on the globe. The dark area in 1914 shows what could be reached in 5 days. In 2014, the dark area is considerably larger, and represents only a 1/2 day of travel.

complex infrastructural networks, physical space and time travelled were closely related phenomena; now space and time have lost this character and in certain circles, an individual's movement across the globe approaches the scale-free character of a network such as the world-wide web. Yi Fu Tuan comments on this "collapse of distance" occasioned by contemporary infrastructure in his "Space, Place, and Nature: The Farewell Lecture" remarking it has impacts beyond mere travel times and changes the nature of our friendships and social interactions generally, making them shallower and less consequential.[22]

8.7. *Trees* and *Meshworks*

Networks, whether they be *hierarchical* "trees" or distributive "meshworks" rarely operate as isolated systems and can form hybrid structures through time. When working with networks, it is important to find the proper balance between what De Landa terms the "self-organized *meshworks* of diverse elements, versus *hierarchies* of uniform elements."[23] On the one hand, De Landa argues, "self-stimulating…dynamics cannot emerge when hierarchical components overwhelm meshwork components,"[24] while at the same time, where *meshworks* dominate, "too much connectivity…leads to unstable patterns.[25]

Two comparisons of network structures from Von Neumann and Alexander are again instructive. Von Neumann in his comparison of the computer and the brain, notes that the computer, at least in his day, structured operations in hierarchical, single-path systems so that engineers could detect errors or bugs, while the brain, on the other hand, was such a complex meshwork of connections that it was nearly impossible to identify where, for example, a memory was stored. This leads to a high degree of autonomy in living organism and dependence in the purely hierarchical structure of the computer. Such computational structures cannot innovate, unlike the brain, but this also prevents an "antagonistic relation between the parts" from developing.[26] Von Neumann speculated that if artificial automata were to achieve any degree of autonomy, they would have to develop these redundant pathways and open themselves up to the selective pressures of competition like natural automata. Von Neumann's observation that computers are rigidly hierarchical is still true of most computer systems, but significant parts of the computing industry are quickly moving towards computers with *meshwork* architectures which will likely again revolutionize computation and artificial intelligence in the coming years.

Alexander also offers an instructive analysis of networks at the urban scale in a small piece from the mid 1960s, "The City is Not a Tree." In the text, Alexander compares the abstract structure of a topological *tree* with his definition of a *meshwork*, the *semi-lattice*. He in turn analyzes urban plans from history and from modernist designers, observing that most planned cities fail because they are conceived of as *trees* in contrast to cities which have grown organically, which are comprised of numerous overlapping sets and networks. Planners, especially with modernist notions of efficiency and reductionism, tend to design *trees* because they have a "compulsive desire for neatness and order."[27] Paradoxically, however, the efficient, simple, and clear order of the tree is less stable than the semi-lattice. Alexander observes:

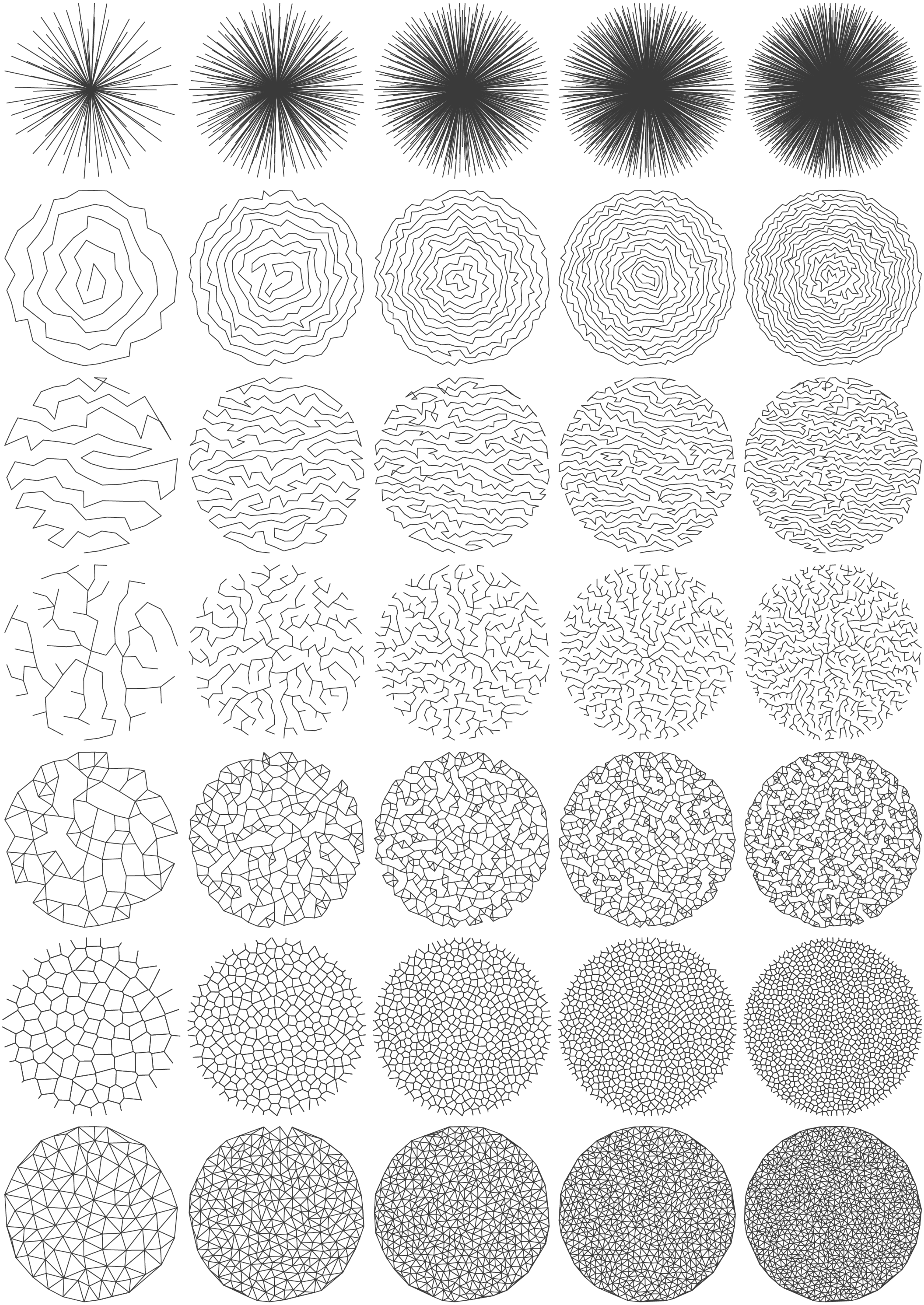
> "It must be emphasized, lest the orderly mind shrink in horror from anything that is not clearly articulated and categorized in tree form, that the idea of overlap, ambiguity, multiplicity of aspect and the semi-lattice are not less orderly than the rigid tree, but more so. They represent a thicker, tougher, more subtle and more complex view of structure."[28]

He goes on to contend that despite intuitive notions that *semi-lattices* are stronger and more stable than *trees*, designers have a very hard time keeping them in their minds eye and of picturing or conceiving of non-treelike organizations. He cites experiments demonstrating that "people have an underlying tendency, when faced by a complex organization, to reorganize it mentally in terms of non-overlapping units. The complexity of the semi-lattice is replaced by the simpler and more easily grasped tree form."[29] Alexander in this essay offers no hints as to how to move beyond this problem. His *Pattern Language, Timeless Way of Building,* and *Nature of Order* texts would offer methodologies he believed could overcome this ingrained human tendency, but it is unclear if attempts to implement his methodology, for example, in New Urbanism projects escape from tree-like thinking and offer a viable model for developing cities with *meshwork* or *semi-lattice* characteristics.

8.8. Summary Conclusion

The contemporary study of form, networks, and systems benefits from an understanding of the potentials and limitations of the mathematical subfield of topology. The relationships between elements (nodes) in a networked space tend to resemble either hierarchical *treelike* structures or lattice-like *meshwork* configurations. While the organization of trees is clear and lack of redundancy increases efficiency in some aspects, the lack of redundancy makes such structures incapable of absorbing change leading to long-term lack of stability. In the context of landscape space, topological thinking is less helpful in purely formal terms, as topological structures related to larger, open systems tend to be evolutionary in nature. The ambiguities of landscape space also make topological relations as expressed in traditional graphs less useful than they might be for architecture. The next chapter will explore these concepts further to see if a topological understanding when combined with notions of *fields* can combine to inform a deeper understanding of landscape space.

Before moving on to these topics, however, this chapter concludes with three sets of algorithms demonstrating various aspects of networks and network behavior. The first set of algorithms (§A8.1) looks at various methods of network formation based on the observations of Peter Stevens, the second set (§A8.2) looks at ideas of transformation in networks. Finally, the third algorithm (§A8.3) presents a method for converting information gathered in databases into graphical representations, in this case of the structure of river watersheds.



Algorithm 8.1. – Network Formation

This section seeks to cover broadly a number of algorithms related to the formation of two-dimensional networks. The first four represent the four basic pattern typologies for non-redundant networks proposed by Peter Stevens and presented in §8.4. Afterwards three paradigms for redundant network formation are proposed—a network which connects each node to its three closest neighbors, a Voronoi diagram, and finally a Delauney mesh. All seven algorithms are deployed on the same random set of points with the same spatial extent, but with an increasing density of points. Finally, several properties of the networks produced are analyzed to demonstrate the efficiencies and inefficiencies of each strategy.

The simplest of the networks is the explosion. Here the algorithm 1) simply finds the point closest to the center of the point cloud, and then 2) connects this point to each other point.

Figure 8.12: *(page opposite)* Overview image of networks derived from the same group of points using the seven different strategies described in this section.

The spiral also starts with a single point. Conceptually, the spiral can be said to start in the center of the cloud, but in order to avoid certain problems with the outer points, in this case the formation is reversed and the outer points are added to the spiral first. To do this the algorithm 1) Finds the point furthest from the center of the spiral and draws a circle through this point, with its center at the center of the spiral. 2) Next a line is drawn from the center of the spiral, through the last point added to the spiral, and continuing to the circle drawn in step one. 3) The intersection point is moved a small amount equal to the average distance between points in the point cloud, in a direction tangent to the circle in either a clockwise or counter-clockwise direction based on the vector of the last segment added (or randomly selected in the first round). 4) The closest point not yet in the network to the translated point from step 3 is added to the spiral.

Similar to the spiral, the meander represents a more chaotic flow of matter or energy and is by far the most difficult of the four basic patterns to model. Various algorithmic strategies were tried but all had defects. The most effective strategy demonstrated here 1) starts the algorithm at the point with the smallest Y value. 2) A radius of a parametrically variable dimension is drawn at this point, and all points within this radius are considered to be added. In this example the circle has a radius 1.3 times larger than the average distance between points in the point cloud. The final decision on which point to add is 3) the point within this radius with the smallest Y value. The algorithm then 4) repeats this process with the radius always determined starting at the last value added. In general, the algorithm produces non-redundant meanders, but errors do appear, especially towards the algorithm's final steps.

The final of the four non-redundant networks, the branching network, is in contrast to the meander very easy to model and error free. The algorithm starts by 1) ordering all the points in the point cloud based on their distance from the center of the point cloud. 2) It then selects the point closest to the center of the point cloud (the first item in the ordered list of points) and adds this to the network. 3)The algorithm then gradually goes through the list, taking the next ordered point, and drawing a line from this point to the closest node already added to the network. Once a node is added to the network, it is removed from the ordered list from step one, and moved to a second list—nodes already in the network.

There are far more strategies for creating redundant networks as explained in §8.5 and only three are briefly presented here, primarily to run comparative tests with the non-redundant networks. The first of these redundant networks has a very simple algorithmic logic. 1) For each point, the three closest points are identified, and a line is drawn connecting this point with its neighbors. Then 2) duplicate lines are removed.

Finally, two algorithmic methods for generating meshes are shown in the last two rows of the overview image but are not explained in any detail here. The first is the Voronoi mesh, named for the mathematician Georgy Voronoi which in contrast to the other methods, creates lines not connecting the nodes themselves, but creates seams at all possible points in 2D space which are equidistant from the two closest points. The intersections of these seams represent points equidistant from the three closest points.[30] The Delauney mesh is generated by a mathematically more complex series of algorithms based on the work of the mathematician Boris Delauney where triangles are created between points such that a circle drawn through the three vertexes of the triangle added contains no additional points within its circumference.[31] The Delauney mesh is closely related, and is the dual of the Voronoi diagram. For the images generated here, a standard tool for generating both the Voronoi and Delauney mesh developed by the programmers of the Grasshopper plugin was used.

Figure 8.13: *(page opposite)* Properties of the four non-redundant network structures, as well as two redundant structures, the 3*n*-network (network where each node has a node degree of 3) as well as the Delauney triangulation.

For each network, the same initial area is populated with 50, 100, 300, 500, 700 and 1000 points, and a network is drawn to connect the points using one of the algorithmic strategies. The overall length and the average distance between two randomly selected nodes in the network are then compared.

Once all of these networks were created, a series of tests using a shortest path algorithm were run on each network to determine the average distance between any two random nodes in the network, using only the associated edges for each network strategy. The results of these tests, comparing average network distance between nodes with the cumulative length of all the network's edges, i.e. the total network length, are summarized in table xxx. For the non-redundant networks, the explosion always maintains a lead in minimizing the average distance between any two random points, but its overall length increases much faster than the other networks as points are added. On the other hand, branching networks while having only slightly higher average distances than the explosion networks, are very economical in minimizing the total network length. The efficiency of this type of networks gives hints to as why it is found in so many natural systems.

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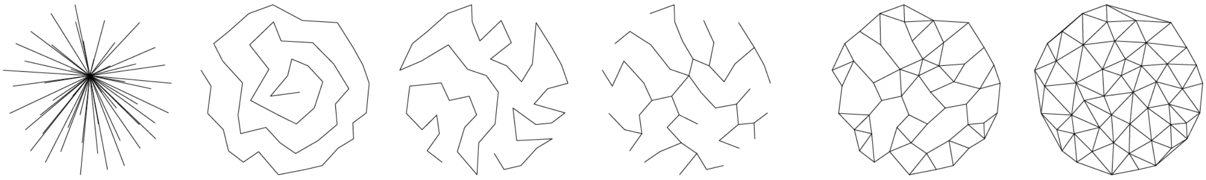
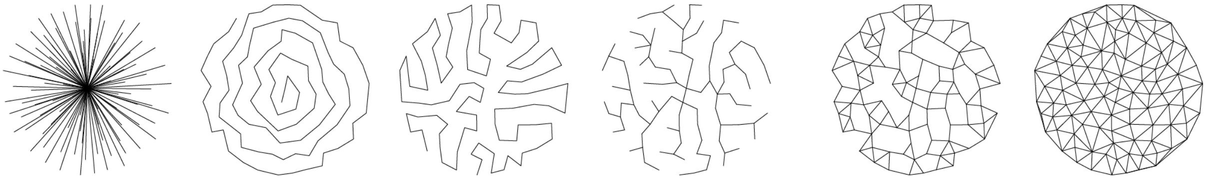


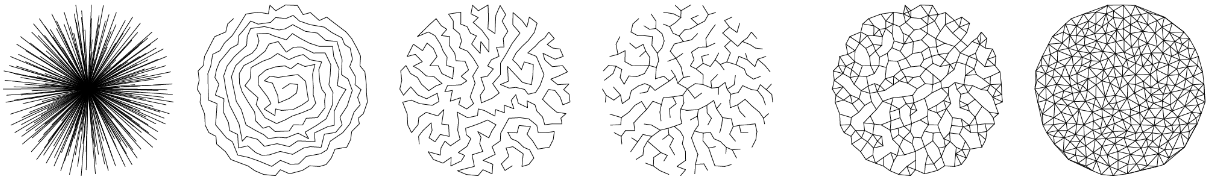
overall length	443	168	165	146	289	486
average dist 2p	17.6	59	58	19.8	14.3	12.6

100



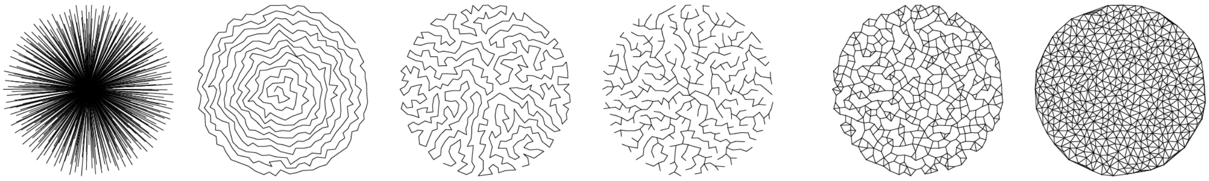
overall length	834	238	234	200	400	702
average dist 2p	16.5	79	78	19.6	14.3	12.2

300



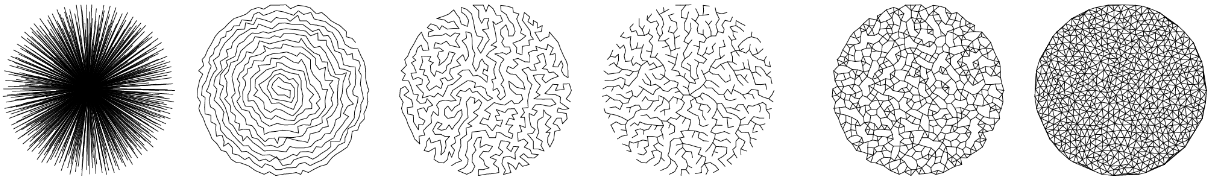
overall length	2458	424	385	343	664	1249
average dist 2p	16.4	143	127	20.4	13.6	11.8

500



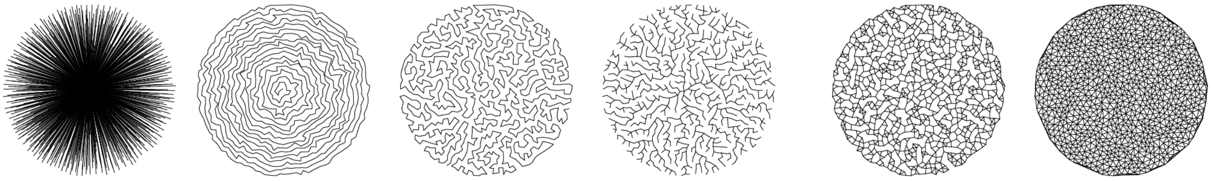
overall length	4075	530	487	443	829	1633
average dist 2p	16.3	173	160	22.5	13.5	11.6

700



overall length	5721	642	574	524	990	1944
average dist 2p	16.5	205	183	21.1	13.7	11.6

1000



overall length	8149	774	679	625	1186	2316
average dist 2p	16.4	260	225	21.6	13.4	11.8

Figure 8.14: *(below)* Diagram of algorithmic formation of explosion, spiral, meander, and branching networks (*page opposite*) All except for the „explosion“ network use a recursive procedure to form the network.

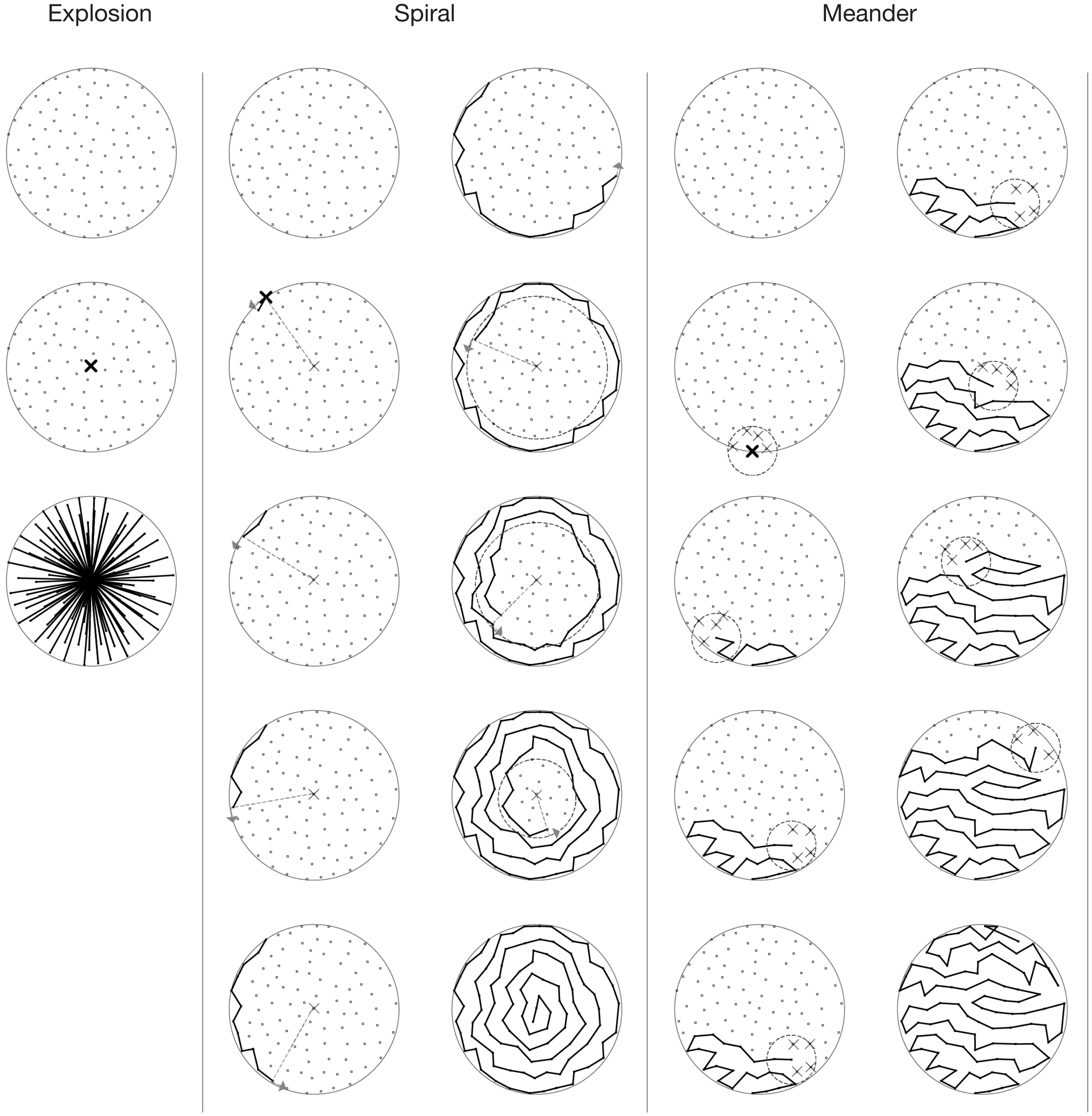
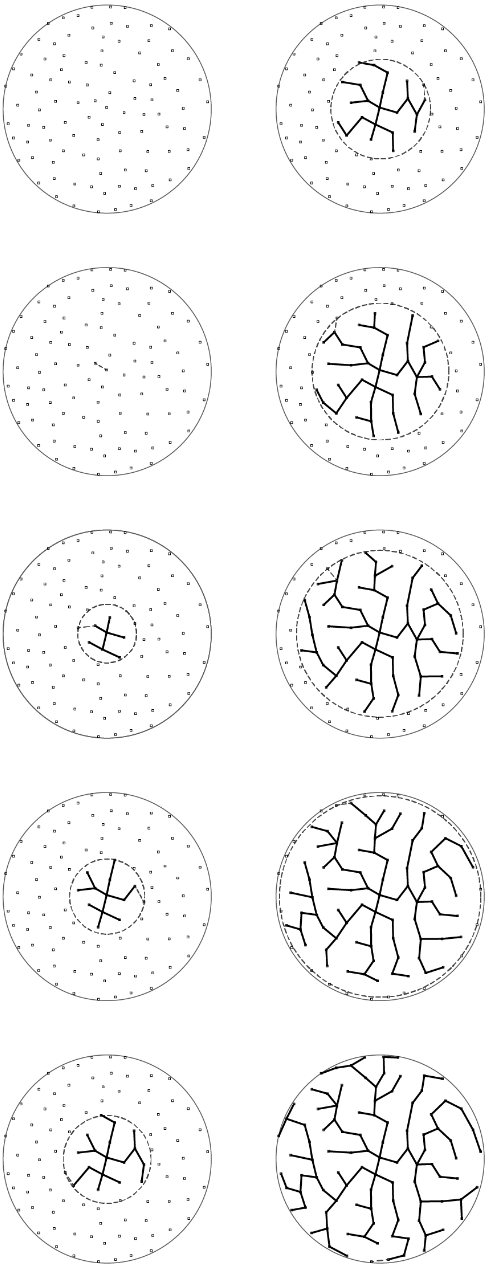
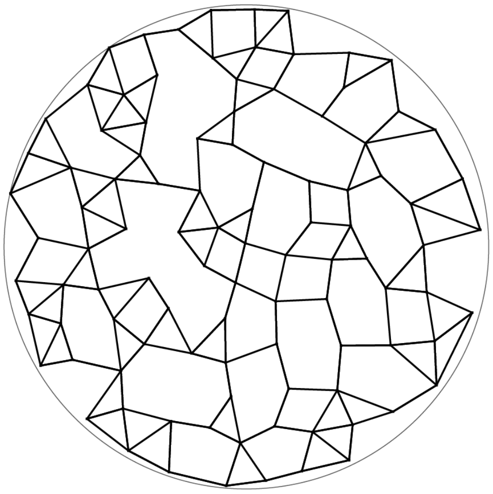


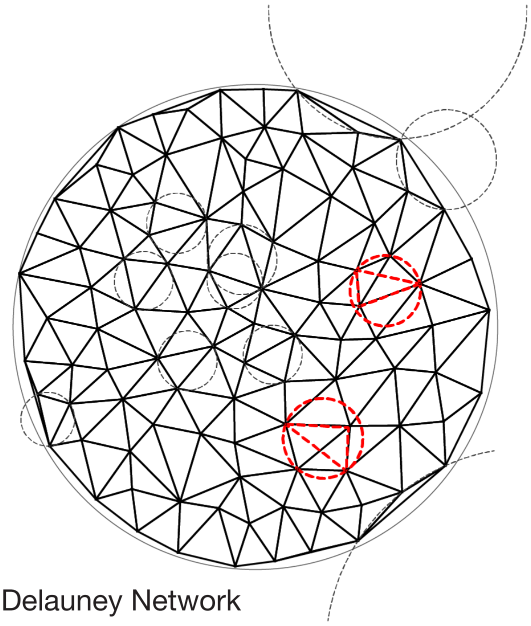
Figure 8.15: *(right)* Diagram three networks exhibiting redundancy-- a 3*n* network, Delauney, and Voronoi network. These are formed through non-recursive algorithmic strategies.

Branching Structure

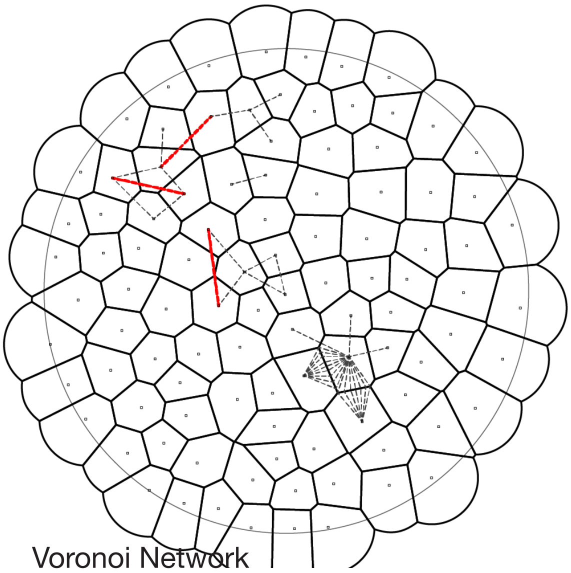




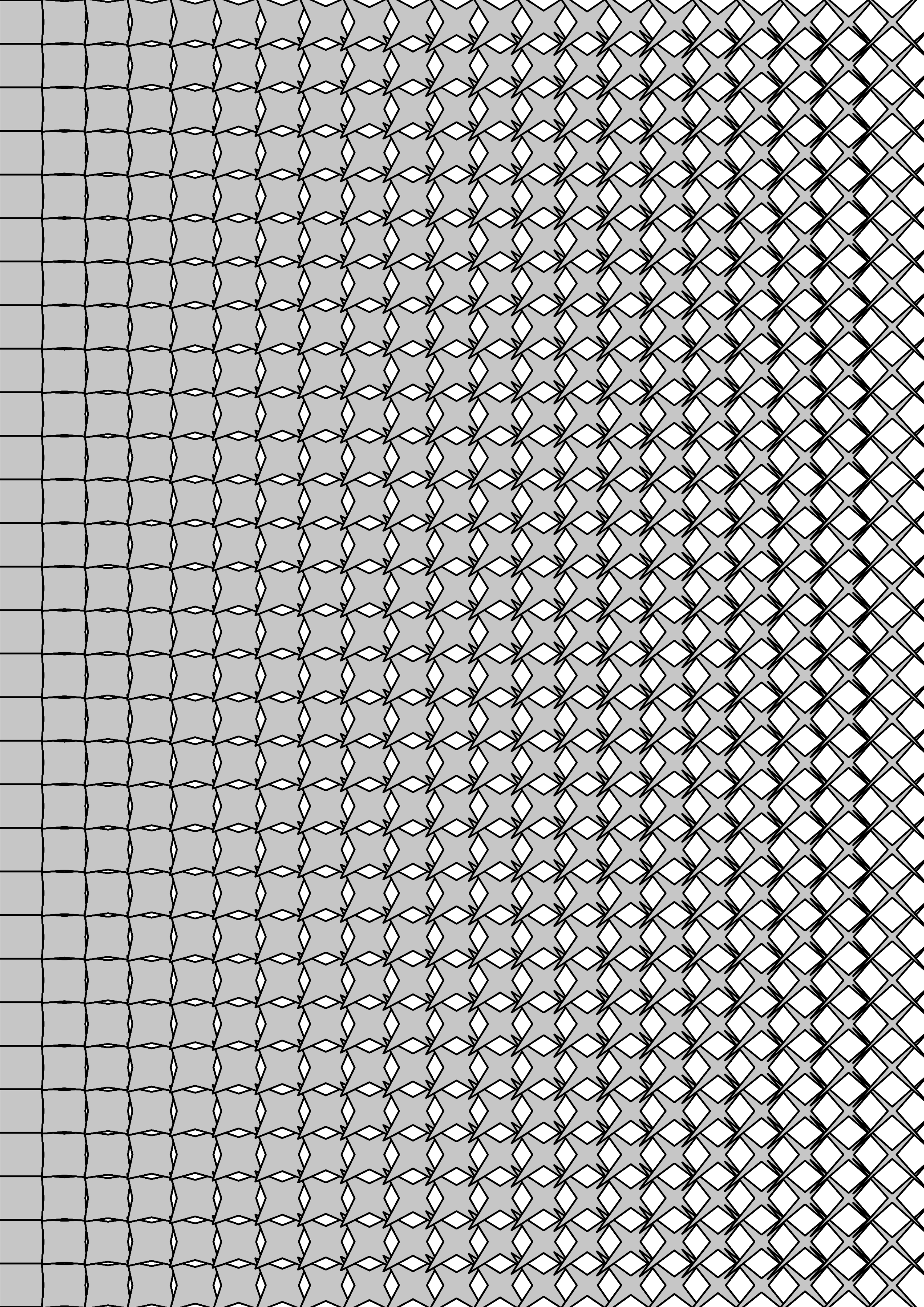
3*n* Network



Delauney Network



Voronoi Network



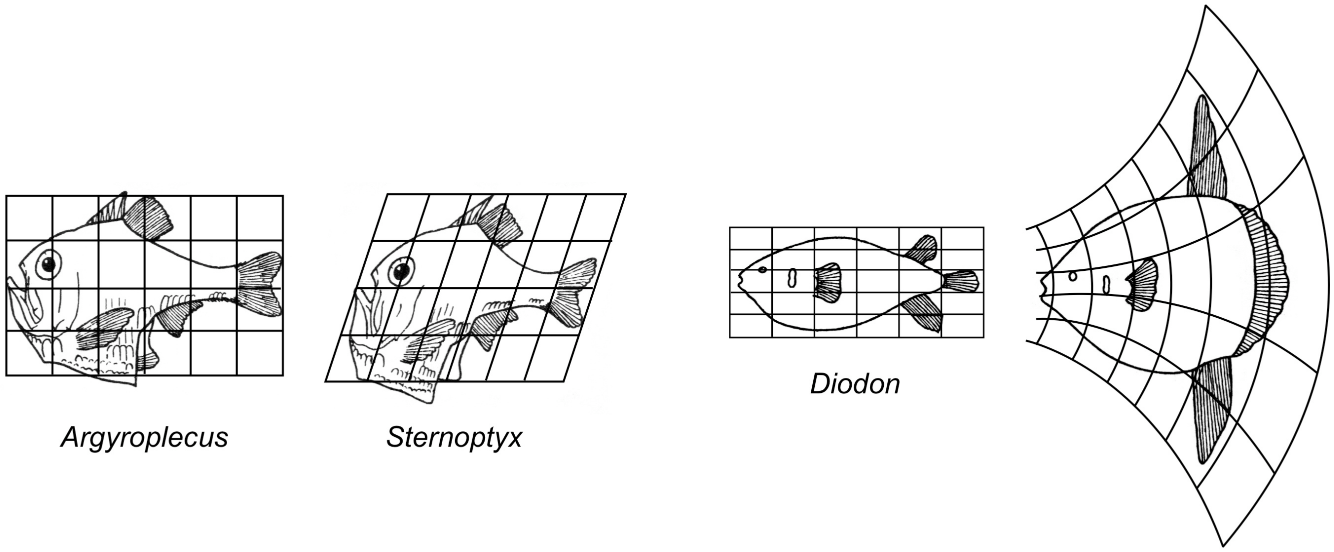
Algorithm 8.2. – Topological Transformations

The previous example focused on the logics of “emergent” networks free from the agency of a designer. Network thinking can also be used for aesthetic purposes to create repeating patterns or structures. When a designer has an understanding of how a pattern is structured, it is then opened up to manipulation and transformation. As mentioned in §8.4, two dimensional, redundant networks with a regular structure can be described in terms of one of seventeen different “wallpaper” groups. These groups are in term classified in terms of various symmetries. Symmetrical relationships are determined if specific operations— specifically translations (shifting or moving), rotations, or reflections—will change the pattern. By controlling how these symmetries are deployed or relate to one another, complex patterns can be created. Here the focus is on the artistic aspects of transformations and deformations, but the principal can also be applied to the study of natural form. D’Arcy Thompson famously in *Growth and Form* made comparisons between similar types of organisms with a similar underlying topology and demonstrated how various species can be considered as rather straightforward deformations of closely related species. In his method, organic structures are mapped to a Cartesian grid which is then progressively transformed with shears, taperings, and rotational transformations, similar to the shifts described in the wallpaper groups.[32] At a certain point this method breaks down where the fundamental topology of the organism changes, but it is helpful for explaining the wide-variety of similar forms in nature.

In this example of a topological transformation, small progressive translations of the nodes of cells are deployed to create a complex, evolving pattern. For each cell, the fundamental relationship of the edges to their respective nodes remains unchanged, but as the pattern evolves, the relationship of edges to neighbors introduces new topological complexities. While the underlying logic of such transformations is rather straightforward, performing these tasks algorithmically can present a significant challenge. The biggest obstacle is properly structuring the data and executing the transformations only on the intended data points.

Figure 8.16: *(page opposite)* Pattern created through a progressive topological transformation (translation). The midpoint of each square in the far left colum is progressively moved towards the square center in the columns progresing to the right. The four corners of the initial squares are likewise gradually moved away from the shape‘s center in a diagonal vector.

Figure 8.17: *(below)* D‘Arcy Thompson mapped topological changes in organisms by mapping a grid of points to certain key points on a body. The grid and bodies undergo evolutionary distortions and transformations. Thompson 1062-1064.

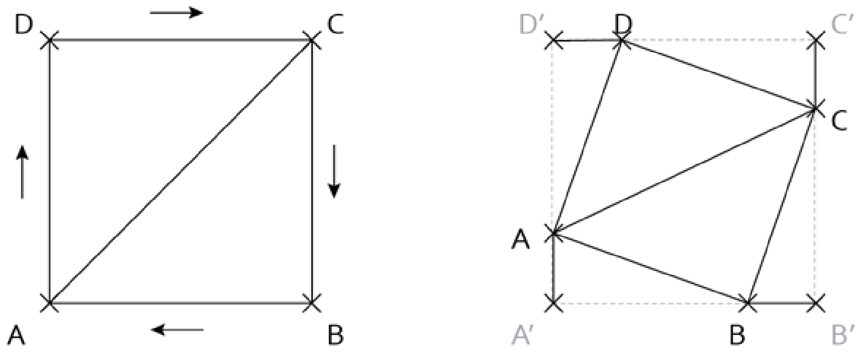


Argyroplecus

Sternoptyx

Diodon

Orthagoriscus



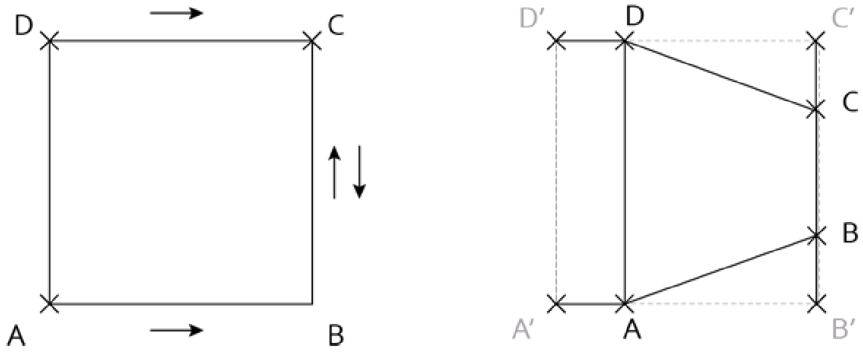
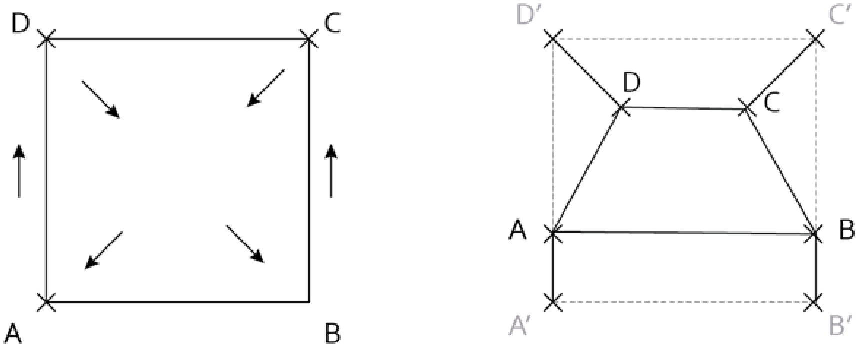
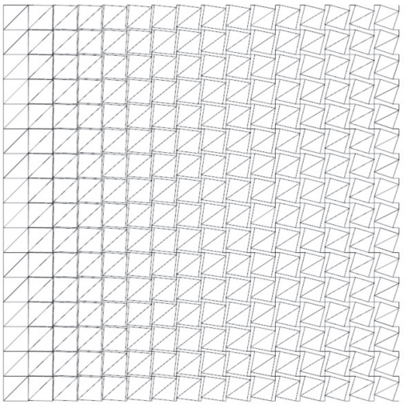
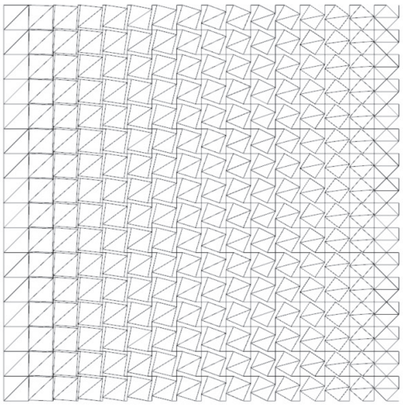


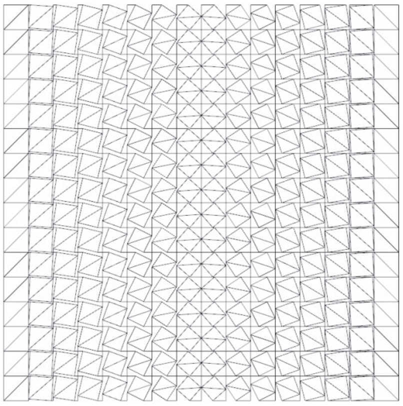
Figure 8.18: *(middle left)* Topological changes in a single cell, showing movment of nodes and edge relationships which are preserved between points which have moved.

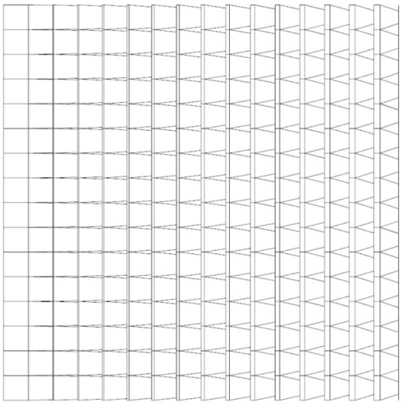
Figure 8.19: *(opposite)* When applied to a larger structure, progressive topological deformations produce complex patterns.

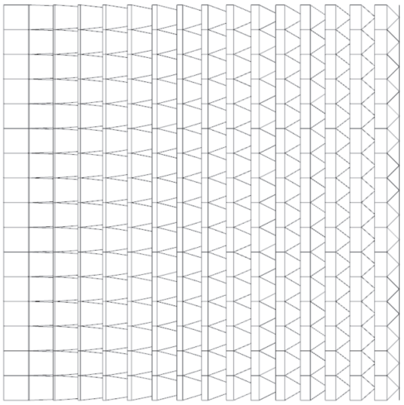


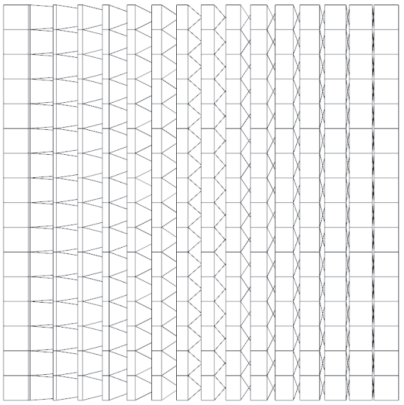


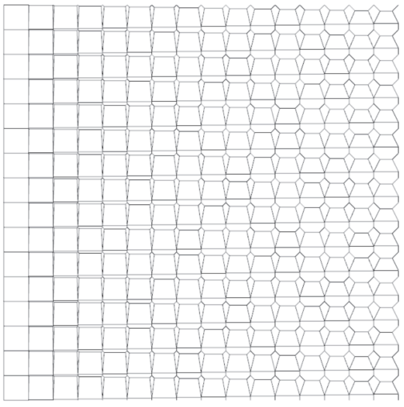


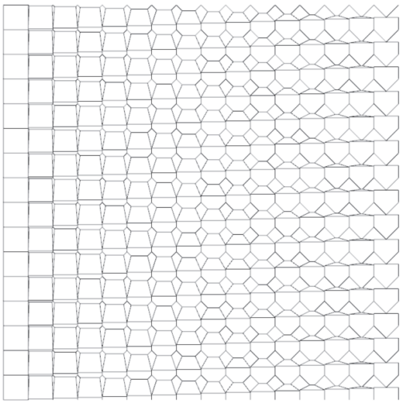


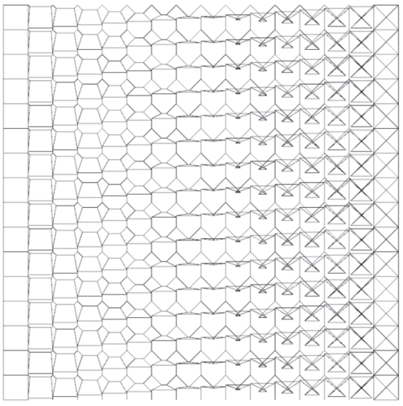


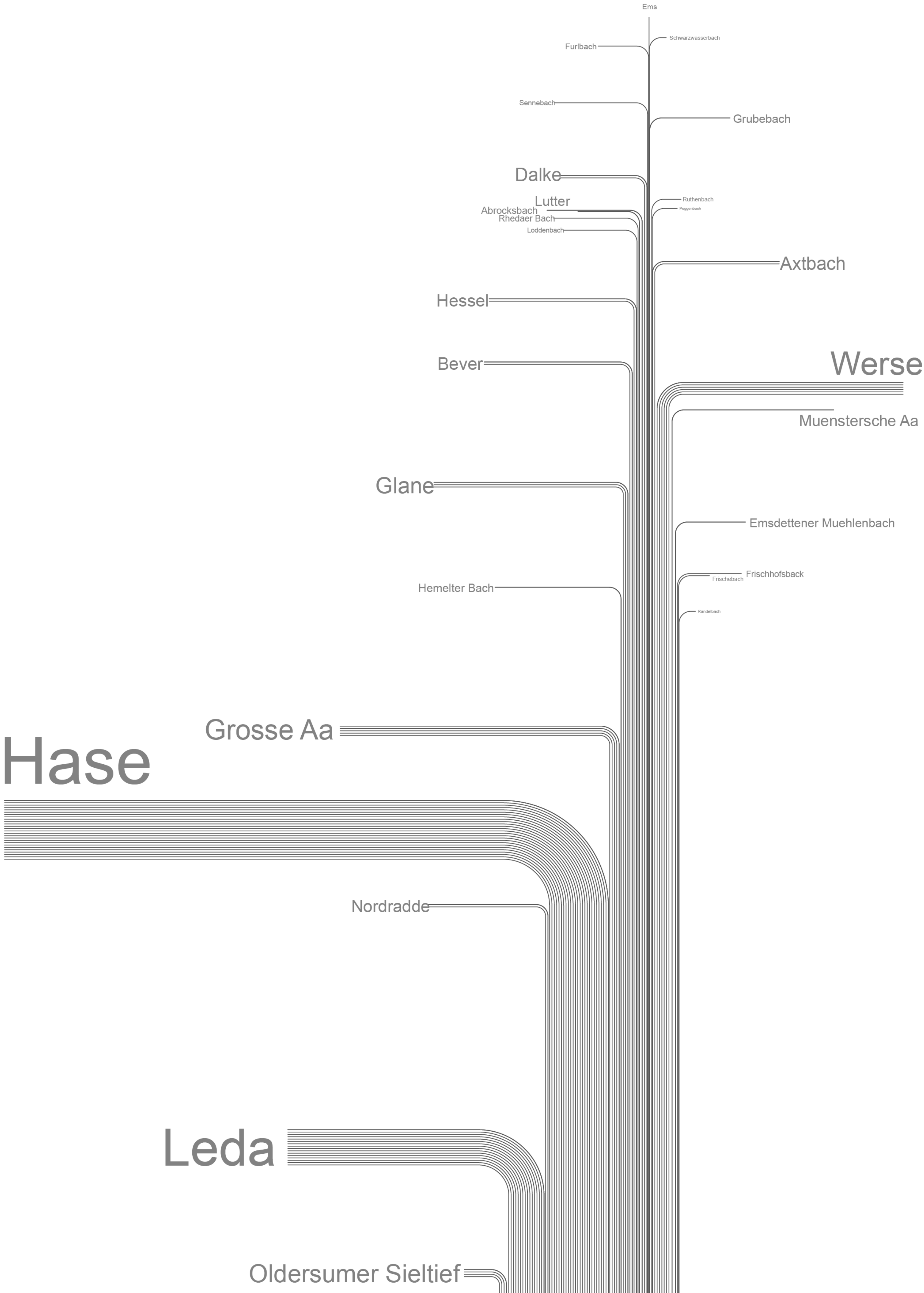











Ems
Schwarzwasserbach
Furlbach
Sennebach
Grubebach
Dalke
Lutter
Ruthenbach
Poggenbach
Abrocksbach
Rhedaer Bach
Loddenbach
Axtbach
Hessel
Bever
Werse
Muenstersche Aa
Glane
Emsdettener Muehlenbach
Frischhofsback
Frischebach
Hemelter Bach
Randelbach
Grosse Aa
Hase
Nordradde
Leda
Oldersumer Sieltief

Algorithm 8.3. – Converting Data Structures to Graphs

This algorithm in contrast to many of the other algorithms explored in Part II of this thesis does not demonstrate any particular principles of emergent geometry in systems, but instead demonstrates the power of algorithmic approaches to working with and visualizing large datasets. A promising aspect of algorithmic approaches is to make sense out of large datasets. If data is well structured and if an algorithm is created to work with the structure of the dataset, visualizations can be quickly created and updated as data points change.

In this example, a fairly simple algorithm was created to draw what is known as a "Sankey Diagram," a powerful visualization technique for explaining the flows of energy, matter, or information. In a Sankey diagram, the width of lines correspond to the amount of energy or material in a particular network, and with nodes and edges structured according to how this energy or material moves through the system.[33] In this particular case, the diagram is of the flows of water in the watershed of several rivers. The most time intensive part of this process was actually collecting data on the various rivers which were diagrammed. For this test, open source data on the Leine, Aller, and Ems rivers in northern Germany were collected and compiled into a table. All of the major tributaries of the three respective watersheds are identified with the following data points: 1) whether it is a left or right tributary, 2) name of tributary, 3) distance from river mouth to branching of tributary, 4) length of tributary after branching, 5) area of watershed associated with each tributary.

Using these data points, for each tributary a line is drawn from the river's mouth, to the point of branching, where it then turns to the left or right, continuing for the total length of the tributary after branching. The tributary flow is estimated here based on the watershed size of a tributary since consistent values for river flow could not be found. This determines the thickness of each tributary line.

The first test shown on the next page shows how this process is developed for the Leine River in Niedersachsen/Thüringen (Fig. 8.23). When similar data points are gathered for the Ems and Aller rivers (Figs. 8.20, 8.24), this data can be imported and the diagram will update in seconds based on the new dataset. Another potentially powerful use of this dataset is to show variable, changing processes. As is well known, rivers can vary in their flow significantly over the course of the year. If a Sankey diagram is linked to real-time sensors of current river volumes, the Sankey diagrams can be updated in real-time to provide a visualization helpful for researchers or communicating with the general public. Fig 8.24 also shows how the relative flows of tributaries of the Aller River might change at particular times of the year and how the diagram could be updated in real time.

Figure 8.20: *(page opposite)* Sankey diagram of the Ems River watershed, per the process described in this section.

Figure 8.21: *(right)* Topology of lines for diagram based derived from a well-structured dataset.

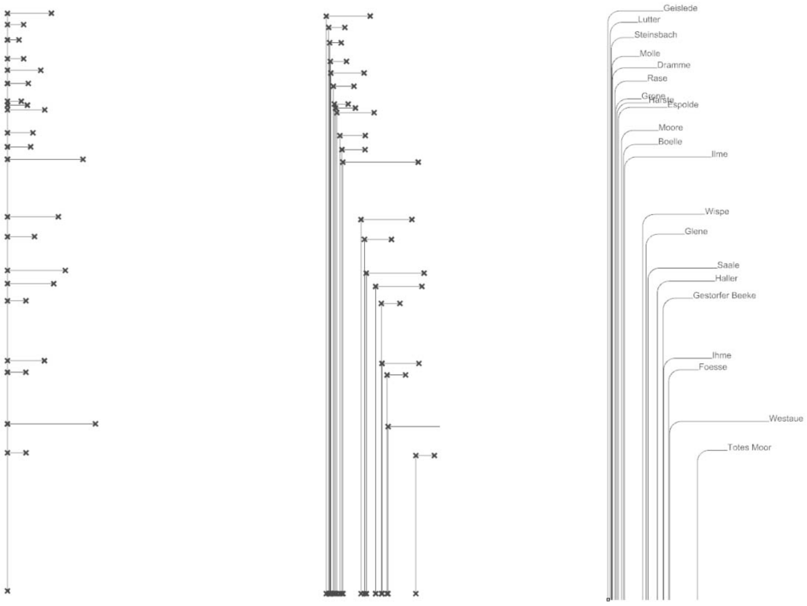


Figure 8.22: *(below, left)* Data in a comma seperated variable (*.csv) list for the Leine River watershed.

Figure 8.23: *(below, right)* Diagram of the Leine River watershed derived from the *.csv data show to the left in Fig. 8.22.

```
R, Grindau, 6.1, 26, 11, 35
R, Grosse Beeke , 12, 26, 5, 30
R, Juersenbach, 18.9, 26, 6, 49
R, Auter, 24, 26, 10, 113
L, Totes Moor, 59.7, 26, 8, 56
L, Westaue, 72.2, 35, 38, 600
L, Foesse, 94.5, 53, 8, 20
L, Ihme, 99.5, 48, 16, 110
R, Innerste, 121.5, 58, 99.7, 1264
L, Gestorfer Beeke, 125.4, 58, 8, 13
R, Roessingbach, 125.5, 58, 14, 36.3
L, Haller, 132.8, 70, 20, 124
L, Saale, 138.5, 73, 25, 202
R, Despe, 142.1, 74, 12, 47
L, Glene, 153.1, 74, 11.7, 40
R, Warnebach, 156, 74, 8, 27
L, Wispe, 161.7, 74, 22, 74
R, Gande, 175.6, 74, 41, 114
R, Aue, 177.7, 103, 23, 113
L, Ilme, 186.5, 105, 32.6, 393
L, Boelle , 191.9, 110, 10, 21
R, Rhume, 192.8, 116, 48, 1193
L, Moore, 198, 118, 11, 43
R, Beverbach, 206.9, 120, 14, 35
L, Espolde, 207.9, 126, 16.1, 65
R, Rodebach, 208.1, 130, 8, 20
R, Weende, 208.9, 135, 9.2, 18.6
L, Harste, 209.9, 138, 8.6, 29
L, Grone, 211.6, 140, 6, 26
R, Lutter, 211.7, 144, 8.1, 38
L, Rase, 219.3, 150, 9, 23.8
R, Garte, 219.4, 152, 23, 87.2
R, Wendebach, 223.4, 162, 16.2, 36
L, Dramme, 225, 161, 14.4, 53
L, Molle, 230, 182, 7, 10
R, Schleierbach, 232.4, 191, 6, 15
R, Rustebach, 236.8, 210, 8, 13
L, Steinsbach, 238.1, 215, 5, 15
L, Lutter, 244.7, 233, 7, 21
R, Beber, 245.4, 237, 7, 30
L, Geislede, 249.6, 260, 19, 52
R, Steinbach, 255.3, 276, 6, 14
R, Etzelsbach, 258.4, 293, 5, 13
R, Leine, 264.2, 337, 7, 18
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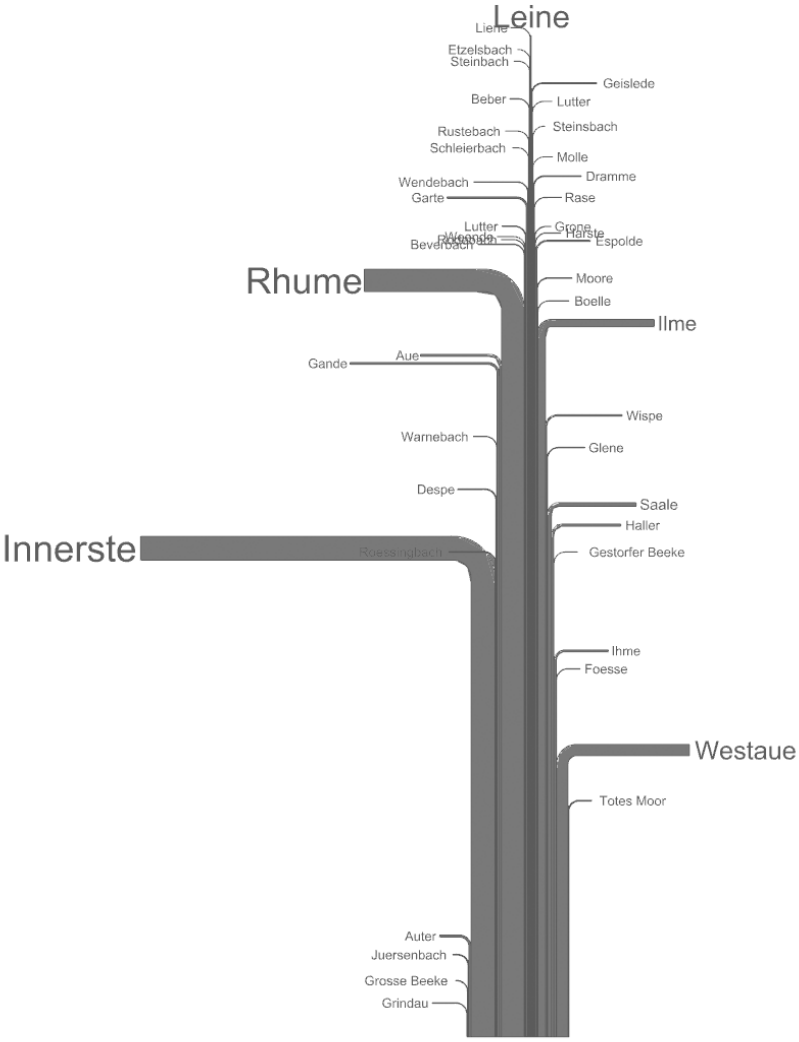
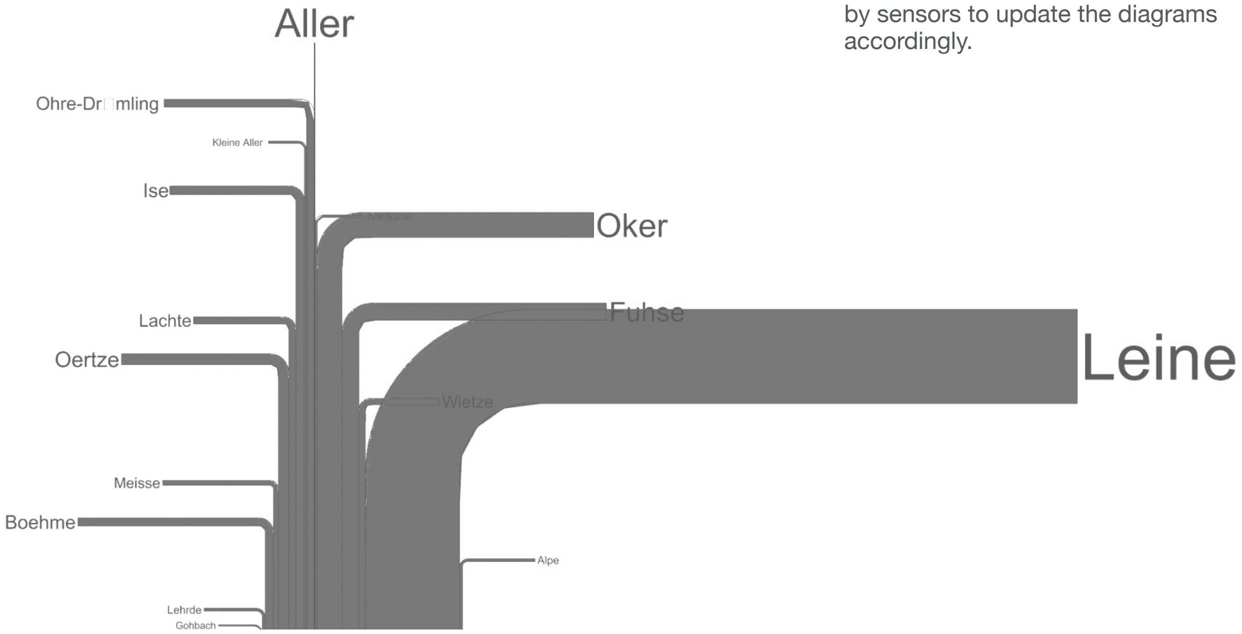
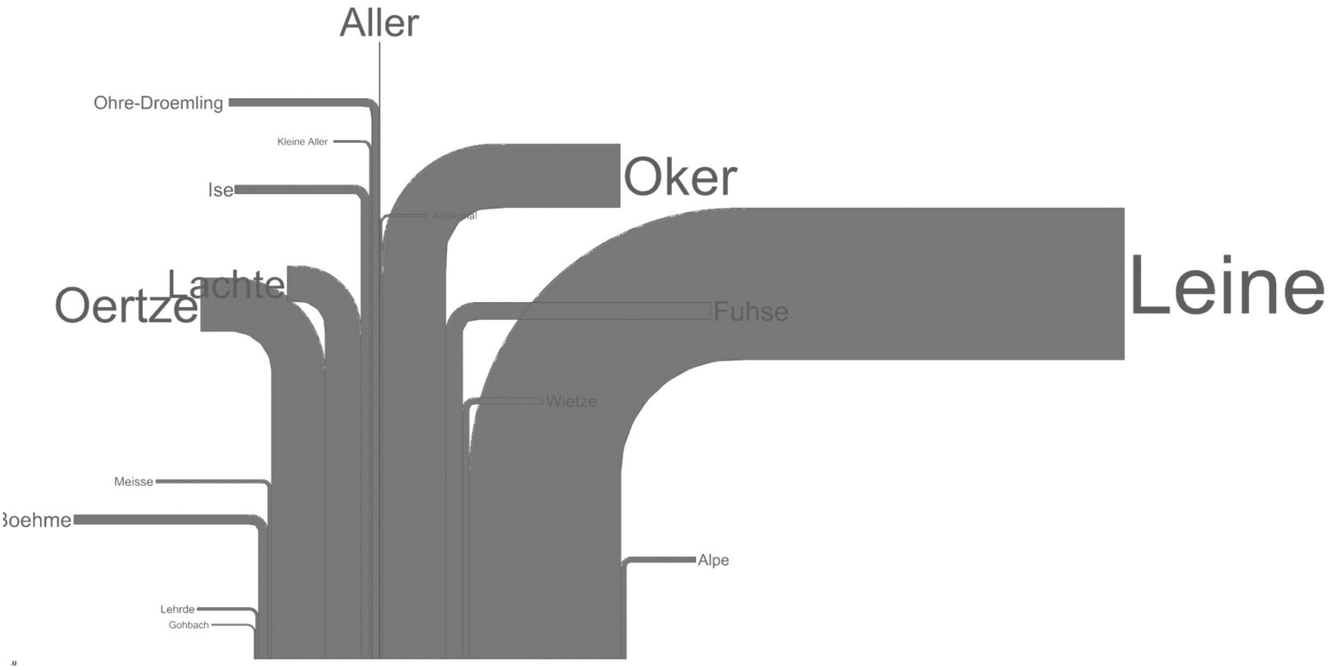


Figure 8.24: *(below)* Sankey diagram for the Aller watershed updated with various values representing variable flows throughout the year. These values could be monitored in real time by sensors to update the diagrams accordingly.





Endnotes

1 Henri Poincaré, *Science and Hypothesis* (London: Walter Scott Publishing Co, 1905), 20.

2 Sanford Kwinter, “Playboys of the Western World.” ,29-30.

3 See §2.11., Chapter 2 note 65 and note 66.

4 John Stillwell, ed. “Translator’s Introduction,” in *Papers on Topology:* Analysis Situs *and Its Five Supplements.* (2009), 1-2, 6.

5 S. Novikov, “Henri Poincaré and XXth Century Topology,” *International Solvay Institutes For Physics And Chemistry: Proceedings of the Symposium Henri Poincaré* (Brussels, 8-9 October 2004): 4.

6 *Ibid.*

7 D’Arcy Thompson, *On Growth and Form* (Cambridge: Cambridge University Press, 1945), 284, 328, 1028.

8 Peter Stevens. *Patterns in Nature.* (Boston: Little, Brown and Company, 1974), 3-4.

9 Ibid, 37-48.

10 Ibid, 37.

11 Stevens, 37-48.

12 Simon Bell, *Landscape: Pattern Perception and Process. 2nd ed.* (London: Routledge, 2012), 20-27.

13 John von Neumann, *Theory of Self Reproducing Automata,* ed. and completed by Arthur Banks (Urbana: University of Illinois Press, 1966), 57-58.

14 *Ibid,* 73.

15 Stevens, 11-16.

16 Christopher Alexander, *Notes on the Synthesis of Form* (Cambridge, MA: Harvard University Press, 1964), 6-7.

17 Donella Meadows, *Thinking in Systems.* (London: Earthscan, 20098), 18.

18 According to Howard J. Dittmer, University of Iowa. As cited in Stevens, 12. This was just one of a number of similar observations made in various sciences just before the dawn of the age of the fractal.

19 D.K. Arrowsmith and C.M. Place. *An Introduction to Dynamical Systems* (Cambridge: Cambridge University Press, 1990), §4.1

20 Manuel De Landa. *A Thousand Years of Nonlinear History.* (New York: Swerve, 2000), 14.

21 Christopher Smith, “The population of Mesolithic Britain”, *Mesolithic Miscellany,* vol. 13, no. 1. Cited in George Monbiot, *Feral: Rewilding the Land, Sea and Human Life.* (London: Penguin, 2013), 10.

22 Yi-Fu Tuan. “Space, Place, and Nature: The Farewell Lecture.” *Yi-Fu Tuan Online.* yifutuan.org/dearcollegue.htm. Accessed 1 Mar 2018.

23 De Landa, 32.

24 *Ibid,* 34.

25 *Ibid,* 41.

26 Von Neumann, *Self-Replicating Machines,* 73.

27 Christopher Alexander. “The City is Not a Tree.” (1965), PDF File. www.bp.ntu.edu.tw/wp-content/uploads/2011/12/06-Alexander-A-city-is-not-a-tree.pdf. (Accessed 1 Mar 2017).

28 *Ibid,*

29 *Ibid, 19*

30 Georgy Voronoi, "Nouvelles applications des paramètres continus à la théorie des formes quadratiques,” *Journal für die Reine und Angewandte Mathematik,* 133 (1908): 97–178.

31 Boris Delaunay, "Sur la sphère vide," *Bulletin de l'Académie des Sciences de l'URSS, Classe des sciences mathématiques et naturelles,* 6 (1934): 793–800.

32 D’Arcy Thompson, “The Theory of Transformations,” in *On Growth and Form*, 1033-1090.

33 Phineas, “Sankey Definitions,” *Sankey Diagrams.* www.sankey-diagrams.com/sankey-definitions/, (accessed 5 Apr 2018).

Chapter 09 – Smooth Space and Striated Space

“Nature is one and continuous; the landscape cannot truly or happily be parceled, subdivided by a geometrical surveyor’s treatment.”[1]

9.1. Introduction

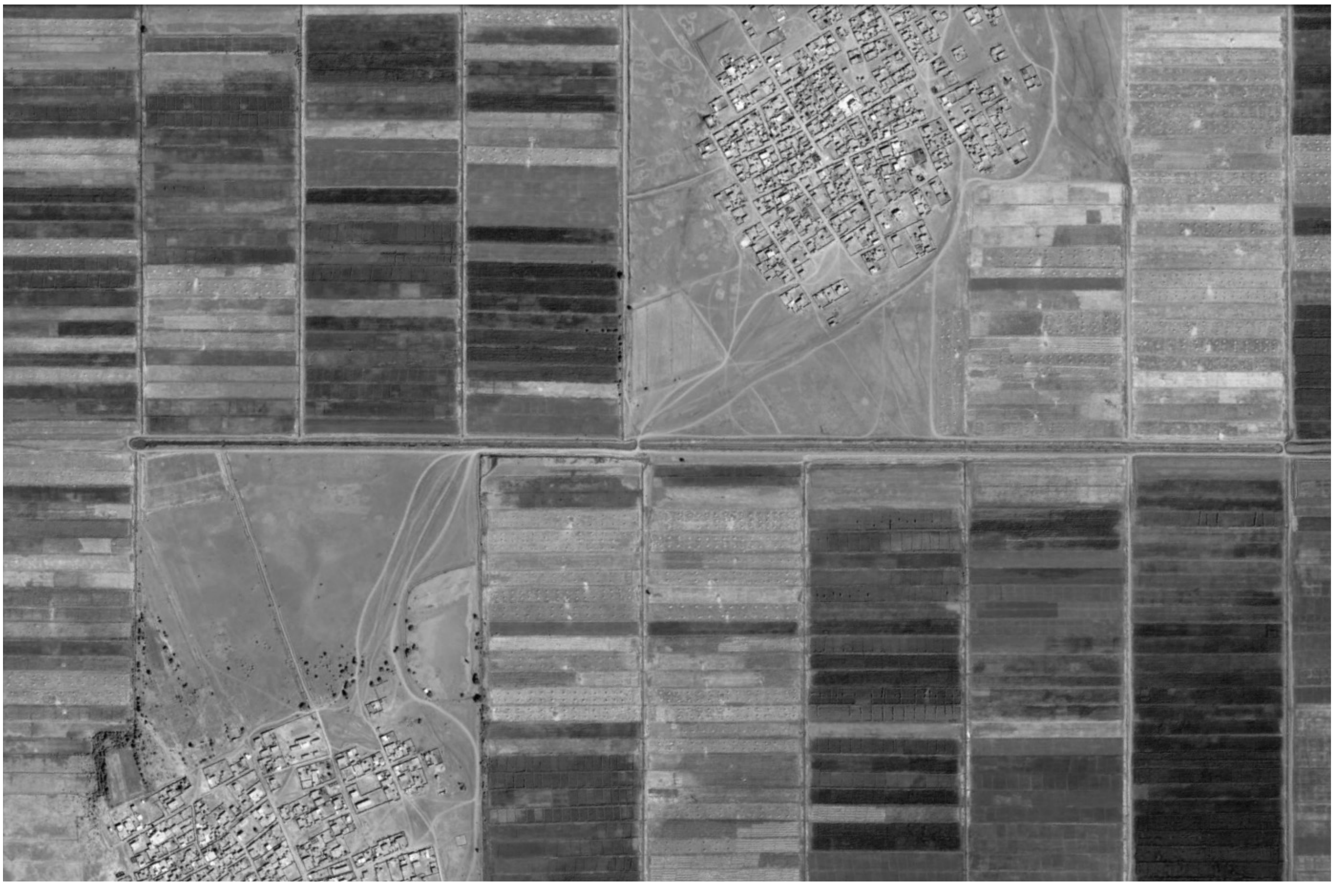
Gazing upon the surface of earth from the perspective of space, three general types patterns emerge. From the distant view, perhaps the long arcs and sweeping curves of mountain ranges and deserts are most recognizable, along with the gentle gradients between wet and dry ecosystems. A closer look reveals the second set of patterns--networks, grids, and tessellations—a striated tapestry of repetitive and discreet elements. Between the continuous spaces evoked by the amorphous curves and gradients of the first group and the discreet spaces implied by the articulated networks on the second, there is third space born out of conflict leaving behind a zone of ambiguity—a fractal pattern neither continuous nor articulated. In common parlance, the continuous forms of the first group of patterns and fractal traces on the landscape in the third are often seen as the handiwork of nature—spaces of disorder—while the articulated and discreet markings on the land are seen as highly ordered human artifacts, but the reality is of course much more complex. Both nature and culture produce articulated and amorphous spaces.

Figure 9.0: (*page opposite*) Textured concrete next to rough rip-rap blocks on the Wilhelmshavener Seedeich.

According to the second law of thermodynamics, the universe is on an inexorable path towards a condition of maximum entropy and equilibrium, but in systems *far from equilibrium*, such as our Earth, “radical, productive and unforeseeable” behaviors emerge, along with increasing levels of order and differentiation.[2] This is not, however, a linear process, and increasing levels of order and stratification require more and more energy to maintain, and eventually forces of increasing instability work to either bring the system back into equilibrium, or to invent new paradigms allowing the system to grow even more but in an altered state. These forces of instability then should not be seen as wholly negative, instability being a “precondition of creativity.”[3] The project to understand the nature of the non-linear interaction between various types of organizing and disorganizing processes is explored in the works of Deleuze and Guattari, who articulate a theory of “smooth” and “striated” spaces in their work *Thousand Plateaus*. This concept shifts the classic man vs. nature dialect to a new position, where both nature and culture contain organizing and disorganizing tendencies.

9.2. Deleuze and Guattari – *Thousand Plateaus*

A recurring theme in Deleuze and Guattari’s *Thousand Plateaus* is the distinction between two types of spaces—what they term *smooth space* and *striated space*. The articulation of the smooth has served as an inspiration to designers of a more philosophical bent since then, and increasingly so after the publication of Deleuze’s treatise *The Fold: Leibniz and the Baroque*, which together with the development of NURBS curves in 3D modeling programs, kicked off the “Blobitecture” phase of the 1990s.[4] Parallel developments seen in landscape architecture include the work of George Hargreaves,



who used first clay models and then CAD modeling to explore the smooth and continuous variation of the earth's surface,[5] or in the work of Charles Jencks, whose Garden of Cosmic Speculation weaves ideas from complexity theory into what Prominski and Koutroufinis critique as a "physics theme park."[6] Their critique of Jenck's work can apply to much of the work of this period, where the authors committed a "'formalistic fallacy'—the error of mistaking the abstract for the concrete."[7] They missed the mark by creating static crystallizations of a concept interested primarily in the indeterminate, the non-hierarchical, and in the open-ended. In *Thousand Plateaus*, smooth space is associated with ideas of nomadism, vectors of movement, and undifferentiated matters, as well as with a number of other equally iconic concepts created by Deleuze and Guattari, including the Rhizome, the Body Without Organs, and the War Machine.[8] Smooth space is contrasted with striated space—spaces of settlement, of gridded and hierarchical systems, and with the State Apparatus.[9] Smooth space is "vectorial, projective, or topological" whereas striated space is "metric."[10] Adapting a concept from Pierre Boulez, Deleuze and Guatarri declare that smooth space "is occupied without being counted" while striated space is "counted in order to be occupied."[11]

Deleuze and Guattari distinguish the spatial qualities of the smooth and the striated and the manner in which the respective spaces are produced initially with a comparison to the production of various types of fabric, specifically contrasting the fabrics woven on looms by sedentary populations with the fabrics of nomadic peoples, such as felts and patchworks. A fabric produced on a loom has a directionality and is bounded, at least in one direction, by the width of the loom. Felts, on the other hand, being a textile composed of mashed together threads of various lengths and with no directionality, is theoretically boundless, as is its cousin the patchwork, which can be extended infinitely so long as enough material to be recycled is available.[12] Likewise, smooth spaces reflect qualities of the infinite, of boundlessness—deserts, oceans, ice sheets and steppes being archetypal smooth spaces[13]—whereas striated spaces always have limits and discreet textures, as seen in the "forest, with its gravitational verticals" and in the space of "agriculture, with its grids and generalized parallels."[14] The two types of spaces—smooth and striated— are not mutually exclusive, and one often overlaps the other. Deleuze and Guattari offer the example of the ocean, an archetypal smooth space, which became to a degree striated with the inventions of latitude and longitude.[15] When smooth and striated spaces come into dialogue, the resulting geometry is often fractal in nature, a striated representation of the geometry of the smooth.[16] There is also an ambiguity between the two types of spaces and structures in them can at first glance appear very similar, but in the end they function very differently. One instance is the road or the trail. In a settled space, the road serves to "*parcel out a closed space to people,* assigning each person a share and regulating the communication between shares. The nomadic trajectory does the opposite: it *distributes people (or animals) in an open space,* one that is indefinite and noncommunicating."[17]

It is easy to come to the conclusion from reading *Thousand Plateaus* that smooth is inherently better than striated, that amorphous should take precedence over formed matters, or that the deterritorialized should have primacy over the sedentary. Deleuze and Guattari are careful to point out that one is not necessarily better than the other,[18] but they do feel that modernity and official histories have privileged one over the other, and they are working to reverse this trend to induce new modes of thinking as the *smooth* is the space of creativity and invention.[19] They are careful, however, to point out that this will not necessarily make things "better," since nonlinear

Figure 9.1 and 9.2: (*opposite page*) These aerial images show *smooth* and *striated* systems working together.

Figure 9.1 (*opposite page top*) is an aerial image is the provisional capital of the Sahrawi Arab Democratic Republic, an unrecognized state with control over some remote pats of Western Sahara. The highly articulated fractal river system is overlaid with emergent paths representing the movements of the desert nomadic guerilla group.

Image Google Earth: 2/8/2016
26°09'00" N, 10°33'26" W

Figure 2 (*opposite page bottom*) show two emergent villages in the unrelenting grid of irrigation canals and cotton fields in the Gezira irrigation scheme in Sudan. The scheme had its origins in cotton production to fuel Britain's textile mills in the early 1900s, but really got underway in the 1960s. It now covers over 8,800 square kilometers. The gridded geometries of the hydraulic landscape are almost instinctively countered by the movements of everyday life.

Image Google Earth: 12/08/2016
14°58'50" N, 33°05'60" E

processes have no teleology, it is impossible to predict the long-term effects of any series of processes or to precisely map out a route from one point to another in a complex and fluid system. A summary of the potentialities of striated versus smooth spaces is contained in the observation that "perhaps we must say that all progress is made by and in striated space, but all becoming occurs in smooth space."[20]

9.3. Maximally Articulated versus Maximally Connected

Deleuze and Guattari's philosophical concept of smooth versus striated space, with progress being made in striated spaces, but with birth occurring in the smooth, corresponds quite closely with Robert Ulanowicz's more scientific concept of *maximally connected* vs. *maximally articulated* systems. In *Growth and Development: Ecosystems Phenomenology*, Ulanowicz describes two extreme conditions for networks or systems, from natural ecosystems to human created financial markets. He describes a network where every node is connected to every other node in the system as being maximally connected. This corresponds closely with Deleuze and Guattari's category of the smooth, "spaces of pure connection"[21] and with the *meshworks* introduced in the previous chapter. On the other hand, in a network where every node has only one connection to another node, the system is "maximally articulated,"[22] a word Deleuze and Guattari consistently associate with elements of striated space, "segmentality, strata and territories"[23] and which correspond with the *treelike hierarchies* also introduced in the last chapter.

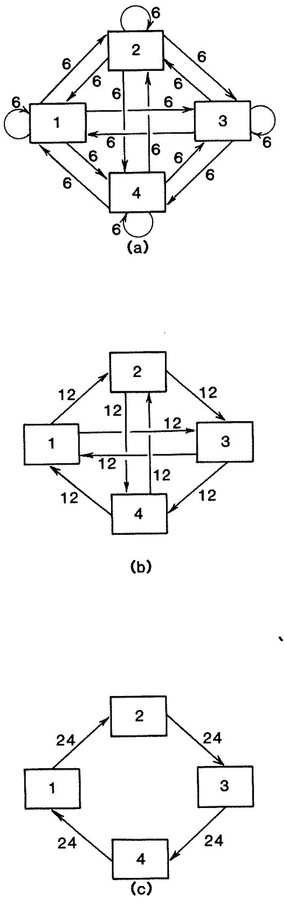


Figure 9.3: Diagrams from Robert Ulanowicz's *Growth and Development* showing at top, a "maximally connected" system,, and at bottom a "maximally articulated system." The middle diagram shows an intermediate step. More information is present in the maximally connected system since one can always predict how a quantity will flow through the system.

To explain the distinction between the two extremes, Ulanowicz ties his concept to the mathematics of information theory. The mathematical concept of information is in turn closely tied with concepts of entropy, probability, and uncertainty regarding a certain outcome. If an outcome can be predicted with more certainty, we are said to have more information about this outcome.[24] In a well-articulated system, there is more certainty to how energy or material will flow through the network, and as such the system inherently carries more information.[25] Take for example a river system, which is highly articulated system, versus the ocean, a classically smooth and highly connected space. If one were to drop a plastic ball in the Elbe in Dresden, there would be no surprise if it turns up in Hamburg a few days later. This would, in fact, be the expected outcome. If the ball turned up on the Leine in Hannover instead, we would know that some outside actor had intervened in the system to alter the outcome. In contrast, the ball's journey from Hamburg onward would be much more uncertain. With knowledge of ocean currents and wind directions, one might be able to calculate the probability of whether the ball would turn up in New York City versus Nordkapp in Norway, but both outcomes *could* happen. In this case, the system contains less information. This does not necessarily reflect ignorance on the part of an observer, it is rather an inherent property of how the system is structured, its degree of articulation.

After defining systems with maximal connections (lowest information) vs maximal articulations (highest information), Ulanowicz goes on to define the two words *growth* and *development*. Growth, according to Ulanowicz, is an increase in the flow of matter through a system and a corresponding increase in the number of nodes.[26] Development, on the other hand, is an increase in the articulation of the system, the elimination of redundant pathways and an increase in the system's information carrying capacity and organization with an accompanying decrease in uncertainty. Ulanowicz sees growth and development as two parts of a unitary process that he calls *ascendency*, with an increase in ascendency being "an increase in network size *and* organization."[27] Many systems, such as multi-cellular animals, can only grow with a corresponding increase in development, that is with an inherent increase in internal hierarchies. This observation has led to the notion that *all* systems must couple growth with development. This is not necessarily the case, and a particular interest of Deleuze and Guattari is in such systems as swarms, herds, flocks, and other "assemblages" where growth is not necessarily coupled with development.

This is related to a major question in Ulanowicz' text, centering around the point at which systems should stop growing or stop developing, in other words what are the limits of growth and what is the configuration of "optimal ascendency"?[28] Ulanowicz makes the point, introduced in the previous chapter as well, that redundant pathways are essential to a system's overall resiliency, and that if a system becomes too developed, it is open to damaging shocks leading to total collapse under less than benign conditions. As a consequence, ecosystems in harsh environments—such as deserts—tend to a lower level of development than a "benign" ecosystem such as the tropical rainforest.[29] He also notes that systems incorporating circular recycling and feedback loops, pathways that inherently increase uncertainty, tend to outcompete rigid hierarchies, so even in an ecosystem that could support maximal articulation, such as the rain forest, redundant pathways encouraging recycling of material still tend to emerge.[30] Returning to Deleuze and Guattari, it is interesting that his smooth spaces of "pure connectivity"—the ecosystems of the desert, steppe, and ice fields—are precisely the ones Ulanowicz identifies as limited in terms of optimal development. The forest, a space Deleuze and Guattari identify with a high degree of striation, is likewise forecast for a high degree of ecosystem articulation and development by Ulanowicz.

Although Ulanowicz is careful to not oversell his argument to apply *too* broadly, he expresses at several points the belief that it does apply to many types of systems and hopes it will "serve as a tool in formulating other precise system-level definitions."[31] Delueze and Guattari are of course more radical and their examples are meant to induce societal self-reflection and to propose organizational structures in contemporary society which can be more innovative, more adaptive, and more accommodating of peripheral and repressed perspectives. Individuals should not feel the need to plant themselves in rigid, non-flexible hierarchical structures, but should act more as free agents moving between assemblages or swarms of activity.

9.4. Smooth and Striated in the Broader Landscape - *Taking Measures Across American Landscape*

In explaining the tension between smooth and striated spaces, Deleuze and Guattari give the example of the ocean and the accompanying striations of longitude and latitude imposed on this smooth space for the purposes of navigation. A similar, but much richer exploration of this tension between systems of striation with their "metric" qualities and the "vector" qualities inherent in the smooth space of the underlying landscape is presented in James Corner and Alex Maclean's *Taking Measures across the American Landscape* (see also §2.9.) The textile like pattern inscribed across much of the United States is an archetypical expression of a striated space. It is an expression of a state apparatus with a "commitment to life, liberty, and the pursuit of happiness, distributing power equally across space" infused with a "belief in a single, rational order in nature."[32] This striated system, however, is not inscribed on a *tabula rasa*, but on a landscape embodying many of the essential characteristics of the smooth. It is, as Corner describes, a landscape of "enormous scale and power," characterized by endless forests, powerful waterfalls, furious storms, and "numberless herds of buffalo and flocks of passenger pigeons."[33]

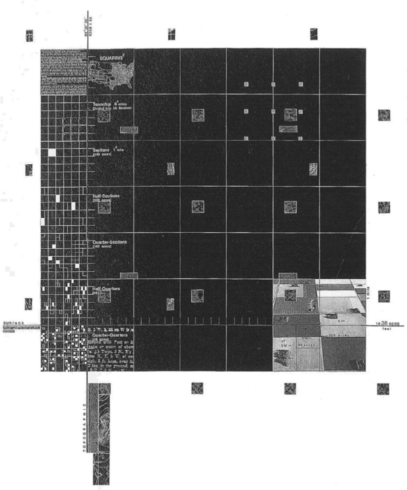


Figure 9.4: *(above)* Collage from Corner and Maclean's *Taking Measures Across the American Landscape,* p. 48. The simple geometric scheme when overlaid on the complex underlying landscape expresses itself in a fractal-like pattern.

Figure 9.5: *(above)* Fields near Lancaster, Pennsylvania. Since the traditional Amish farmers of the region still use horse drawn plows and tend to follow the contours so as not to exhaust the horses, the typical striations of the agricultural landscape take on the smooth quality of the underlying landscape.

The system itself followed a sort of algorithmic logic with flexibility at the scale of the individual section (a 1-square mile module) which could be recursively subdivided down to half sections, quarter sections, or even further.[34] This straightforward and universalizing system, however, was constantly altered by *local conditions* which could hardly be predicted in advance, and to which surveyors had to make creative adaptations. The exploration in *Taking Measures* greatly contributed to Corner's thinking from that point onward, and particularly informed his concept that landscapes should be analyzed and later designed in terms of layers (§2.9) having a degree of independence at least initially, but which in a synthetic process work to alter and inform each other.

9.5. Stan Allen's *Field Conditions*

Around the same time as James Corner and Alex Maclean were working on their classic exploration of the American landscape, Corner's associate and for a short time business partner was developing his concept of the *field* as introduced in §2.9. This was not an entirely original construct—Alexander also had a well-developed concept of the field, and as observed by Kwinter, Goethe's concept of metamorphosis "unfolding" in gradient fields was developed over two-hundred years ago (§4.11). Leibniz also saw all matter as part of a continuous field of forces, foreshadowing quantum theories also by several centuries (§4.5). Perhaps no one did more to clarify the concept in the contemporary design context, however, than Allen and to relate it specifically to computational thinking.

Allen was interested in the conceptual shift away from object-based thinking, which had dominated the profession of architecture for much of its history and was interested in an emerging "relational" paradigm in architecture which he believed was captured in the concept of the field. He was especially inspired by developments in quantum mechanics, where subatomic particles are not seen as points or objects, but as constituents of wave-like fields, and by the manifestations of this theory in computer simulations on the one hand and in art on the other.[35] Allen's "field conditions" were also closely related to the "infrastructural elements of the modern city," and sought to find new ways to "reflect the complex and dynamic behaviours of architecture's users and speculate on new methodologies to model programme and space."[36] Through field conditions, Allen hoped to tap the potentialities of "bottom-up phenomena: defined not by overarching geometrical schemas but by intricate local connections." Summarizing, he states that: "form matters, but not so much the forms of things as the *forms between things*."[37]

In describing his sketch of "field conditions," Allen's ideas parallel closely the thinking of Deleuze and Guattari. *Thousand Plateaus* is cited specifically only once in the endnotes, but their notion of smooth and striated spaces is evident in Allen's iconic diagrams of patchworks, striations, grids, and felts[38] and in his interest in flocks, schools, swarms, and crowds.[39] He also shares strong affinities with Corner's thinking, citing the precedent of the Jeffersonian grid, carefully documented by Corner, as an example of an ordering field while also sharing Corner's interest in "layering" fields of information, and seeing how the interplay between fields—*field-to-field* relations—can play out.[40] Where Allen moves beyond Deleuze and Corner is in his interest in computer simulations and in the potential of algorithms to describe and document, and perhaps *design* field conditions. He is particularly mesmerized by the work of artificial life theorist Craig Reynolds, who created simple computer programs to simulate the flocking behavior of birds, based on very simple rules, in a simulation known as the "boids". This text will return to Reynold's boids in Chapter 12 on agent-based design, but

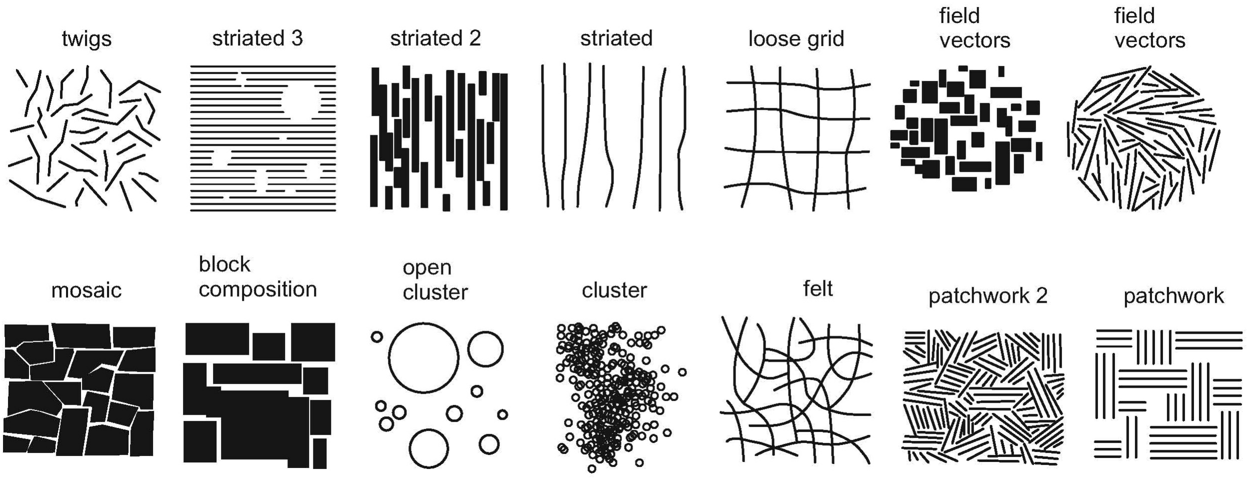


Figure 9.6: (*above*) Diagrams of Stan Allen's "Field Conditions"

Allen's description of the boid simulation clearly shows what elements he saw as important in the field:

> "The flock is clearly a field phenomenon, defined by precise and simple local conditions, and relatively indifferent to overall form and extent. Because the rules are defined locally, obstructions are not catastrophic to the whole… Over many iterations, patterns emerge…not as a fixed type, but as the cumulative result of localized behavior patterns."[41]

Allen was optimistic that similar simulations could be devised to reveal inherent patterns and formal possibilities "in the movement of "crowds and swarms [operating] at the edge of control."[42] In the larger context, he believed field conditions could "reassert the potential of the whole, not bounded and complete (hierarchically ordered and closed), but capable of permutation: open to time and only provisionally stable."[43]

9.6. Unfolding forms in Fields

It is important to note that Stan Allen never suggested doing away with objects, merely that the priority of the object with respect to the field should be reassessed. Objects should respond to "field conditions," not dictate them. Again, numerous authors had come to this conclusion long before Allen. A commonly used concept for the *process* by which objects express themselves in fields is expressed by the word *unfolding*. Unfolding is the word chosen in the English translation of Goethe's poem presented in §4.10 to describe the process of plant development, where Goethe observes the "*unfolding* of the delicate leaf."[44] Deleuze traces the concept of folding back to Leibniz, and further posits that "you can always get from one form on the organic stratum to another, however different they may be, by means of 'folding.'"[45] Alexander also uses the phrase "the sequence of *unfolding*" to describe his process of deploying *patterns* into *fields*.[46]

9.7. Fields, Forces, Gradients, and Fractals

The organizing forces in some fields, or deterritorializing forces in others, are generally invisible, only becoming visible when we observe how objects "unfold" in the field. These forces should be considered, however, and as observed by von Humboldt, as physical realities as strong as "mountains" or "seas." (§4.7) The reason they are sometimes not recognized as such is the fact that changes in field conditions, at least in natural systems, tend to operate along continuums or gradients making it hard to define, for example, where a dry climate ends and a wet one begins, or where a hydric soil becomes mesic and then xeric. This is reflected in Neutra's quote cited at the beginning of this chapter, which contains echoes of Leibniz's law of continuity, positing that changes in nature never occur abruptly or suddenly. The gradients present in fields are also sometimes hard to detect because of complexifying factors and forces in fields; Von Humboldt was only able to see the clear transitions between the fields of influence in the Andes, which informed the development of distinct plant communities at different altitudes, because of a lack of what he terms "complications" which make the isothermic lines which govern plant distribution invisible elsewhere.

These complications, it turns out, are also an important part of understanding fields. As introduced in the beginning of this chapter, and as hinted at by Deleuze, the continuous gradients present in natural fields, when entering into a state of conflict with other natural or human forces, tend to produce forms of a fractal nature. Mandelbrot begins his study of fractal forms with a famous analysis of the British coastline, expounding on the difficulties of obtaining a true length of the coastline. Without getting into the problem of *how* one measures the coastline, perhaps more interesting is to ask *why* it is fractal in the first place. The answer has to do with these "complicating" forces, the struggle between land and sea. Later in his text, Mandelbrot associates fractal forms with forms of turbulence, struggle, and competition. The result is the smooth transitions are not always observed as such, creating a fractal boundary between, for example, the treeless high alpine community and the first spruce forests, with contending forces making the "tree line" anything but a line.

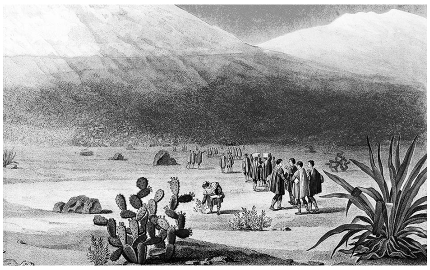


Figure 9.7: The phenomenon known as the tree line is in fact a complex fractal boundary informed by many processes. Von Humboldt's engravings show these fractal boundaries as clear lines in the Andes environment.

In some cases, the fractal boundaries so characteristic of natural space are erased through heavy-handed acts of human parcelization and striation of nature. These clear and sudden boundaries characteristic of androgenic interventions, as observed by Richard Forman, can lead to a loss of biodiversity in some cases since many animal populations have evolved to live in fractal edges, or ecotones, moving between two biomes to sustain life.[47] In other cases, however, these human interventions increase biodiversity. Zooming out, perhaps one can see why. While human parcelization often creates discrete spaces at the scale of the site, in the broader picture, similar fractal patterns emerge from the image of competing systems of control on the one hand, and deterritorialization on the other. The striated, the smooth, and the fractal in-between.

9.8. Summary Conclusion

Both natural and cultural systems contain forces leading to increased levels of territorialization on the one hand and deterritorialization on the other. The territorializing forces correspond with Deleuze and Guattari's concept of striated spaces, with Ulanowicz's definition of development as "maximum articulation", and the network concept of *trees*. Deterritorializing forces, on the other hand, correspond with Deluze and Guattari's smooth spaces, Ulanowicz's definition of growth as "maximum connectivity," and the network concept of *meshworks*. These forces exist in complex *fields* of relationships which can be analyzed in terms of either rigid or fluid topologies. Objects in the natural environment respond to these fields in a process of *unfolding*. Similar processes can be observed in human societies. Often, the words "order" or "chaos" are associated with striated spaces and smooth spaces respectively, but as we have seen, hybrid *meshworks* tend to be more stable than rigid hierarchies, (§8.7) and ecosystems with many levels of redundancy and feedback loops (connectivity) often outcompete highly articulated ones. (§9.3)

This chapter also introduced the concept of the field as a counter, but also a complement to the reading of space as a series of topological networks. Interestingly, Mandelbrot also sees his fractal geometry, which together with topology can be seen to inform the nature of field conditions, as a concept which fills a gap topology cannot fill. He observes that topology "teaches that all single island coastlines are of the same form, because they are topologically identical to a circle. And that the topological dimension is the same for coastlines and circles: equal to 1."[48] He concludes that the "mathematical study of form must go beyond topology."[49] In the final part of this thesis, we will test the assumption that a dialogue occurs between a topological reading of landscape space as a series of networks and the presence of fields as a continuous gradient of forces and fractal boundaries.

In the next three chapters, however, this thesis will focus on specific algorithmic strategies which might be associated with the construction of striated and smooth spaces. Chapter 10 on "Growth and Development" contains algorithms associated with striated networks and fields. Chapter 11 and 12 will focus on algorithms whose logic tends towards smooth space. Before moving to these more in-depth studies, however, three algorithms are presented in this chapter to demonstrate intersections between the striated and the smooth. The first series of algorithms (§A9.1) attempts to recreate some of Stan Allen's "fields" with contain a mixture of logic from the smooth and striated spaces described by Deleuze and Guattari. The second algorithm (§A9.2) explores the intersection between a recursively subdividing grid and an underlying, continuous topography. Finally, a rather simple algorithm (§A9.3) inspired by a landscape architecture project in Copenhagen by Karres en Brands, combines a pattern of individual cells with "point attractors" that generate a simple gradient field.

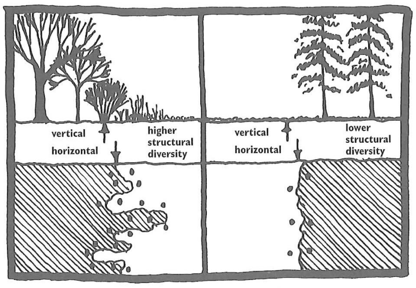
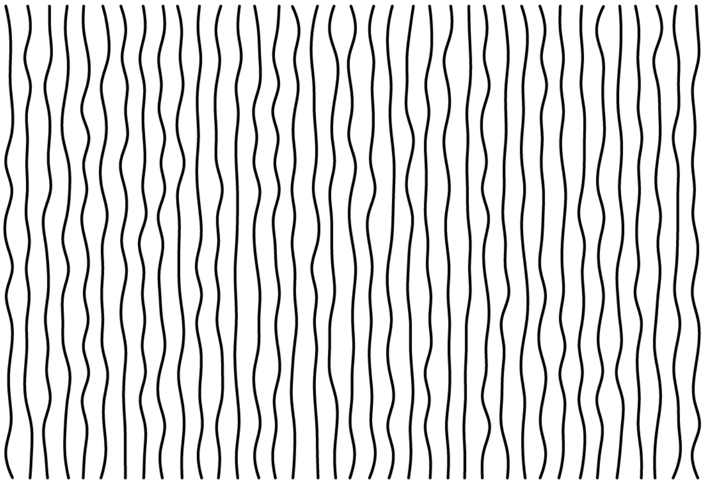
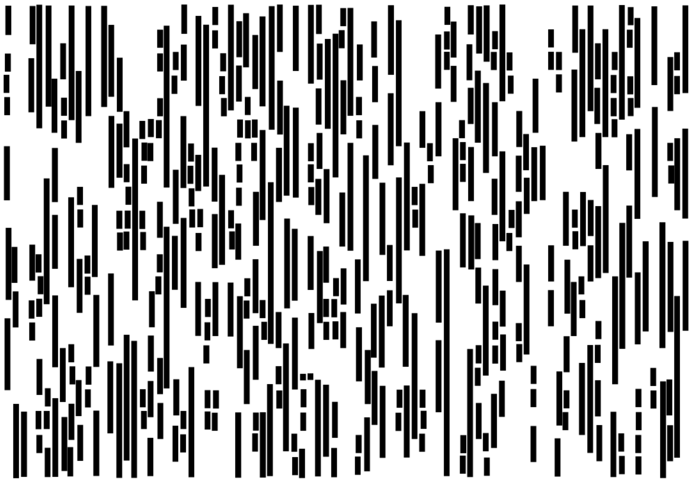
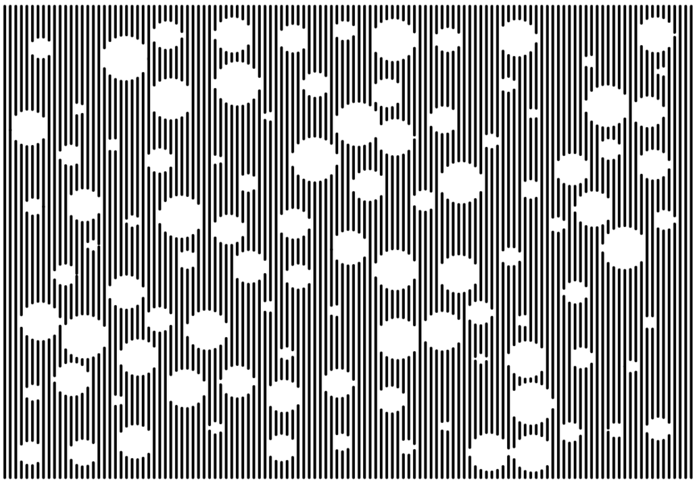
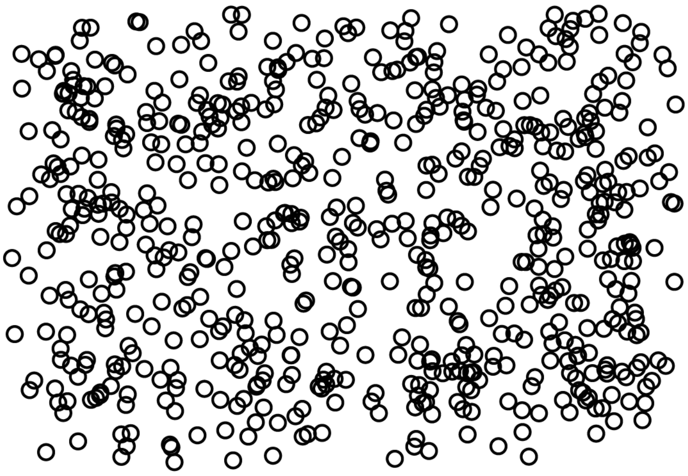
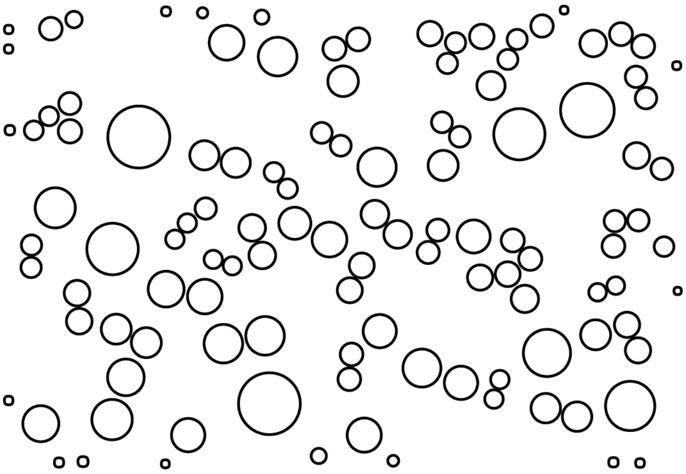
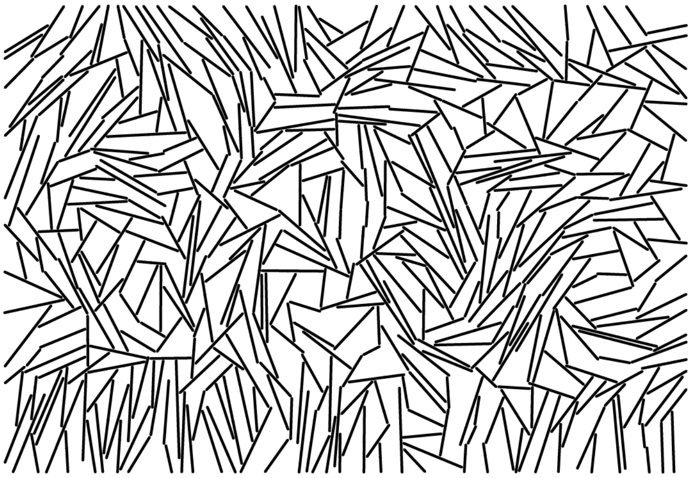
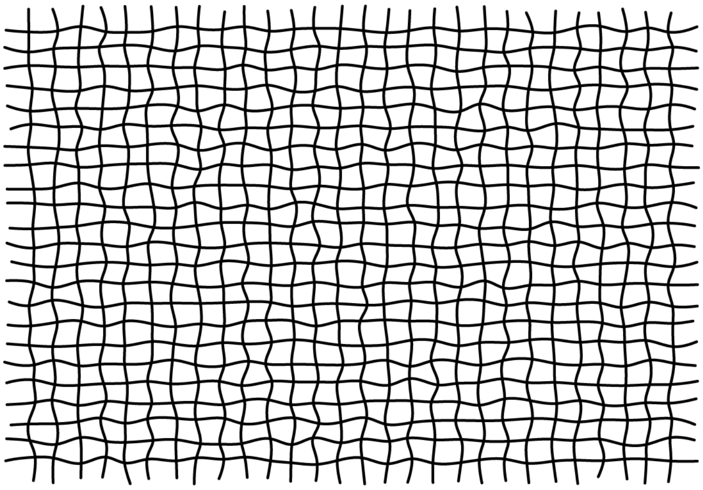
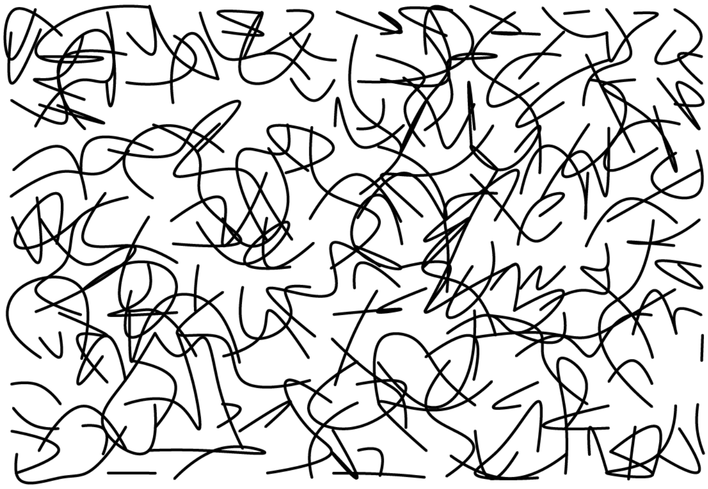


Figure 9.8: Richard Forman illustrates how gradient and fractal boundaries support more biological diversity than sudden, hard edges. p. 28.

Algorithm 9.1. – Stan Allen's "Field Conditions"

Stan Allen's "Field Conditions" represent some of the most iconic diagrams to come out of the architectural discourse of the late 1990s when architecture was at the tail end of a first wave of computational mania. The diagrams themselves were not generated computationally, but their inclusion in Allen's essay "From Object to Field" which made a powerful argument for adopting computational methods in the design process pointed to the fact that the diagrams *should* be reproducible with an algorithmic logic. As the research of Part II of this thesis progressed, the author set the challenge of deriving an algorithm for each of the depicted "Field Conditions." This was a useful exercise, and while some proved to be quite easy to describe algorithmically, others proved much more challenging. A few have not yet been successfully modeled algorithmically by the author while other new conditions not drawn by Allen but with a similar aesthetic were derived along the way.

Figure 9.9: *(page opposite)* Algorithmic "fields" generated from the logic of Allen's "Field Conditions"

In writing Part II of the thesis, it became clear why some were easier to model while others more difficult. In general, the straightforward algorithms are titled with names corresponding with Deleuze and Guattari's category of "striated space," such as striation 1, 2, and 3 and loose grid, and generally use a non-recursive logic in their formation. In contrast, the difficult diagrams to model tend to make heavy use of vectors and recursive processes, having names corresponding to Deleuze and Guattari's "smooth space" such as felt, patchwork, and field vectors. The process for eight of these diagrams is presented in this section in the form of three diagrams or slides showing steps in the process. Due to space limitations, the methodology of the eight is only briefly described. Full descriptions will be made available on *generativelandscapes.wordpress.com*

Striated: A simple grid of points is created, and points are moved a small random amount to the left or right along the X Axis. The points are then connected through the grid of points in the Y direction.

Striated 2: A grid of rectangular cells is created and large random amount of them are removed. The cells are then scaled in a non-uniform way around their centerpoint.

Striated 3: A series of lines in the Y direction are populated with a random point cloud, with circles of varying sizes drawn at each point. The circles are used to trim the lines, which are then removed.

Cluster: For each circle created from a point cloud, find the vector to all neighbors within a defined radius. Sum these vectors together into an average, and then move the circle along this average vector.

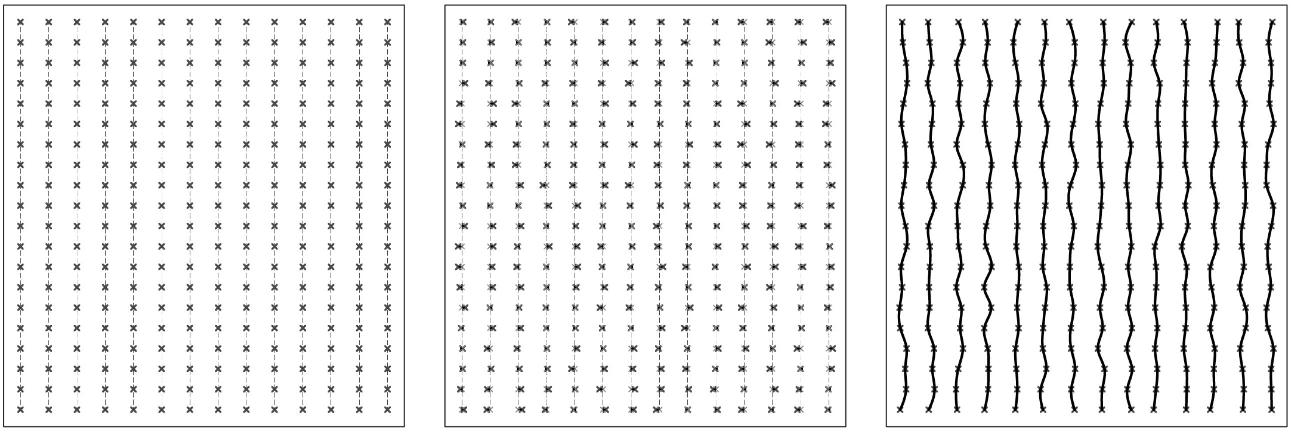
Figure 9.10: *(following two pages)* Algorithmic process for 8 of Allen's "Field Conditions."

Open Cluster: In a sparse cloud of points, find the distance to the nearest neighbor and to the edge of the field. Select the smaller of the two values, construct a circle with a radius 40% of the selected distance.

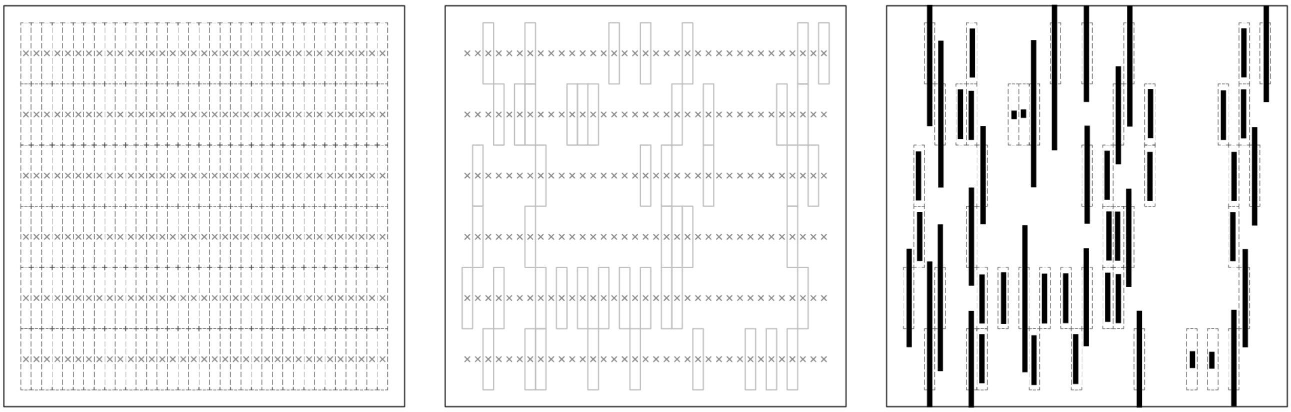
Field Vectors: Draw a field of random vectors and adjust each vector to the heading of *N* nearest neighbors. Then grow the lines until come close to intersecting a neighbor or the filed edge (see §10.3)

Loose Grid: Move a grid of points a random amount in both the X and Y directions. Then connect the points in both the X and Y directs, maintain the original grid topology.

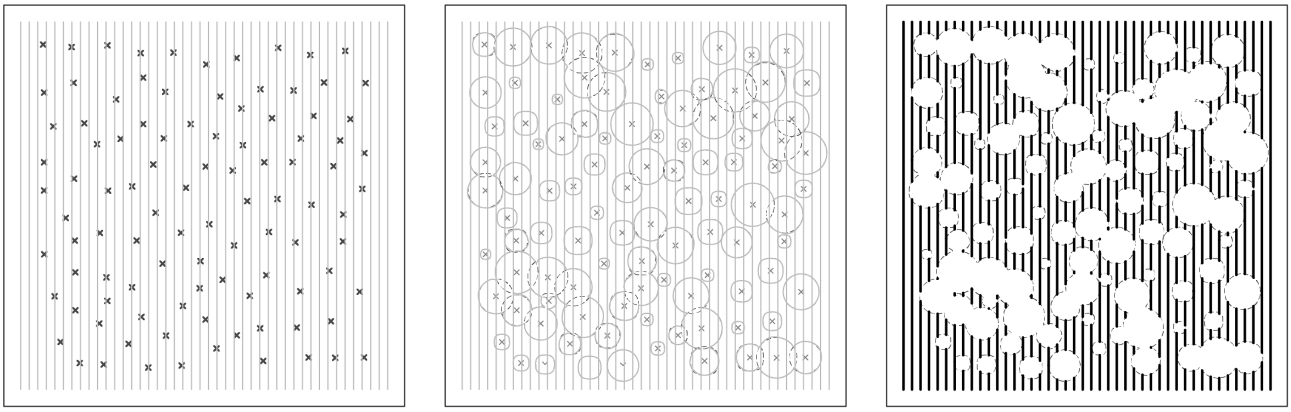
Felt: Select a random point from a point cloud. Connect it to a randomly selected point with a distance *R* recursively either 3, 4, or 5 times. Remove points selected from the cloud. Repeat until all points are used.



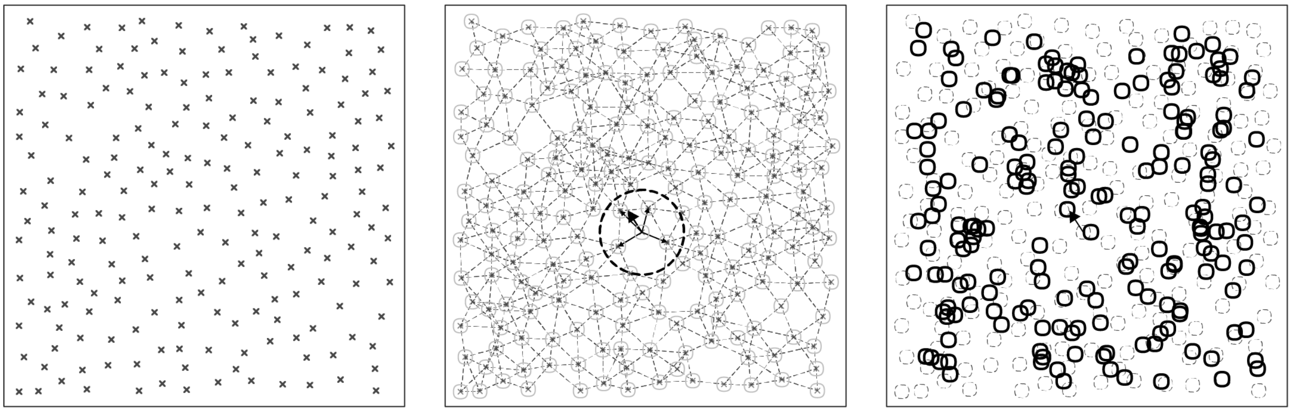
Striated



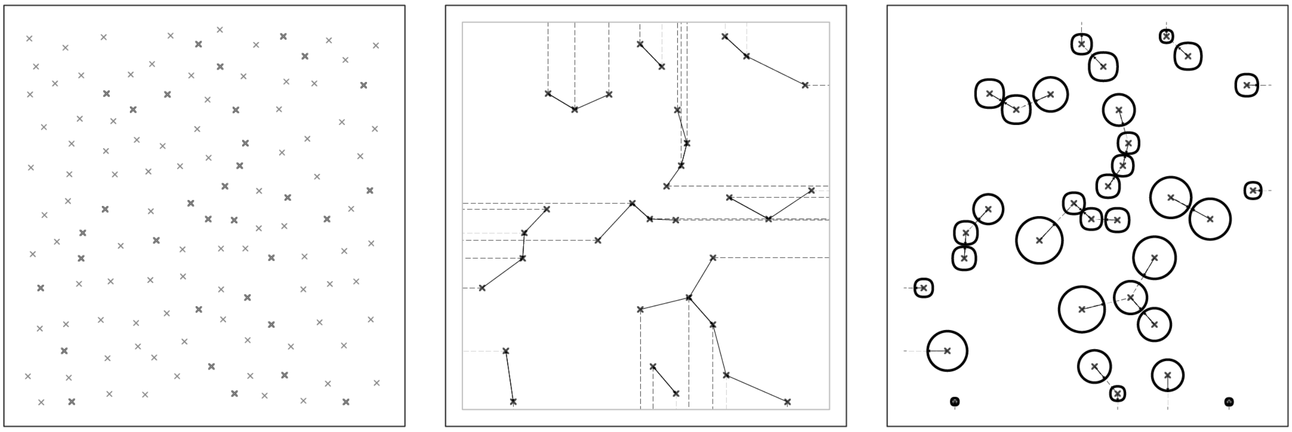
Striated 2



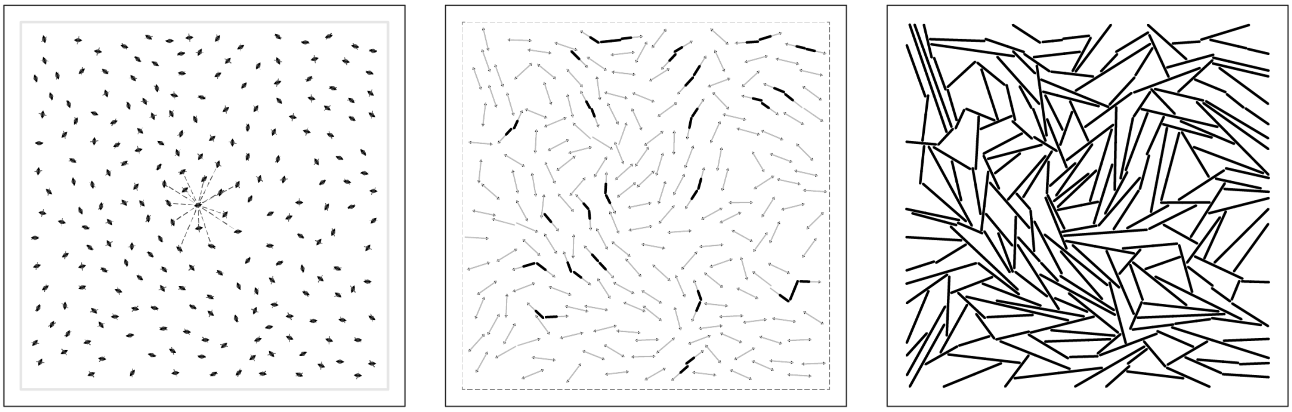
Striated 3



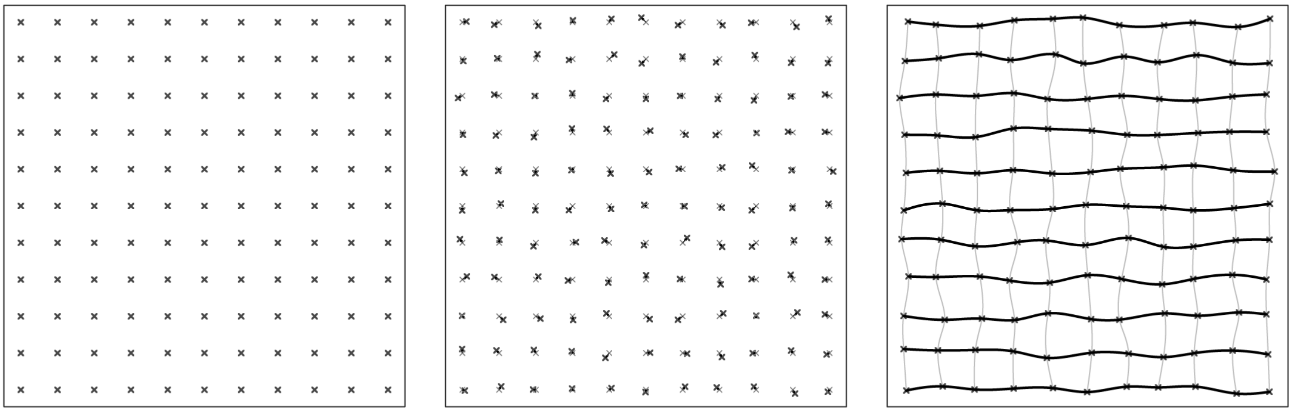
Cluster



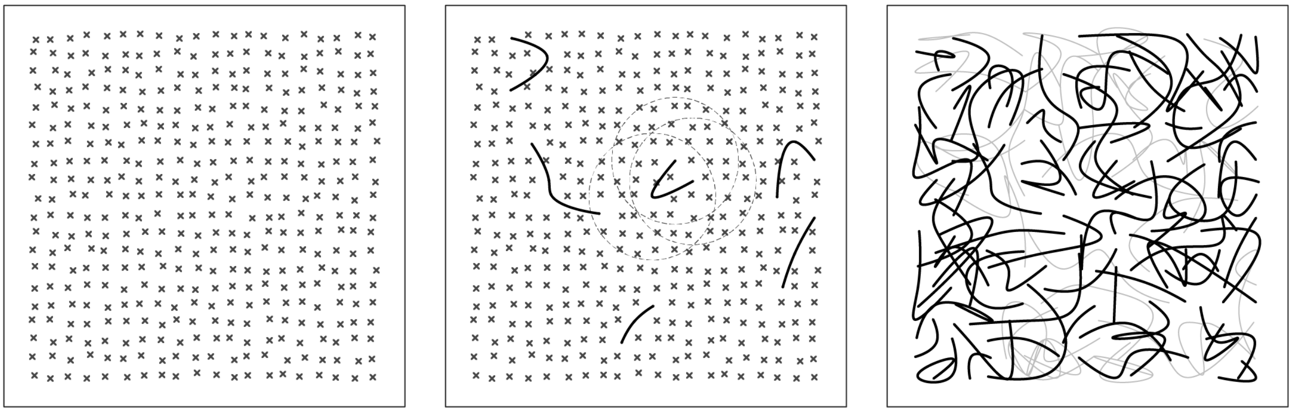
Open Cluster



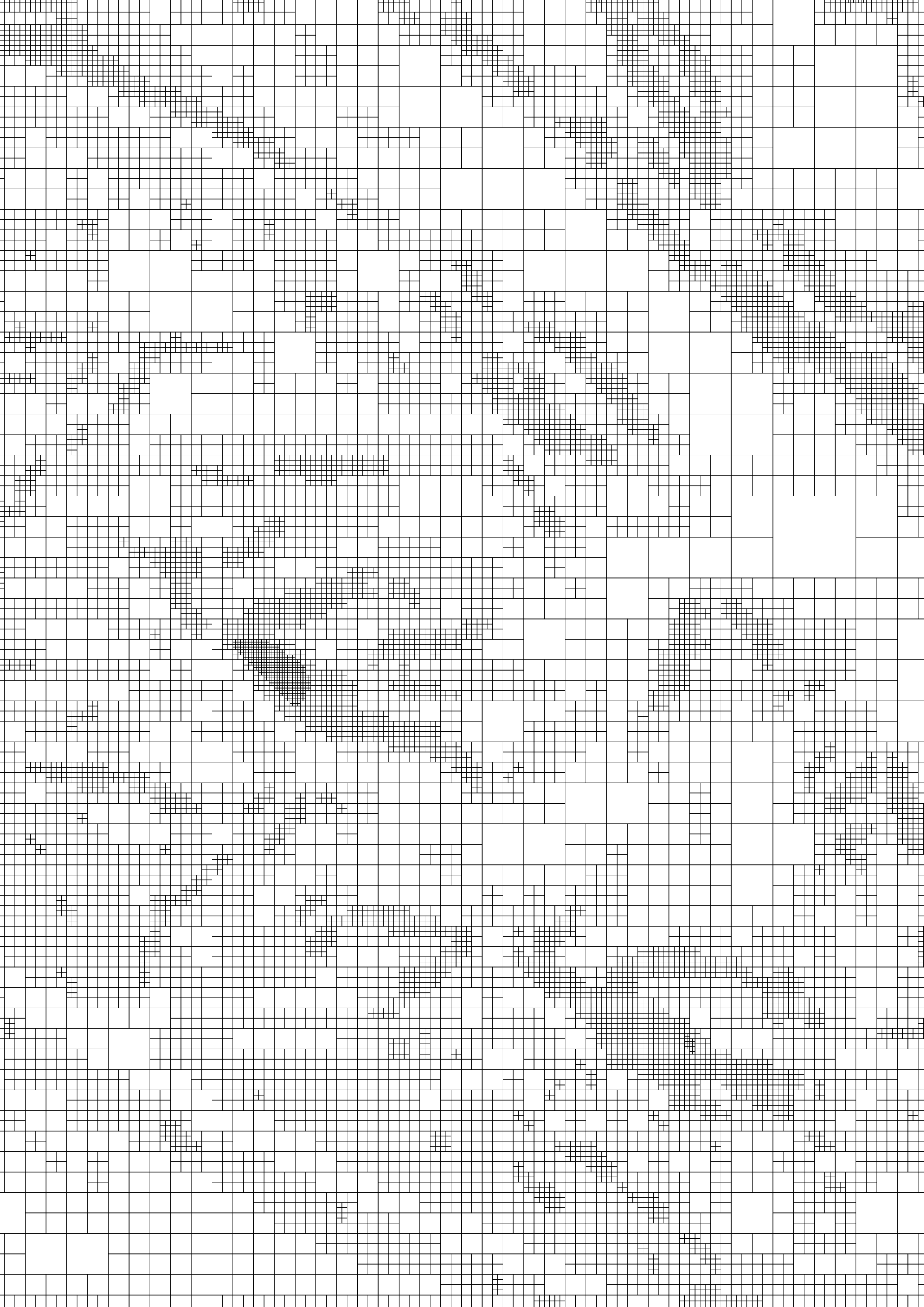
Field Vectors



Loose Grid



Felt



Algorithm 9.2. Topographical Panelling

This algorithm takes a slightly different approach to show how a system of striation and the smooth space of the underlying topography might interact. The algorithm was inspired by a problem common in recent architectural projects, where free-form shapes have to be subdivided into a regular series of panels in order to achieve a desired aesthetic quality at a reasonable cost. Many of these algorithms can become quite complex using various optimization strategies to test efficiencies.[50] In this comparatively simple algorithm, a topography is divided into parcels where large parcels are allocated to regions of low slope, and small parcels to high slope regions to present a graphic description of slope steepness without using contour lines or hill shading. A variation of this algorithm is incorporated into the Medellin case-study project described in chapter 3.1. where a steep topography is divided into individual field parcels which have sufficiently low slope.

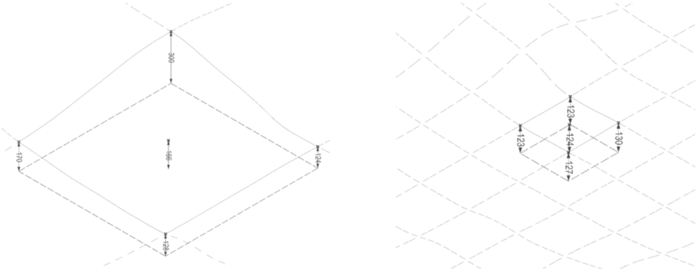
The user gives the algorithm only two inputs, a topographical NURBS surface and a parameter E representing the elevation threshold at which a parcel is considered sufficiently "flat" and at which point a sub-surface will be removed from the loop. The algorithm begins by dividing the initial surface into 4 sub-surfaces, which are then fed into a recursive loop. At each time-step of the loop, the four corner points as well as the center point of each subsurface are identified. The Z value of each corner point is then entered into a numeric domain associated with each subsurface, and the minimum Z value is subtracted from the maximum Z value for each subsurface to obtain a ΔZ value. If ΔZ for a particular sub-surface is less than parameter E, the subsurface is deemed sufficiently flat and is removed from the recursive loop. If $\Delta Z > E$, then the subsurface is divided once more into four equal subsurfaces, which are in turn sent back to the beginning of the recursive loop. Eventually every subsurface will meet the test where $\Delta Z < E$ and will exit the loop, at which point the algorithm stops.

The only real decision on the point of the user, but one which is very important, is the judicious selection of a value for parameter E. A good value will take into account the size of the initial terrain as well as the overall character of the topography. A relatively flat terrain should have a lower value, for example, than a mountainous and steep landscape.

Figure 9.11: *(page opposite)* Topographic panelling algorithm run on a site near Dellingsen, Lower Saxony, Germany.

Figure 9.12: *(top right)* The topography at each square is measured at the corners and at a the square‘s center. The Z values are compared for these survey points, and if they fall within a certain range, the square will not be further subdivided.

Figure 9.13: *(below)* Recursive divisions of the topography through six rounds. After each round, the Z values of each square are compared per Fig. 9.12. Light squares represent areas for further subdivision, while dark squares undergo no further subdivision.



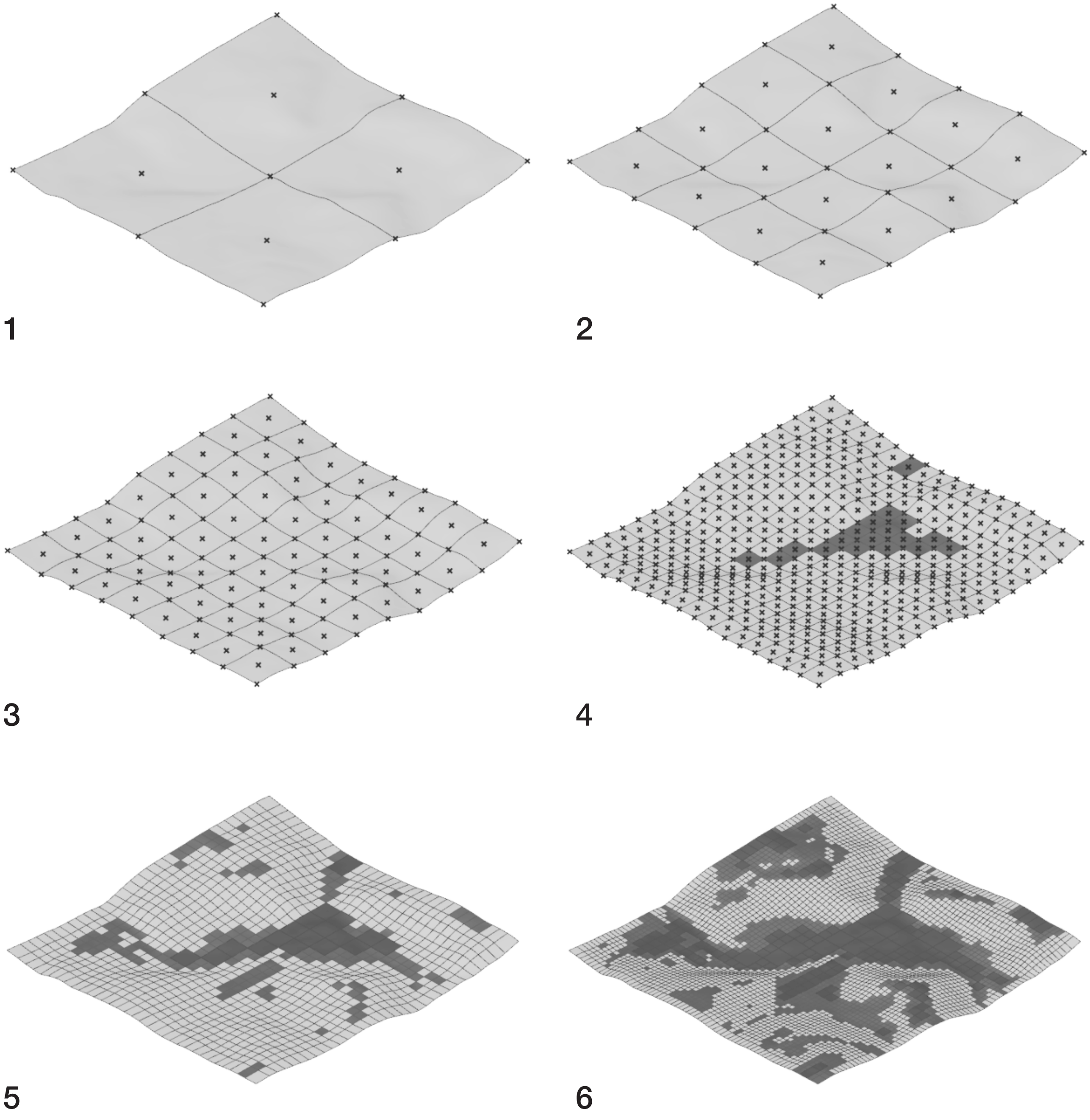
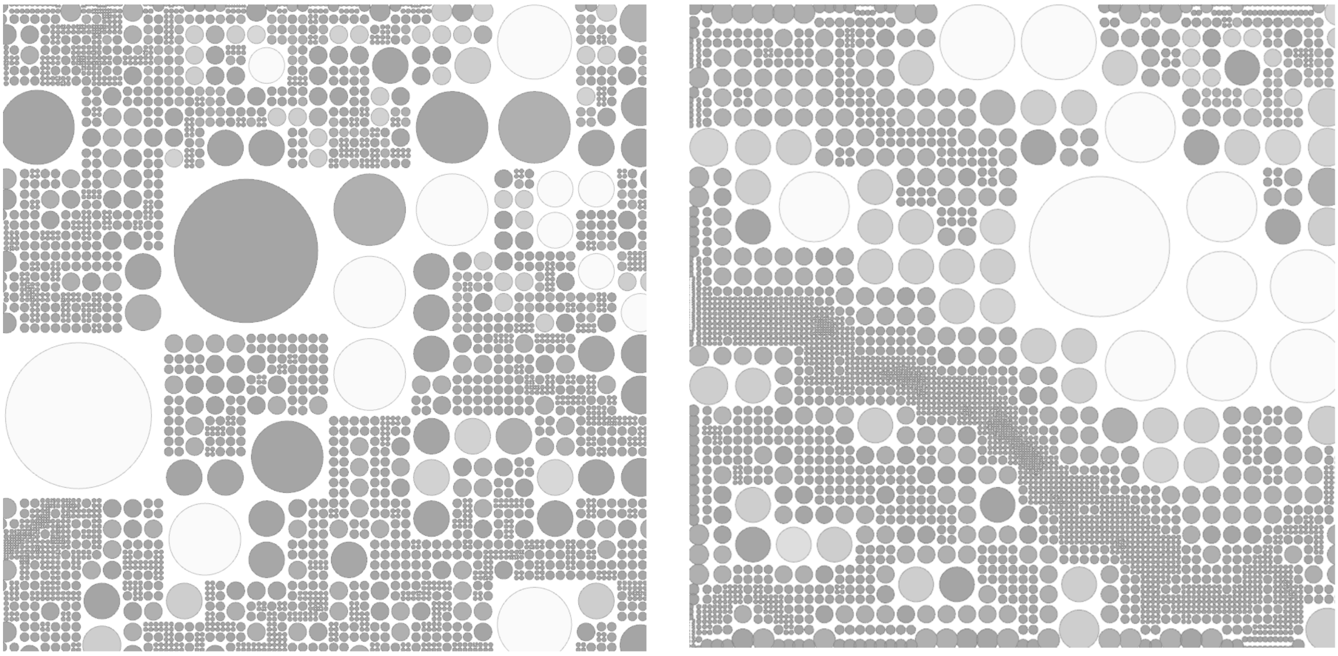
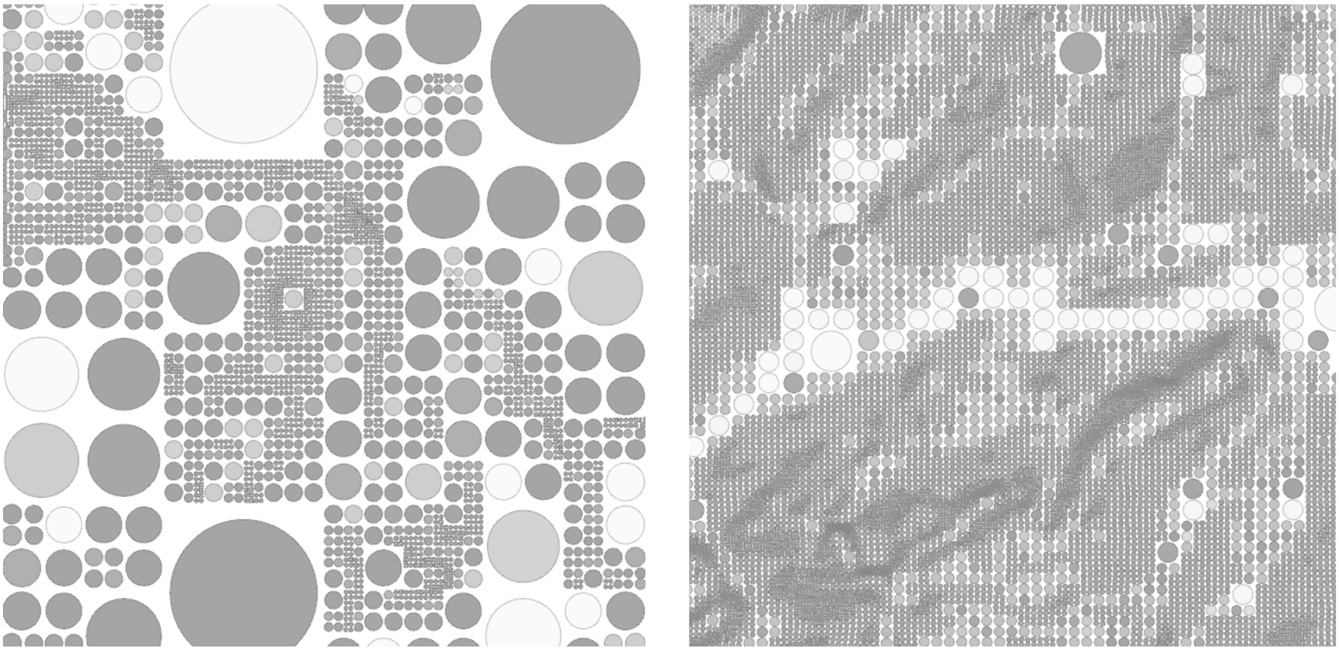


Figure 9.14: *(below)* Variation of the algorithm on four different landscapes, where squares are filled in the end with circles.



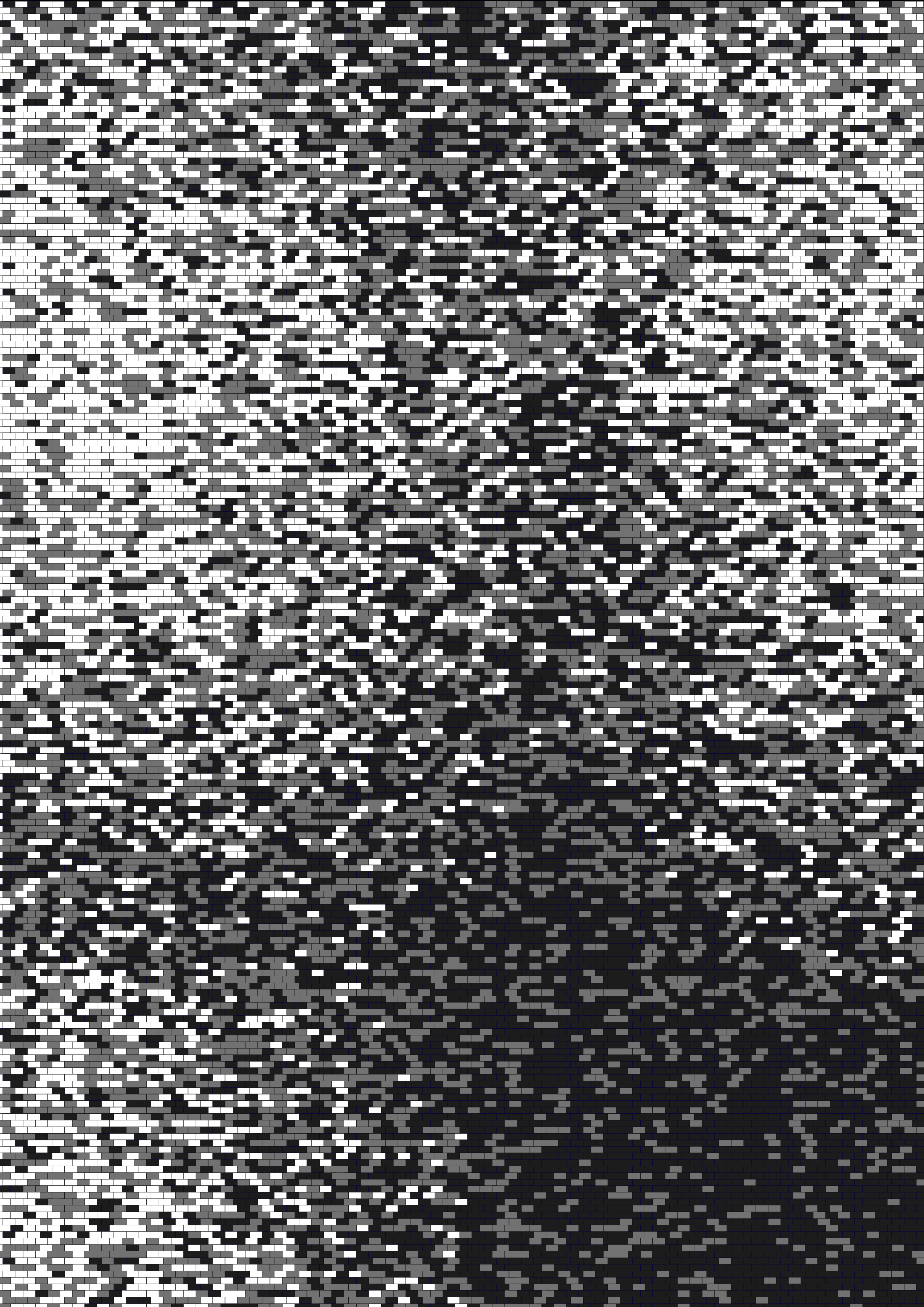
São Paulo Brazil

Bueren an der Leine, Germany



Hannover, Germany

Rougemont, Switzerland



Algorithm 9.3. – Købmagergade

The algorithm was inspired by a design for a pedestrian street in Copenhagen, Denmark by the landscape architecture office Karres en Brands—the Købmagergade. The design has multiple shades of paving distributed in an apparently random pattern, but where the proportion of light, medium, and dark pavers gradually changes as one moves through different parts of the pedestrian zone. This simple project inspired a blog post on generativelandscapes, which has since become one of the most visited pages on the site.[51] Some of the assumptions made in the blog post, such as that there were only three shades of paving, or that they were randomly distributed, proved wrong—there are actually five shades, and the paver color for each stone was painstakingly set individually. The method proposed on the blog, however, as conceded by the project landscape architect could have saved a considerable amount of time.[52]

The algorithm demonstrated here combines the logic of two systems. The first is the random distribution of three different shades of tiling. The second system employs a technique known as a *point attractor*. With this method, the attributes of an element vary with their distance from another point. This creates a quasi-smooth space evocative of Delueze and Guattari's concepts of multiplicities and Rhizomes, where "each element ceaselessly varies and alters its distance in relation to others."[53] Here, what "ceaselessly varies" is the probability of a tile being assigned to one of the three shades—light, medium, or dark. (Five shades, as in the actual project, could also be done with a few simple modifications.) Pavers close to a point have a very high chance of being light in color, and a low, but not non-existent chance of being dark. Pavers not designated as light or dark are by default designated as having a medium tone. As one moves away from the point, the chance of being assigned as either a medium or dark paver increases. Pavers far from points have a high chance of being dark, and a low chance of being assigned to white. Once this system is set up, the designer can vary the pattern rather easily by adding or moving points in lighter zones and can also change the rate at which the light to dark gradient falls off.

Figure 9.15: *(page opposite)* Paving pattern with three shades of bricks determined through the algorithm described in this section.

Figure 9.16: *(right)* Attractor logic applied to a sample set of pavers.

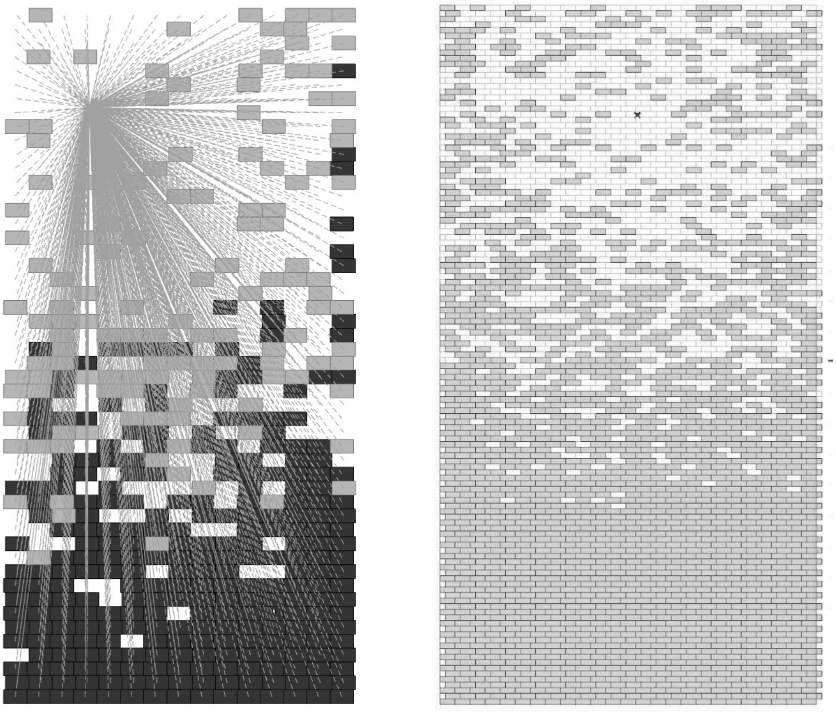


Figure 9.17: *(below)* Algorithm applied to a sample set of pavers with various parameters.
1 - A single point attractor with low attractor stregth.
2-A single point attractor with high attractor strength.
3 - Two point attractors with low attractor stregth.
4- Two point attractors with high attractor strength.

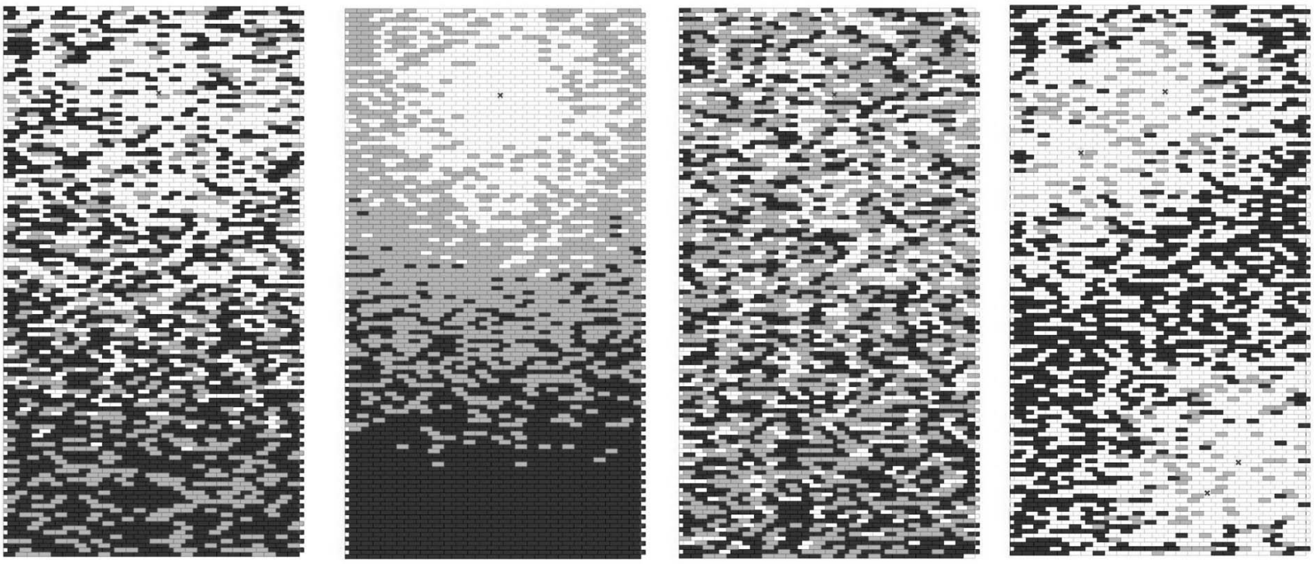


Figure 9.18: *(below)* Algorithm applied to the Købmagergade in Copenhagen based on the design concept developed by Karres en Brands.

Endnotes

1 Richard Neutra. “Inner and Outer Landscape.” In György Kepes, *The New Landscape in Art and Science.* (Chicago: Paul Theobold and Co., 1956), 84.

2 Sanford Kwinter, “Introduction: De L’Audace,” in *Far From Equilibrium,* 16.

3 *Ibid.*

4 Mario Carpo. Introduction. *The Digital Turn in Architecture 1992-2010* (London: Wiley, 2013), 9-10.

5 George Hargreaves. Foreward. *Digital Landscape Architecture Now!,* by Nadia Amoroso. (London: Thames & Hudson, 2012), 7.

6 Martin Prominski and Spyridon Koutroufinis. “Folded Landscapes: Deleuze’s Concept of the Fold and Its Potential for Contemporary Landscape Architecture.” 157-158.

7 *Ibid*, 158.

8 Deleuze and Guattari, Many of the concepts introduced throughout the book are summarized in the conclusion essay on pages 584-597. The War Machine is the subject of a lengthy essay on pages 409-492.

9 The smooth and striated are discussed in detail in pages 551-581. The concepts are critical to earlier chapters, however, especially to the aforementioned concept of the War Machine.

10 *Ibid*, 421.

11 *Ibid*. Original quote from *Boulez on Music Today,* trans. Susan Bradshaw and Richard Bennett (Cambridge, Mass.: Harvard University Press, 1971), 85.

12 *Ibid*, 552-555.

13 573. Emphasis in original.

14 *Ibid*, 448.

15 556-561.

16 *Ibid*, 565-566.

17 *Ibid*, 443.

18 See for example, in reference to the War Machine (smooth space) with respect to the State (striated space) “The war machine answers to other rules. We are not saying they are better, of course…” 418. In reference to the distinction between sciences of “iteration and reiteration” (repetition/striated) on the one hand and sciences of “itineration” (travelling around/smooth) on the other, they declare that one is “not better, just different.” 433.

19 *Ibid*, 24-26.

20 *Ibid.*

21 Deleuze and Guattari, 573.

22 Robert E. Ulanowicz, *Growth and Devleopment: Ecosystems Phenomenology.* (Berlin: Springer, 1986), 101-102.

23 Deleuze and Guattari, 2.

24 Ulanowicz, 87.

25 *Ibid*, 97.

26 *Ibid*, 96.

27 *Ibid*, 201-103. Emphasis added.

28 *Ibid*, 152.

29 *Ibid*, 118.

30 *Ibid*, 108.

31 Ulanowicz, 7.

32 James Corner and Alex Maclean, 8.

33 *Ibid*, 7-8.

34 *Ibid*, xx.

35 Allen, “Architecture After Geometry,” 24.

36 *Ibid.*

37 *Ibid*, emphasis added.

38 *Ibid*, 26.

39 *Ibid*, 29.

40 *Ibid*, 27-29.

41 *Ibid.*

42 *Ibid*, 29.

43 *Ibid*, 31.

44 Johann Wolfgang von Goethe, *The Metamorphosis of Plants,* trans. By Douglas Miller. (Cambridge, MA: MIT Press, 2009), 2. In the German original the term “keimender Blätter” is used instead, but “entfaltend” is used later in the poem, hence the choice of the English translation here.

45 Deleuze and Guattari, 53.

46 Christopher Alexander, *The Nature of Order: vol. 2, The Process of Creating Life.* (Berkeley, The Center for Environmental Structure, 2002), 299-322.

47 Wenche Dramstad, James Olson, and Richard Forman, *Landscape Ecology Principles in Landscape Architecture and Land-Use Planning* (Cambridge, MA: Harvard University Graduate School of Design, 1996), 27-33.

48 Benoit Mandelbrot, *The Fractal Geometry of Nature.* (New York: W.H. Freeman, 1983), 16.

49 *Ibid.*

50 Michael Eigensatz, Martin Kilian, Alexander Schiftner, Niloy J. Mitra, Helmut Pottman, Mark Pauly. “Paneling Architectural Freeform Surfaces.” ACM Siggraph 2010.

51 The post is the third most visited with over 18,000 views.

52 Joost de Natris, Comment on blog, *generativelandscapes*. 27 Jul, 2017. generativelandscapes.wordpress.com/2015/05/19/kobmagergade-copenhagen-karres-en-brands-case-study-3/.

53 Deleuze and Guattari, 34.

Chapter 10 - Growth & Development

"Complex machines have to be made incrementally and often indirectly." They have to be grown.[1]

10.1. Introduction

In the last chapter on the Deleuzian categories of *smooth* and *striated* spaces, smooth spaces were identified as spaces exhibiting high degrees of connectivity, which express themselves as topological *meshworks,* while striated spaces were observed to exhibit increasing levels of articulation, associated with topological *trees* and *hierarchies*. Growth can occur in some natural and artificial systems without a corresponding increase in development, but in other systems this is not the case, and the system can only grow if the system becomes more articulated. This is part of a *unitary process* which Ulanowicz terms "ascendancy." The aim of this chapter is to look at *processes* of articulation in increasing detail and to introduce some common algorithmic methods associated with *growing hierarchical* structures.

Figure 10.0: (*page opposite*) An emergent network formed through the cracking of mud. Growth processes are evident in inorganic as well as organic systems.

The processes of growth and development are often associated with organic or living forms, but not all growing structures are biological in nature. Inorganic matter, through various incremental processes of growth, also forms complex structures. The same is true of urban agglomerations and cities, whose patterns of growth can often be modeled using algorithms nearly identical to those used to model much simpler agglomerations, such as bacterial colonies. This is because, as Steven observes, space only provides for a limited set of strategies for relating or connecting objects, and organisms, no matter how complex, must adhere to the fundamental constraints of space. For designers working with algorithmic systems, this realization can help in mining potential strategies for understanding and ultimately manipulating form as strategies used to solve a problem in one context or disciplinary field can often be transferred to solve problems in a seemingly unrelated context.

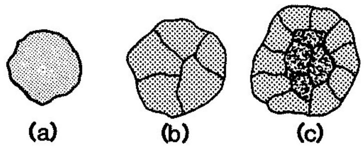


Figure 10.1: (*above*) As certain organisms grow, stratification and differentiation become inevitable, and developed hierarchies must form. Ulanowicz, 159.

An understanding of the patterns and processes associated with growth and development is fundamental for anyone interested in working with complex networks and systems, which has consistently played an important role in landscape architectural discourse. Nearly every complex form, machine, or system, as noted by Kelly in the quote introducing this chapter, should be seen as the product of a process of growth rather than as creation or construction. This same concept, as explored in §4.4. was expressed over 300 years ago by Leibniz in his "Monadology," who asserted that there is "no absolute birth [generation] nor complete death, in the strict sense…what we call births [generations] are developments and growths, while what we call deaths are envelopments and diminutions."[2] It is the aim of this chapter to explore these "developments" and "growths" which generate complex form and ultimately complexity itself.

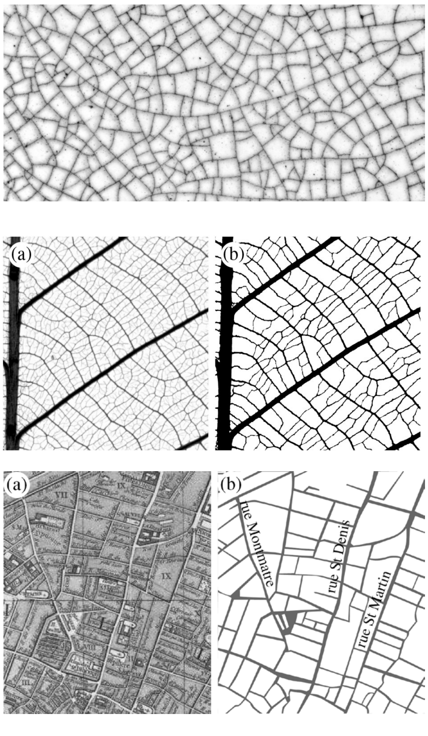
10.1. The necessity of development in complex organisms

The vast majority of life forms that live or have lived on earth are relatively simple, single-celled *prokaryotes* such as algae and bacteria, classified into the kingdoms *monera* and *archaea* (and in some older texts called "monads").[3]

While these organisms often form free-associations and colonies, they do not depend on each other for survival and carry out all life processes independently. Such organisms can multiply and grow rapidly until they reach *homeostasis* with their environment, but they cannot transcend their environment, and as soon as conditions become unfavorable, they die *en masse*. Only organisms which reach a high level of growth *and* development are able to transcend their environment in the state called "ascendancy." For much of earth's history, only *monera* and *archaea* existed, until organisms evolved which were able to catalyze the toxic waste gas oxygen, which soon formed cellular associations known as *eukaryotic* organisms, which made multi-cellular life possible.[4]

Every multi-cellular organism begins life as a single-celled organism, but as the zygote develops, in the articulation happens when by necessity, cells become differentiated into those on the inside and those on the outside of the growing cluster. (Fig. 10.1) The interior cells are protected by sudden changes in environmental conditions, but they also have no access to this environment and cannot obtain nutrients or perform fundamental processes such as respiration and waste removal unless a system develops allowing them to perform exchanges with the outside. The systems in plant and animal bodies need to develop in a fashion with a high degree of articulation to ensure the distribution and removal of resources is not left up to chance, so in general, non-redundant networks (*trees*) are favored as opposed to meshworks. In animals, the body plan generally falls into the category of the "spiral" body plan or the "radial" (branching) body plan. The decision which of these two plans will be used is made early in the organism's development—upon the second division of the developing zygote—where the use of either "radial" or "spiral" cleavage determines whether the animal will become a protostome (mollusk, insect, worm), or a deuterostome (starfish, bird, human). The process is actually much more complex than what is here described, but even with this simplified description, it should be evident that early morphological variations in a developing system will have long-term impacts on that system's developing topology.

Figure 10.2: (*below*) The process of cracking can be compared to the development of tree structres as well as urban plans. In the top image of cracked porcelain, the longest cracks are generally the earliest ones, just as in an emergent city, where the longest streets often represent the earliest roads. Such patterns contain, in a way, a history of their formation.



10.2. Branching Structures – Functional or Aesthetic?

The presence of a complex topology, however, does not always denote the presence of a complex system. As previously discussed, growth and development in organisms requires a mechanism for articulation, with branching structures being one of the most suitable for distributing matter or information from a single point to many destinations. Both Stevens in *Patterns in Nature* and Ball in *Nature's Patterns: A Tapestry in Three Parts* devote significant attention to the properties of branching structures as it is a key strategy for articulation in so many systems. The presence of a branching structure, however, does not necessarily correlate with the presence of a functional system, and branching networks with no apparent function form spontaneously in nature. An example of this is the intricate, but ultimately purposeless crystalline structure of a snowflake.[5] Other examples presented by Ball include mineral dendrites[6] or the cracks formed by paint or mud drying.[7] Intricate branching patterns are also formed by many bacterial colonies. These are of limited functional importance for the bacteria, as they can survive independently of the colony, but the image may convey the notion of a complex interdependency or even of a multi-cellular organism, but in reality, this appearance of complexity is somewhat superficial.

These examples of snowflakes, mud cracks, and bacterial colonies are mentioned here as they can all be modeled algorithmically using simple logics. (Fig. 10.2) The example of the "Koch Curve," also known as "Koch Snowflake" has already been presented in §6.12. Cracking mud can be modeled by one of the algorithmic examples presented at the end of this chapter. (§A10.3.) Bacterial colonies are often modeled with an algorithm known as the "Diffuse Limited Aggregation" model,[8] (Fig. 10.3) with Batty proposing in his book *Fractal Cities: A Geometry of Form and Function* that the growth of metropolitan agglomerations can be modeled with this system as well.[9] While superficially resembling growing bacterial colonies, can urban dynamics be so reductive in the end that the form of the city corresponds so closely to the function of the city as Batty hypothesizes, or is this a fake image of complex relationship between form and function like the crystal structure of a snowflake? This is an important consideration in all the algorithmic models discussed in this thesis, but especially here. We will return to this question again at the end of this chapter and in the thesis' conclusions, but it is helpful to first look at some of the models of growth showing promise for landscape architects in two quite diverse but related applications—in algorithmic botany and in urban modeling.

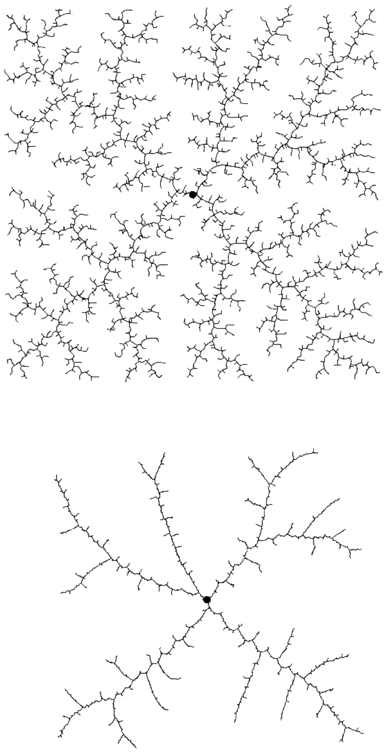


Figure 10.3: (*above*) Results of a Diffuse Limited Aggregation algorithm.

10.3. Algorithmic Botany

One of the clearest potential applications of algorithmic methods in landscape architectural practice is with the use of procedurally generated plants. While such tools are developed mostly for the use of computer artists aiming to create visualizations for games and films, at least one engine, Lenné 3D was developed by a team of landscape design professionals specifically to create a software environment addressing landscape architectural practice.[10] This engine specifically aimed to create visualizations to aid in the communication between experts and the general public with a user-friendly interface which hid most of the algorithmic logic in background processes. [11] [12] In reflecting on the processes of digital botany in their practice, two of the creators of the Lenné3D software, Paar and Rekittke sardonically quip:

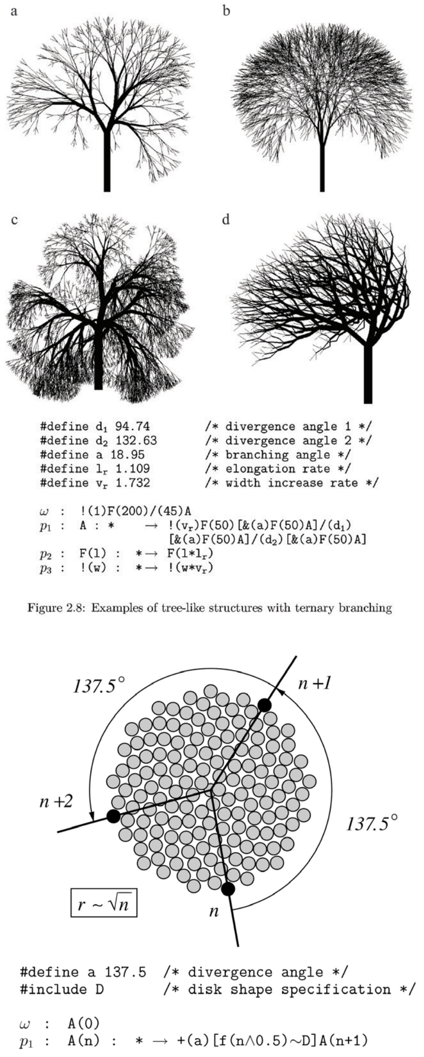
> "Should landscape architects and planners continue to doodle with green crayons until Domesday? Is it really acceptable for the representation of vegetation to remain little more than a pretty and decorative, though unidentifiable, botanical metaphor-even where projects make use of otherwise highly detailed computer-based design plans?"[13]

Paar and Rekittke continue:

> The unique, fascinating and complex potential of vegetation as a design element becomes overwhelmingly apparent as soon as one tries to create digital models of vegetation, especially when the aim is to replicate as nearly as possible the mosaic structure, distribution and forms of actual natural herb vegetation communities."[14]

Twelve years after Paar and Rekittke's article, the tools of digital botany have improved considerably, but their use remains largely confined to high-end visualizations and their use as a design tool is limited. Perhaps a deeper understanding of the algorithms at work to create the plants would expand their use as a design tool.

One of the most comprehensive collections of algorithms used for digital botany, with applications transferred to other design processes, comes out of the collaborative research of Astrid Lindenmayer at the University of Utrecht and Przemyslaw Prusinkiewicz based at the University of Regina, later at University of Calgary, and published in 1990 in their text *The Algorithmic Beauty of Plants*. They note that mathematicians have long been



```
#define d1 94.74        /* divergence angle 1 */
#define d2 132.63       /* divergence angle 2 */
#define a 18.95         /* branching angle */
#define lr 1.109        /* elongation rate */
#define vr 1.732        /* width increase rate */

ω  :  !(1)F(200)/(45)A
p1 :  A : *     →  !(vr)F(50)[&(a)F(50)A]/(d1)
                   [&(a)F(50)A]/(d2)[&(a)F(50)A]
p2 :  F(l) :  *→  F(l*lr)
p3 :  !(w) :  *→  !(w*vr)
```

Figure 2.8: Examples of tree-like structures with ternary branching

```
#define a 137.5  /* divergence angle */
#include D       /* disk shape specification */

ω  :  A(0)
p1 :  A(n)  :  * → +(a)[f(n∧0.5)~D]A(n+1)
```

Figure 10.4: (*above*) Code snippets from Lindenmayer and Prusinkiewicz‘s *The Algorithmic Beauty of Plants.* The top image represents the results of advanced L-systems for creating trees, while the bottom image simulates the plant process of phyllotaxis. Prusinkiewicz and Lindenmayer (199

fascinated with certain geometric structures in plants, such as the "bilateral symmetry and beauty of leaves, the rotational symmetry of flowers, and the helical arrangements of scales in pine cones"[15] In this vein, their research extends this legacy through an exploration of first, "the elegance and relative simplicity of *developmental algorithms*, that is, the rules which describe plant development in time" and second, through a study of the process of self-similarity, identified by Mandelbrot as a characteristic of fractal forms.[16] In their book, they use a family of algorithms known as "L-systems" as a point of departure, which are explained at the end of this chapter in the first algorithmic example (§A10.1). They describe numerous additional algorithmic processes able to model other morphological features of plants, including several models of inflorescence,[17] the rotational "packing problem" known as phyllotaxis,[18] and methods for organs such as leaves.[19] (Fig. 10.4)

Prusinkiewicz has continued Lindenmayer's legacy through the Algorithmic Botany Lab associated with the computer science department at the University of Calgary. The group continues publishing several papers every year in this unique interdisciplinary collaboration between "computer science (computer graphics, formal language theory, programming language design, and simulation), as well as biology, artificial life, mathematics, and physics."[20] Such studies from various disciplines outside the spatial design disciplines can provide a valuable resource for extending and enriching the design capabilities of the computer in the fields such as landscape architecture. In addition to a description of the L-system, an additional example derived from the Algorithmic Botany Team is presented in the second algorithmic example. (§A10.2)

10.4. Procedural Cities

On the other end of the spectrum from plants, algorithms of growth and development have also proven useful in procedural urban modeling. Batty was an early pioneer in using algorithmic methods to model and simulate processes of urban growth as he recognized the patterns which Mandelbrot had ascribed as being part of a language of nature applied also to the growth and development of many artificial constructs such as cities.[21] Batty's observation that fractal patterns are so evident in the patterns of human settlement, at least on the macroscopic scale, suggests that humans are perhaps not so removed from nature as the classic nature-culture binary might suggest. Batty describes how:

> "All the great Utopias from Plato onwards have sought to impose the geometry of Euclid on the city as an example of man's triumph over nature. In this way, art has been separated from science. But this viewpoint has always been opposed in some measure. In the last 50 years, with the realization that social and economic order belies the physical form of cities, the idea that the naturally or organically growing city is optimal in countless ways which we have hitherto ignored, has grown in strength. In short, our view now about the shape and form of cities is that their irregularity and messiness is simply a superficial manifestation of a deeper order."[22]

While Batty's initial interest correlated with the "fractal mania" of the early 1990s, he has since extended his algorithmic methodology for simulating patterns of urban growth in development using other models, such as cellular automata and agent-based methods, which appeared in his 2005 publication *Cities and Complexity: Understanding Cities with Cellular Automata, Agent-Based Models, and Fractals*.[23]

One of the most influential publications in the development of methodologies for algorithmically modeled cities, however, is the concise 8-page paper by Parish and Müller “Procedural Modeling of Cities.” Based on research work conducted at ETH Zürich, they proposed a simple yet robust methodology for generating convincing cities based upon a few input datasets and an “extended” “context-sensitive L-system” inspired by Lindenmayer’s work in algorithmic botany.[24] The system as developed by Parish and Müller takes raster maps containing physical data such as topographic elevation, land, water, and vegetation, as well as socio-statistical maps such as population density.[25] Variables such as housing density and height and overall street pattern can be parametrically changed. The algorithm then begins to generate a street network based on a simple set of global goals and local constraints. The global goals might be, for example, to connect population centers. Local constraints deal with how new streets connect to existing geometry.[26] The system is, in effect, a more developed interpretation of the system of growing lines presented as algorithmic example 3 at the end of this chapter (§A10.3). Once roads are generated, building blocks and parcels are identified, after which buildings themselves can be modeled.[27] In the end, the cities generated parallel existing urban morphologies in striking detail. (Fig. 10.5) The system was so successful, Esri paid for the rights to their methodology and it forms the core methodology of their CityEngine software.

Several adaptations of the Parish and Müller model have been created by others. One such interesting plugin for Rhino-Grasshopper was created by Sven Schneider and Martin Bielik of the Bauhaus University in Weimar. The plugin, called decodingspaces, contains among several well-developed tools for urban analysis, a methodology for procedurally generating a street network informed by topography and existing urban geometries, after which blocks can be extracted and in turn divided into parcels.[28] Results of some preliminary tests are contained in Figure 10.6. The use of such tools to enact large scale planning projects was one of the initial goals of many associated with landscape urbanism, where the underlying landscape would better inform planning models rather than relying on superimposed grids. These “adaptive” plans could be further informed

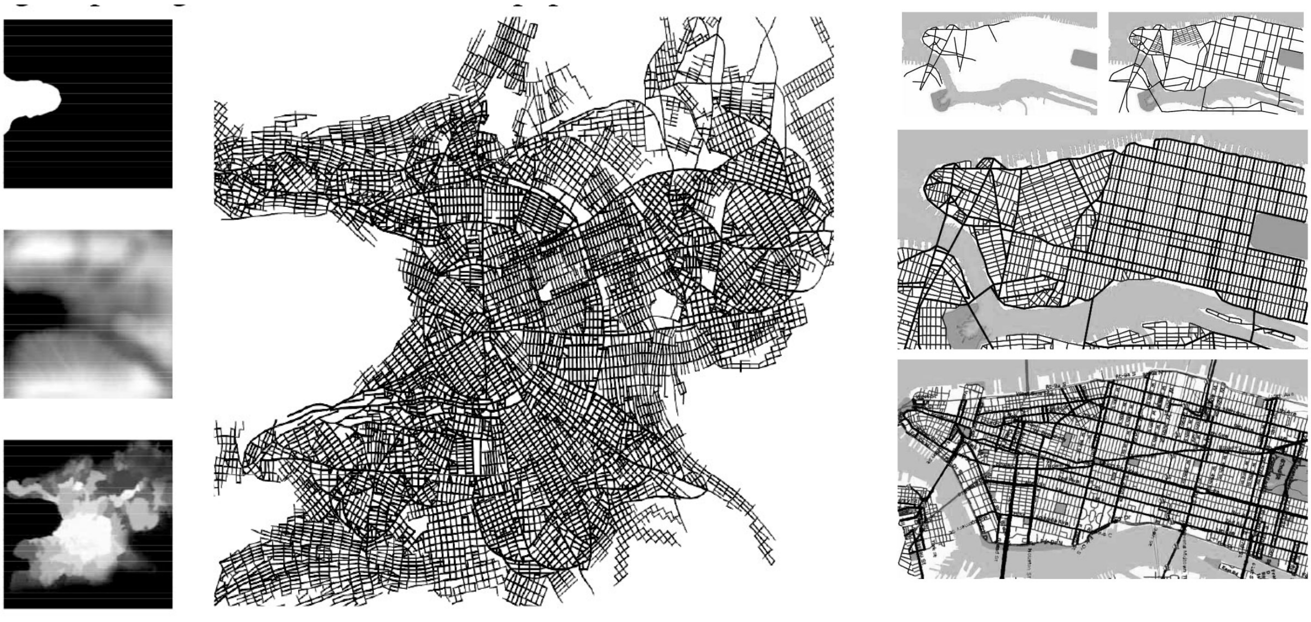


Figure 10.5: (*below*) Diagrams from Parish and Müller‘s explanation of the CityEngine System. Heightmaps for factors such as topography and population density (left) and a series of general rules for block type inform the internal and external logics of the system. At right, a comparison between a procedural generated Manhattan, and the actual street network of th earea is shown.

Figure 10.6: (*above*) Preliminary tests of the block and parcel subdivision algorithm developed by Schneider and Bielik applied to the Limmer Wasserstadt in Hannover.

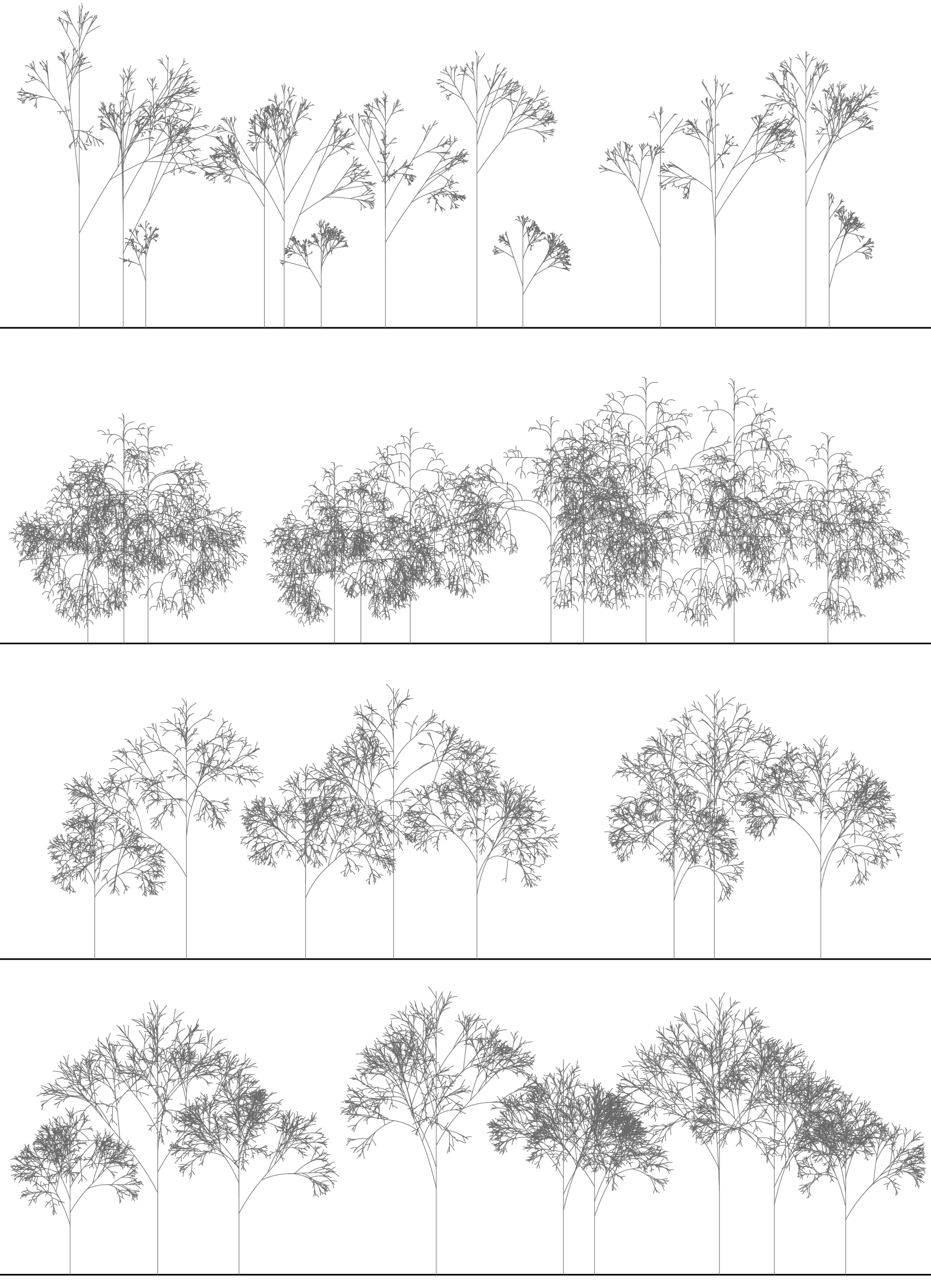
with other algorithms to “evolve” planned cities, giving them the character of cities that had grown organically from day one. Already introduced of computationally evolved cities were Thom Mayne’s proposals in *Combinatory Urbanism*. (§5.12.) Another excellent book demonstrating such approaches is Tom Verebes’ *Masterplanning the Adaptive City: Computational Urbanism in the Twenty-first Century*, whose goal of developing a “new toolbox for adaptive masterplanning” relies on to tools of simulations and video games such as those described above.[29] Despite the rhetoric of the last 20 years, however, and despite the fact we still are in the middle of the fastest period of urbanization in world history,[30] there remain few convincing models of such methodologies being implemented, and planning practices are still producing static masterplans largely with analog thinking, even when digital tools are used as production instruments. Verebes and Mayne both present numerous examples in their books, but these are mostly speculative projects or as yet un-built. The New Urbanists were able to showcase their ideas with Seaside and Celebration; computational urbanism needs to show a counter example to demonstrate the benefits of their methodology as well.

10.5. Chapter Summary and Conclusion

This chapter introduced how many of the spatial apparatuses which promote the growth and development observed in natural and in human systems, and which in turn can be *approximated* through algorithmic modelling. Straightforward algorithmic processes have been used to productively model form in organisms such as plants on the one-hand, and cities on the other. A significant question lies open, however, as to whether these models are, to use a concept introduced in §2.6, *isomorphic*—that is, do they really express the deeper reality of the underlying processes which produce form in systems, or is the similarity only superficial?

As noted earlier in this chapter, the appearance of complex structure, such as in snowflakes or magnetic dendrites, also does not necessarily reflect underlying complexity of process. A caution to the methods introduced in this chapter is offered by Orly Shenker in his text “Fractal Geometry is not the Geometry of Nature.” The text appeared in 1994—the same year as Batty’s *Fractal* Cities—at the end of the period of “fractal mania” when fractals seemed to explain *everything*. Shenker provides arguments that: “there is no ground to say that natural objects have a fractal geometry. Mandelbrot’s hypothesis rests on the fact that the so-called fractal images *prima facie* seem to imitate natural forms. However, close examination reveals that this *prima facie* resemblance is both superficial and misleading.”[31] He continues with the observation that there is a “difference between a system and its approximation or idealization. Whenever the two are so qualitatively different that they seem governed by different scientific paradigms, the paradigm relating to the real system is of course to be preferred to that relating to the approximation.”[32] Shenker’s caution seems to have dampened enthusiasm for fractal studies, with Batty and others expanding their inquiry—but his critique may be applied more broadly. Perhaps part of the failure of the computational urban models described previously could have something to do with this lack of *isomorphism*, that computational urban projects appear complex, but that this is only a superficial coincidence, and that upon close inspection, they lack substance. We will return to this thought in the overall conclusion to the thesis, but it is important to bear in mind moving forward.

In concluding this chapter, as in the previous chapters in Part II of this thesis, three algorithmic models are clarified in more detail. The first set of algorithms (§A10.1) looks at Lindenmayer’s L-systems used in algorithmic botany but also in Parish and Müller’s procedural city engine, the second set (§A10.2) looks at another set of algorithms coming out of algorithmic botany for drawing plants with "space colonization procedures." Finally, the third algorithm (§A10.3) presents a method for creating a wide range of patterns through the context sensitive growth and branching of lines.



Algorithm 10.1. - L-System Trees[33]

One of the most commonly used and cited algorithms for generating plant-like forms is the Lindenmayer-System, usually abbreviated to L-system, which grew out of theoretical formalism Astrid Lindenmayer developed in 1968 to explain the “development of simple multicellular organisms” with it being “subsequently applied to investigate higher plants and plant organs.”[34] Like the fractal systems examined in §6.11., L-systems have a set of *production rules* which are repeated through a few recursions or generations. In contrast to the example in Chapter 6*, instead of replacing* each segment or “base” at each recursion with the “generator” geometry, the generator is *added to the end* of certain segments of geometry from the previous generation. In the subsequent generation, these new instances of the generator are scaled down, *self-similar* versions of the geometry from the previous recursion.

Figure 10.8 shows a basic example of this process, with results after two and three generations. The algorithm starts with a single line segment as a “base” or “root.” The *production rule* could be defined mathematically as:

> In each generation (G), add two line segments (S_G) to the endpoint of each line segment from the previous generation (S_{G-1}) (or to the base or root in the first generation). The two lines are added at angles of $A°$ and $-A°$ with respect to the vector of the base segment from the previous generation (VS_{G-1}). The length of the line segments added (Sl_G) is obtained by multiplying the length of the segments from the previous generation (Sl_{G-1}) by a scale factor (f). $Sl_G = Sl_{G-1} * f$.

In natural language, this process might be expressed as: starting with a single line segment, add two segments in a “V” form with the axis of symmetry of the V corresponding with the “base segment.” The segments added are scaled proportionally based on a scale factor and the overall length of the “base” line segment. After this first generation, the overall structure looks like a “Y.” In the second generation, two more “V” forms are added to the two uppermost tips of the “Y” using the same global scale factor, but this time scaling the geometry proportional to the segments of the “V” from the first generation. Also the new “V” forms are added relative to the axes of symmetry of the segments to which they are appended respectively. A tree-like pattern is beginning to emerge. The same process is repeated in the third generation, now with four “V”s added to the endpoints of the segments from the second generation, also scaled proportionally to the segments from the second generation. With these particular *production rules*, after each generation the number of lines doubles. By varying the angle of branching (the inner angle of the “V” and the proportion of reduction for each generation, though, the formal expression of the production rules can be quite different. See Figure 10.9.

By modifying the initial *production rules*, a wide-variety of plant-like forms can be produced. A few examples are demonstrated in Figure 10.10. showing the initial “base” which also indicates where segments in the following generation can legally be added. Additionally, if this process is deployed in 3-dimensions, with factors inducing random variation (stochastic L-systems),[35] the forms begin to resemble real plants. In such a system however, the plants only follow their own internal set of rules, exhibiting no responsiveness to their surrounding context or even to other parts of their own anatomy. If two L-system trees are allowed to develop right next to each other, their branches will overlap and interlock as if the neighbor was not there. This is contrary to the pattern of growth exhibited by plants in nature, where overall form responds to the plant’s relationship to neighbors. An attempt to solve this, at least internally, is introduced in so called context-sensitive L-systems.[36]

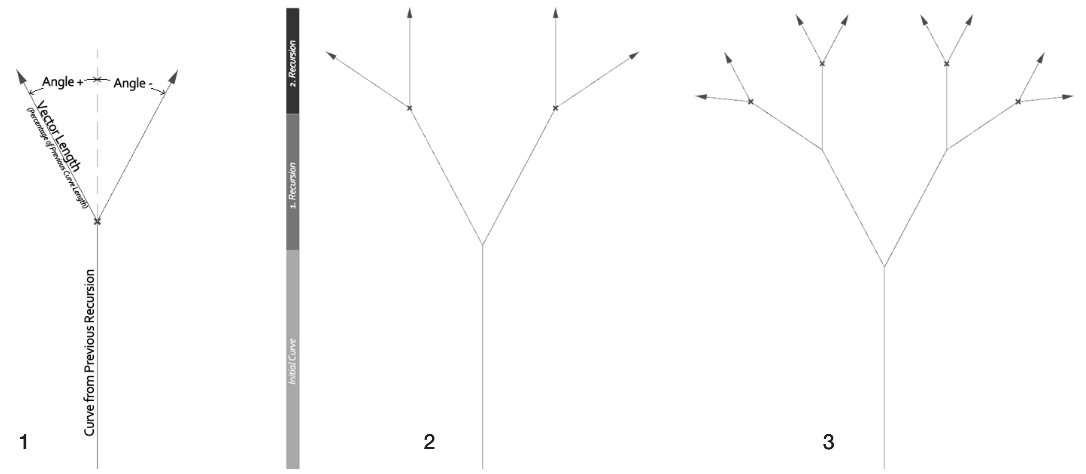
Figure 10.7: (opposite page) Four iterations of a fairly sophisticated L-system algorithm. All trees follow the same general ruleset for branching. Differences between the trees are expressed by changing the arc of branching, changing the random domain of plant height, and modifying a stochastic variable expressing the chance that a new branch might die at each round.

In the top row, the stochastic branch death variable is relatively high. The branches have no arc. The domain for height variation is broad.

In the second row, the stochastic branch death variable is average, with a high branching arc.

In the third row, the branches show a slight arc with a low stochastic branch death.

In the bottom row, there is no branch death, and the amount of branch arc is minimal.



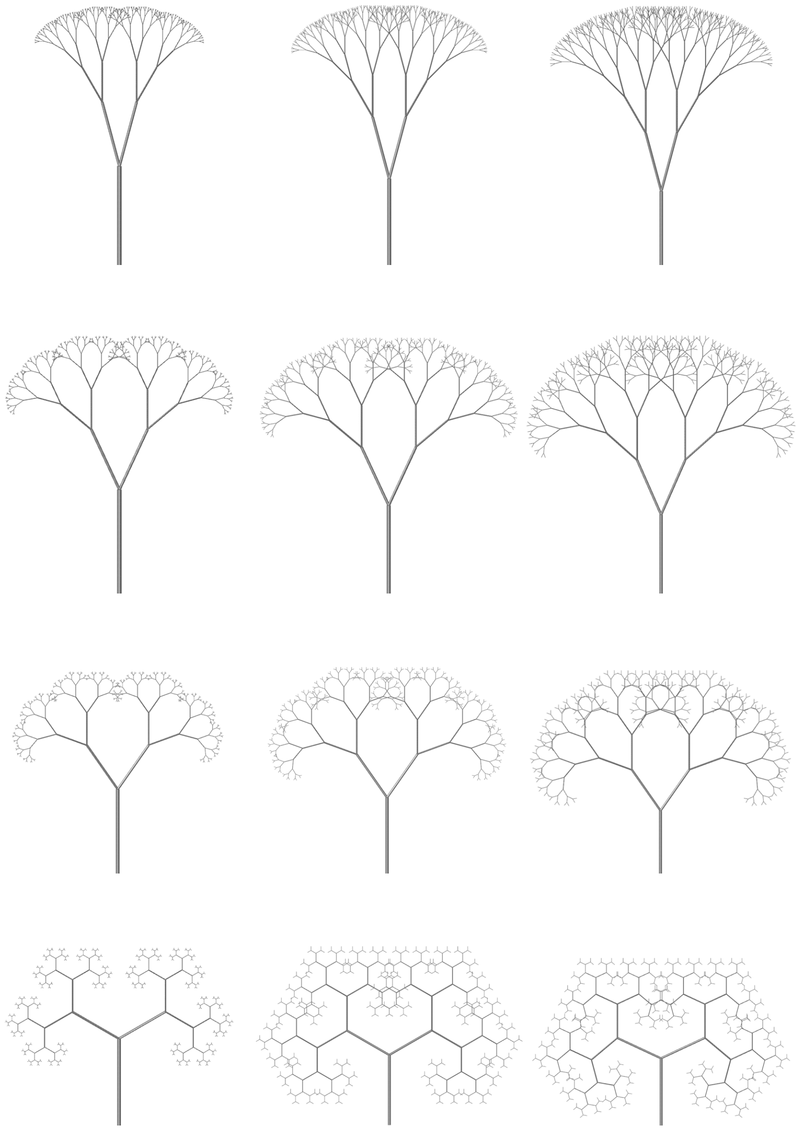


Figure 10.8: (top) The simplest *production rule* adds a V-like branch to segrments from the previous round at each recursion. Here after 1, 2, and 3 recursions.

Figure 10.9: (left) This matrix shows the effects on branching by changing 2 parameters, angle of branching and percentage each subsequent generation is scaled downward relative to the previous generation.

Row 1 - 15° branching
Row 2 - 25° branching
Row 3 - 35° branching
Row 4 - 60° branching

Column 1 - 60% scale reduction
Column 2 - 65% scale reduction
Column 3 - 70% scale reduction

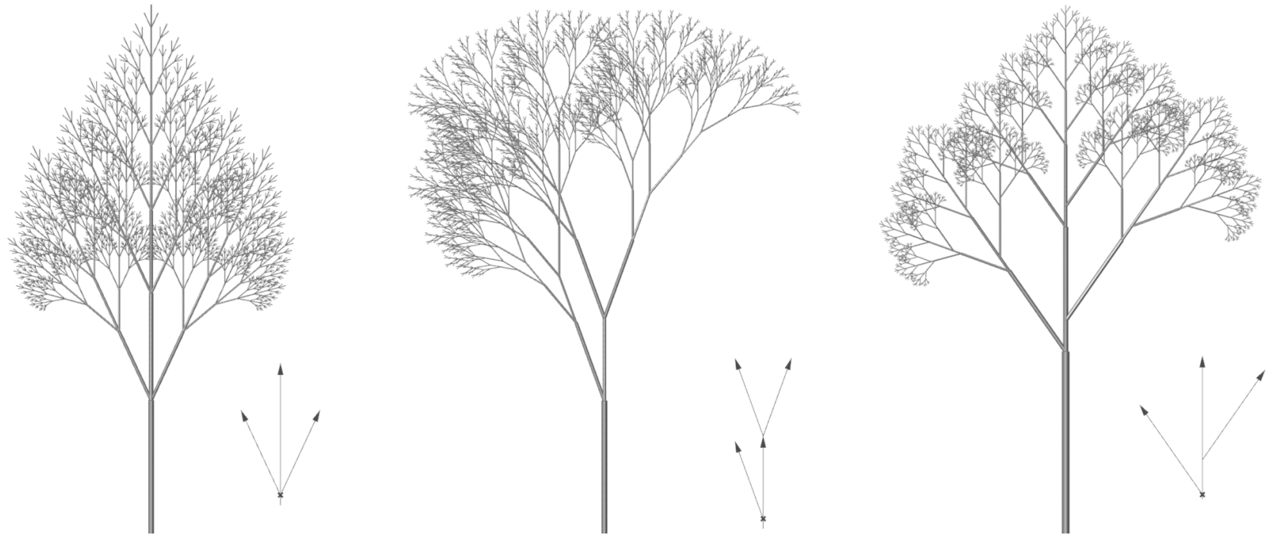


Figure 10.10: (above) Resultantant trees with various production rules. The top left image uses a 3-pronged fork at each generation instead of a V. The middle image uses two sets of branching-a left branch followed by a V in each generation. The right image uses an alternating sequence of branching.

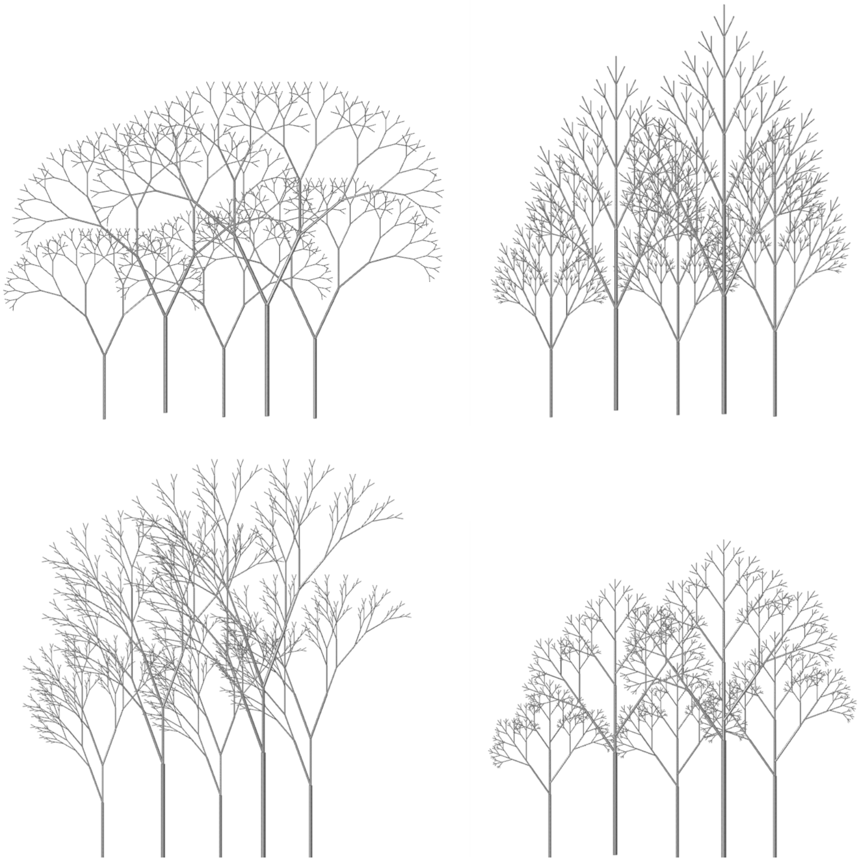
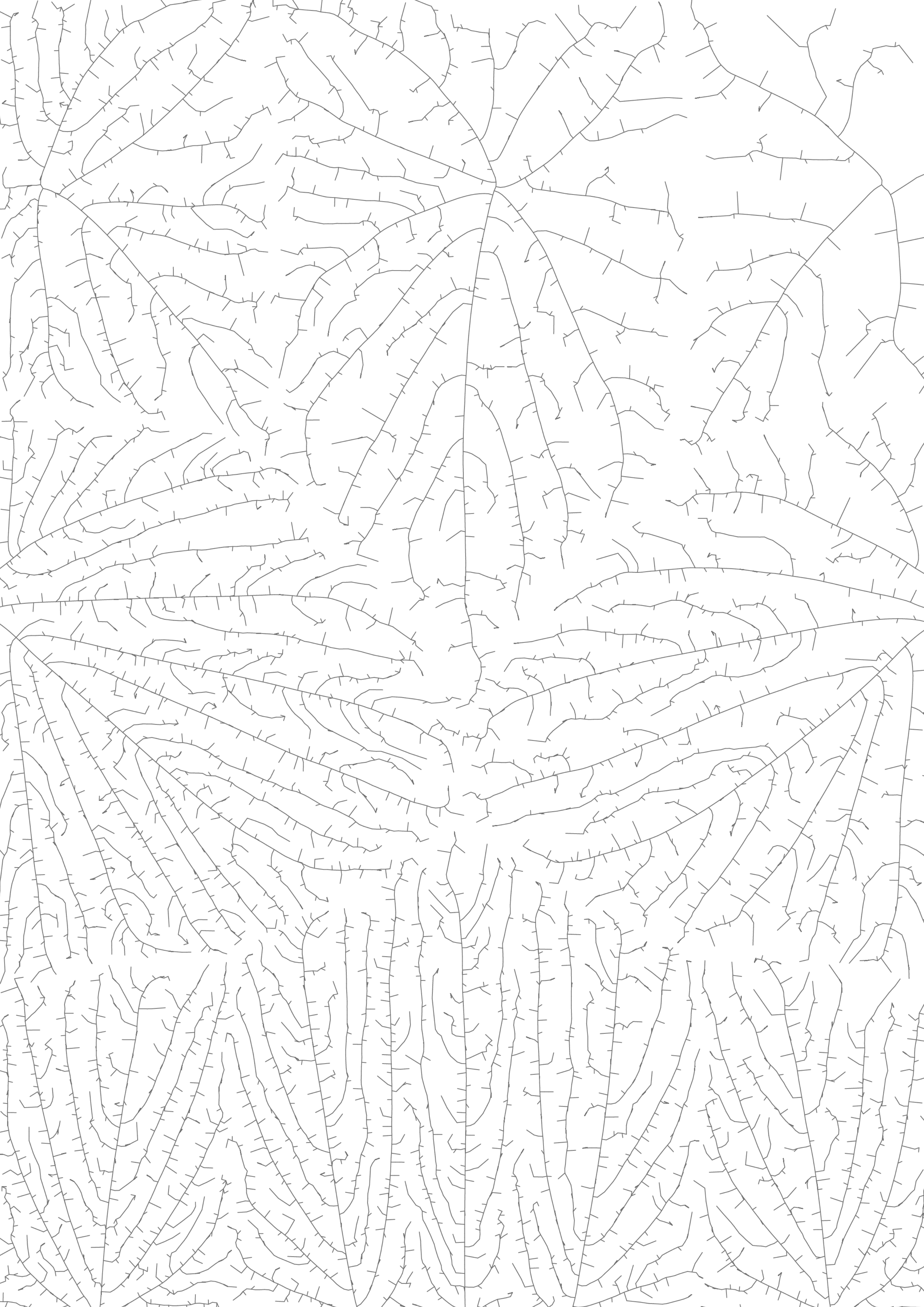


Figure 10.11: (left) Here are small groups of trees using the same production rules, but with initial segments of various lengths. The trees are not context sensitive, and will overlap with their neighbors, unlike vegetation in nature.



Algorithm 10.2. - Auxin Canalization and Space Colonization

L-systems were among the earliest algorithmic studies of the processes of plant development. Based on these initial foundations, the Algorithmic Botany Lab has continued to produce more refined models of plant growth which account for morphological properties that cannot be described by L-systems, or to address deficiencies, such as the neighbor problem, already mentioned. A productive approach to the neighbor problem can be derived from a model for exploring leaf venation patterns, also known as the "auxin canalization method," devised by Adam Runions et. al. at the lab in 2005.[37] [38] "The algorithms," as described by Runions et. al. "simulate the interplay between three processes: (1) development of veins towards hormone (auxin) sources embedded in the leaf blade; (2) modification of the hormone source distribution by the proximity of veins; and (3) modification of both the vein pattern and source distribution by leaf growth."[39] The algorithms as described by Runions et al. deal with many particularities only of interest when looking at the "unfolding leaf" itself, but the core logic can be expanded to problems of many different natures. In developing this algorithm, a simplified explanation of the Runions system provided by the designers Jessica Rosenkrantz and Jesse Louis-Rosenberg at the design studio Nervous System, which they used to design their "Hyphae Lamp," proved extremely helpful.[40]

The algorithm as presented here requires two initial inputs. The first is a "cloud" of points, corresponding to hypothetical "auxin" or hormone sources, with the second input being one or more points from which initial growth begins. Here two initial growth points, with 100 "auxin" attractor points are shown. (Fig. 10.13) The shape, density, and other properties of the cloud of points will have a significant effect on the final outcome. The following steps illustrate what the algorithm does with each recursive loop. For better results, smaller step-sizes and a denser cloud of attractor "auxins" is desirable, but again in the interest of clarity, atypical values are shown.

Looping Procedure in Figure 10.13

1)determine the closest growth point to each auxin attractor.

2)divide the auxin attractor points into sets depending on which of the growth points is closest to them.

3)draw a unit vector from each growth point to each auxin attractor in its associated set. Sum all the vectors together, and reduce the resultant vector length to equal the step size parameter.

4)draw a new growth point in the direction of the vector, connecting these with a "vein" or "canal." Old growth points still remain active and future branching can come from these later.

5)remove auxin attractor points that are close to the growing structure. The auxin hormone has been "absorbed" and no longer has an effect on future growth.

Figure 10.14 show how the structure develops with each round. With few attractors and a low step size, this can happen quite quickly (here after 15 rounds). Figure 10.15 shows the results when many more auxin attractor points are used. Finally Figure 10.16 shows how a row of trees using this methodology would look.

A few refinements to the auxin canalization methodology will improve the scripts results and give it more flexibility. This methodology makes quite convincing leaf venation patterns and is also good for modeling root growth, two patterns where a rigid skeletal structure is not required. The trees themselves feel "weak," however. This is because in contrast to the L-system, which develops its structure based purely on internal rules, this methodology is quite the opposite, where there is no internal rule set, and

Figure 10.12: (*opposite page*) Results of the Auxin Canalization / Space colonization algorithm described in this section.

The initial setup consists of a gradient field of random auxin attractor points, with higher density towards the bottom of the image and a lower density at the top. Veins grow until they colonize all available space but they never overlap.

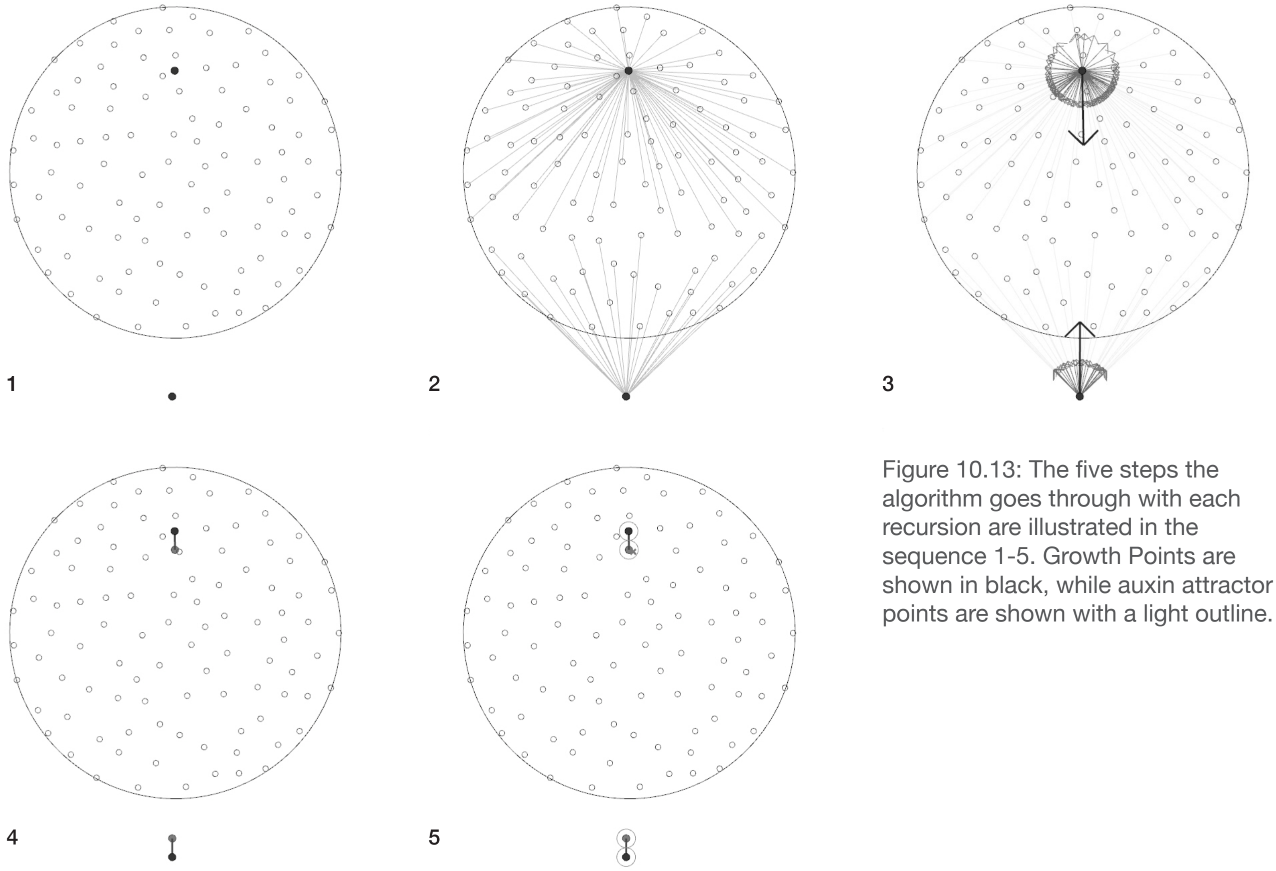
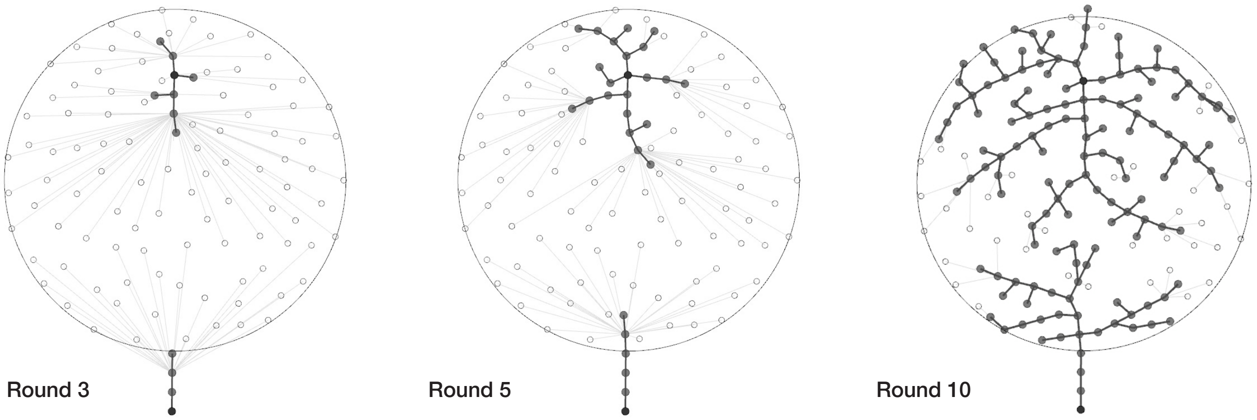
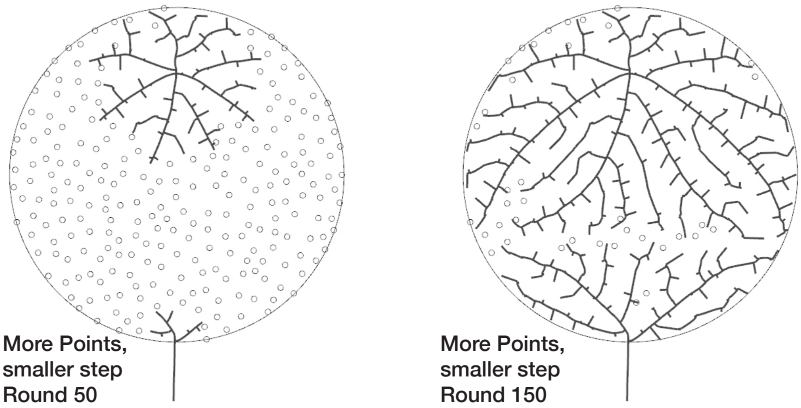


Figure 10.13: The five steps the algorithm goes through with each recursion are illustrated in the sequence 1-5. Growth Points are shown in black, while auxin attractor points are shown with a light outline.



Round 3 **Round 5** **Round 10**

Figure 10.14: (*3rd row from top*) Here the results of the algorithm described are displayed after 3, 5, and 10 recursions.



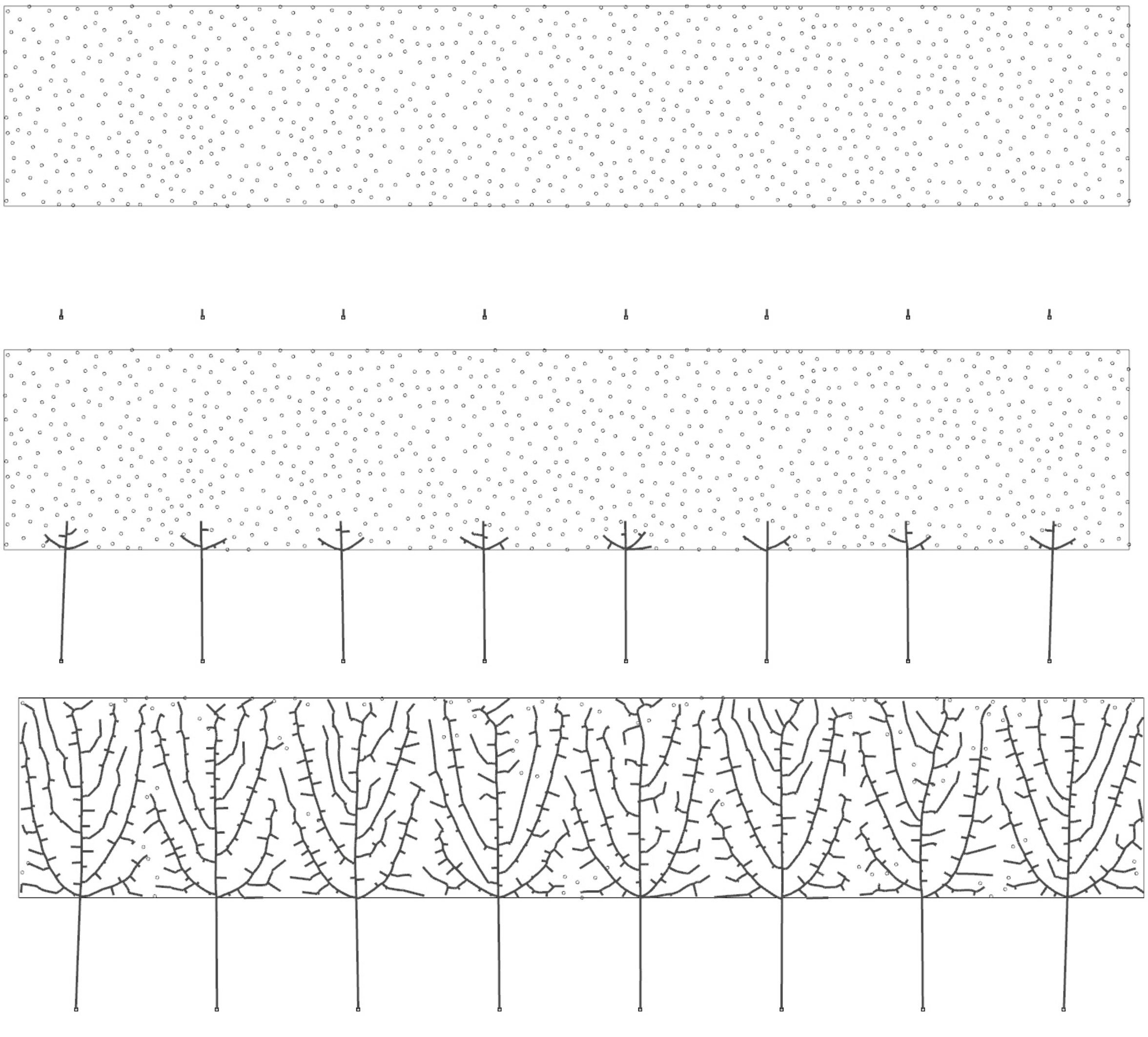
More Points,
smaller step
Round 50

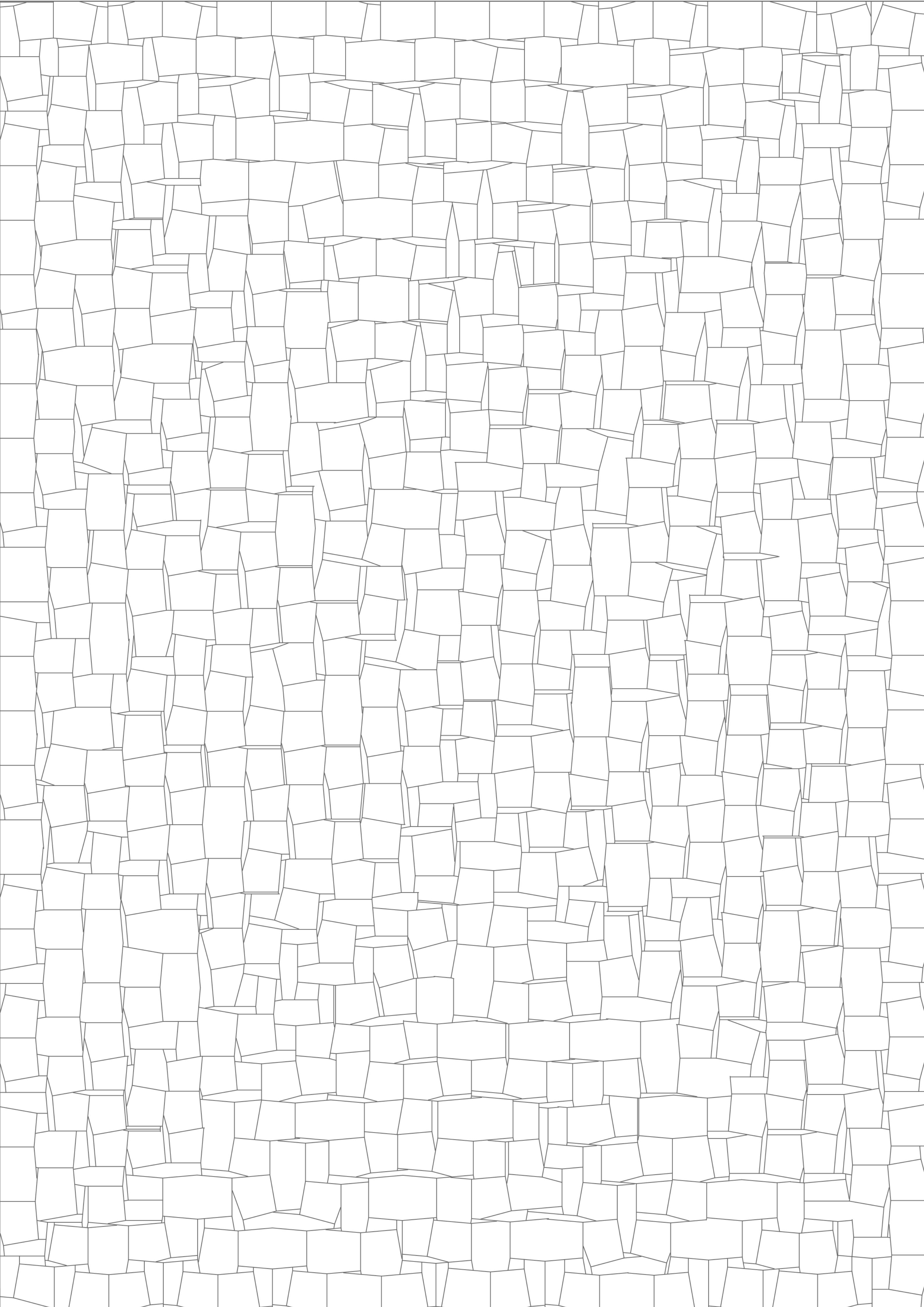
More Points,
smaller step
Round 150

Figure 10.15: (*left*) Here the density of attractor points has been increased and the amount of growth (step size) in each round has been reduced.

the venation patterns deploy themselves purely based on their relation to the field. In the end, the most convincing way to algorithmically model trees in such circumstances would hearken back to Goethe and his musings on the developments of plants (§4.11.), where a strong model for development unfolds into a field of relations, with neither being compromised. Runions himself extended the model originally used in leaf venation into a more robust, 3-dimensional model which accomplished some of these goals, describing the approach as "space colonization." Runions explains how: "Although the space colonization algorithm has been formulated in abstract geometric terms, it is biologically justifiable. In nature, the competition for space is likely mediated by quantity and quality of light. It has been previously postulated that this competition has a significant impact on plant form, and therefore should be incorporated into plant models. Our results amplify this postulate: the competition for space appears to play the dominant role, overriding other factors in determining the overall branching structure of temperate-climate trees and shrubs."[41]

Figure 10.16: (*below*) - In these images, 8 "trees" grow from towards a cloud of points representing the space to be colonized. Branches do not overlap, similarly to plants in nature, but the limbs lack internal structure, being governed almost solely based on "exterior relation."





Algorithm 10.3. - Growing and Branching Lines[42]

A classic lesson on the topic of abstraction in modern art looks at the series of paintings by the artist Piet Mondrian between the years 1908 and 1921. A sequence of six of his paintings are show in Fig. 10.18. Most students of art history will recognize the last painting as a Mondrian painting, and perhaps some of the earlier iterations as well, but the first painting in the series, *The Red Tree,* would generally not be described as "Mondrianesque." Also, if you were unfamiliar with Mondrian's work and someone told you the last painting in the sequence was an abstraction of a tree, you would probably be unconvinced until seeing the entire sequence of Mondrian paintings over the decade of 1910-1920 as he developed his signature style. The individual steps are clear. But the overall jump is not. This story is instructive in the context of the following algorithm which "abstracts" the logic of a growing and branching tree, and when the parameters are properly set it is able to generate abstract patterns that are very close to the patterns to which Mondrian had become famous for. Other modifications of the parameters will generate completely different associations, perhaps to the plumage of a bird, or the cracking of mud baking in the hot sun, to a field of cobblestone paving. This is partly because so many patterns in nature, as previously contended, develop in space using similar procedural logics, if not actual processes of morphogenesis.

The generative logic for these patterns makes use of a very simple "internal" logic of branching combined with a "relational" logic that halts growth. The algorithm develops as follows.

1)Draw starting Lines. In this case, the lines start "growing" from the outer boundary, always at a 90° angle to the outer boundary curve. A random length is assigned to these initial lines based on a random domain.

2)Define two sets of lines— "living" lines which are subject to growth, and "dead" lines which will not grow. The outer boundary curve is the only "dead" line at the start of the simulation, while all other lines can grow.

3)The simulation starts. At each time step, the "living" lines grow by a small parametrically controlled variable amount. After growing, they are tested through a decision tree to see if they will A) continue growing or B) "die." If they pass the first test, a second test determines if their growth will A1) continue growing along the line's current vector or A2) branch into two separate lines.

Figure 10.17: (*left*) - Results of the growing lines algorithm with a 170° angle of branching and a high probability of division once reaching a certain minimum length.

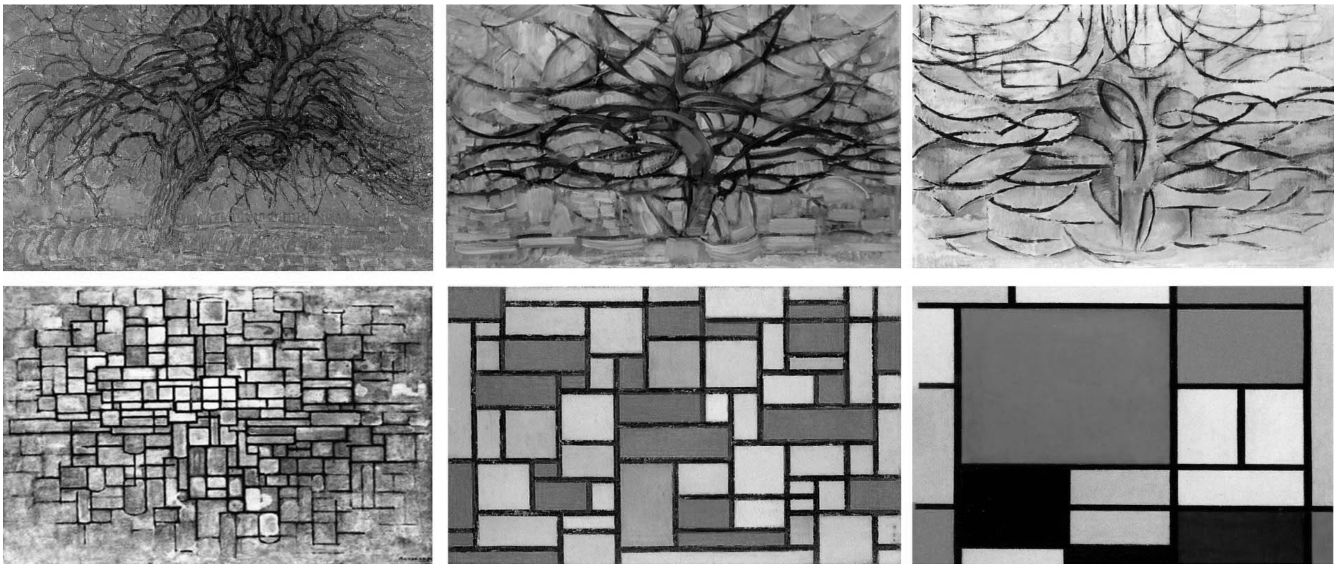


Figure 10.18: (*bottom*) - Evolution of Piet Mondrian Paintings between 1908 – 1921. From figure top left –
1. The Red Tree (1908-1910)
2. The Grey Tree (1911)
3. Flowering Apple Tree (1912)
4. Composition in Blue-Grey-Pink (1913)
5. Composition with Gray, White and Brown (1918)
6. Composition with Large Red Plane, Yellow, Black, Gray and Blue, 1921.

To determine the outcome of the first test, the endpoint is checked for its proximity to all other lines, including both the "living" and "dead" lines. If it is too close to either another "living" or "dead" piece of geometry, it will no longer grow and it is moved from the "living" set to the "dead" set of lines. If it is determined that the line can continue growing, the second test makes use of a random number generator to see if the line will continue growing or if it will branch. The probability of branching starts only when the line has reached a certain minimum length, after which the probability increases gradually as a function of how long it has grown since its last branching. When branching occurs, the root is added to the set of "dead" geometry, and two new lines representing the two new branches are added to the set of "living" geometry. The angle of branching can also be parametrically controlled.

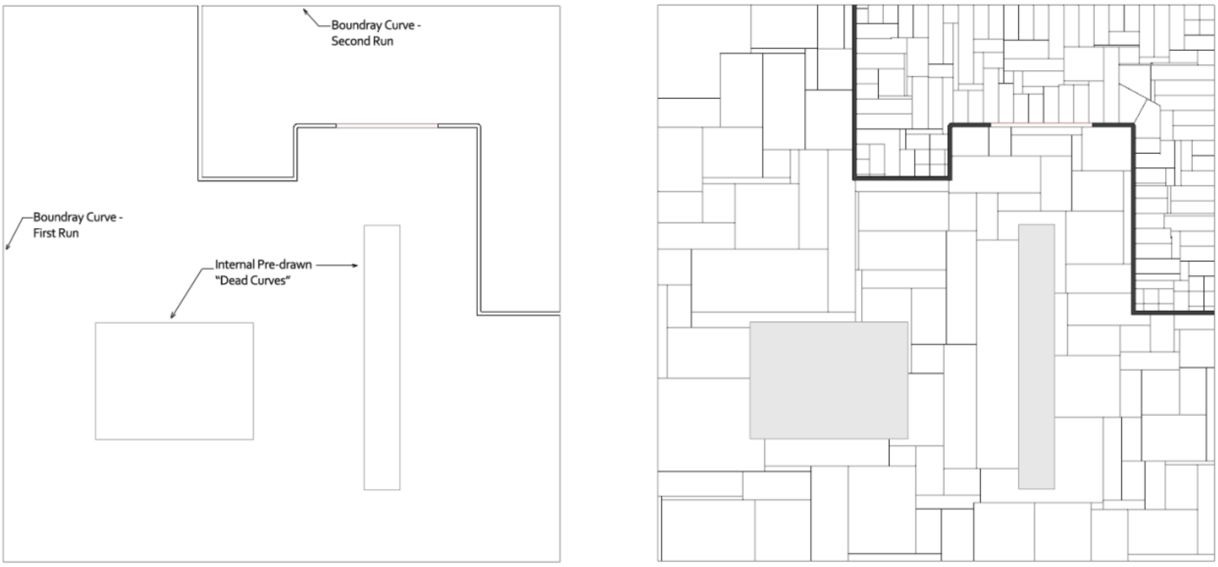
4)The simulation continues until all lines have stopped growing, that is, all lines have been moved to the "dead" set.

Results of running this simulation are shown in Figure 10.19, 1-12, with a description of the parameters below each image.

In these demonstration examples, the simulation takes place in a regular square canvas with randomly generated starting conditions. The algorithm can also work with more complex initial conditions, with boundary curves, initial dead "curves," and the position of initial "living" curves all determined by the user. An example of the algorithm applied to such a context is shown in Fig. 10.20.

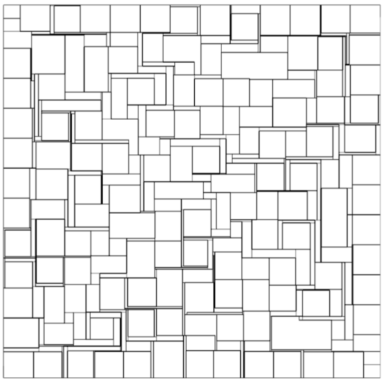
Figure 10.19: (*opposite page*) - Results of the growing lines algorithm with various parameters as indicated.

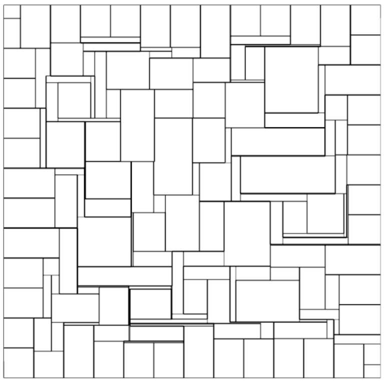
Figure 10.20: (*below*) - Results of the growing lines algorithm as a applied to a hypothetical design problem. The growing lines are context sensitive to user given geometry.

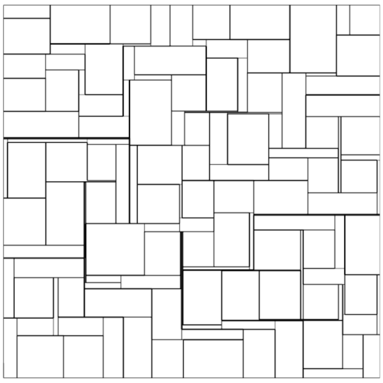


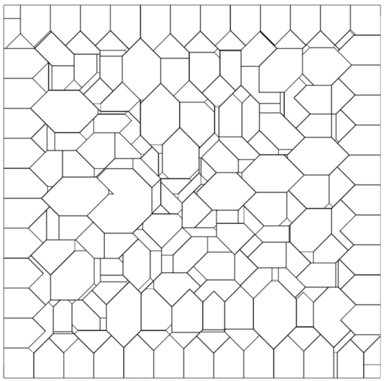
Initial Setup Curves - Practical Implementation

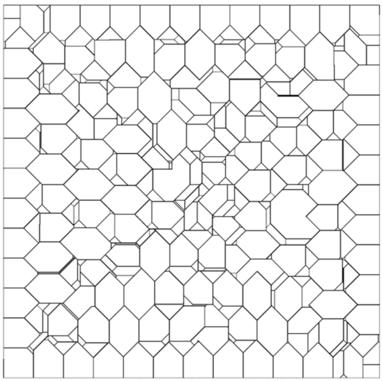
Version 1

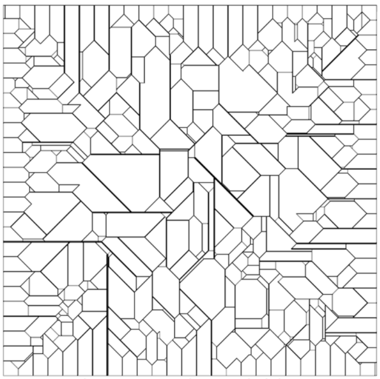

1 - 180° Angles - High Branching Probability

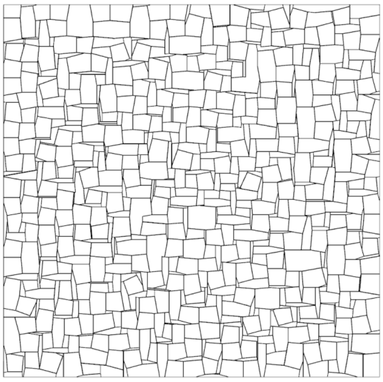

2 - 180° Angles - Low Branching Probability

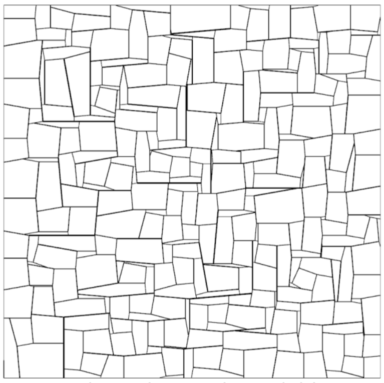

3 - 180°Angles - Fewer Starting Lines

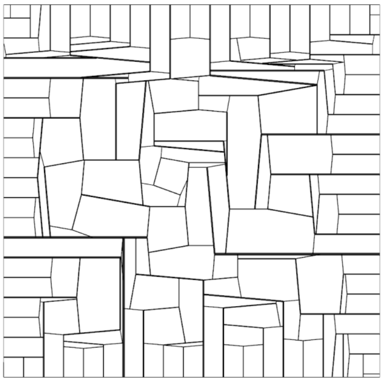

4 - 90° Angles - Medium Branching Probability

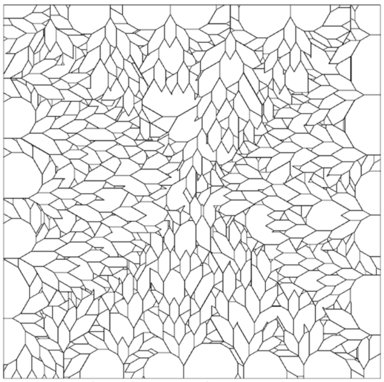

5 - 90° Angles - High Branching Probability

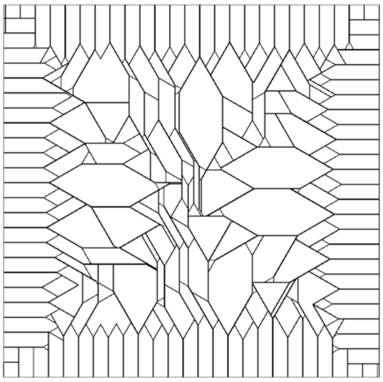

6 - 90° Angles - Low Branching Probability - Many Starting Lines

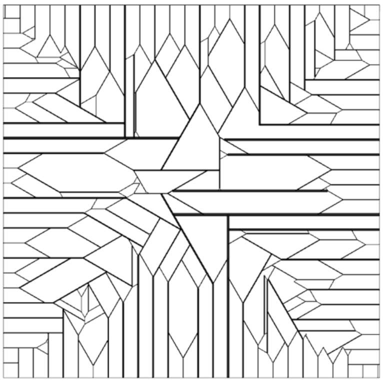

7 - 170° Angles - High Branching Probability


8 - 170° Angles - Medium Branching Probability


9 - 170° Angles - Low Branching Probability


10 - 60° Angles - Short Branching Length - High Probability


11 - 60° Angles - Long Branching Length, High Probability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Endnotes

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Chapter 11 - Forces & Flows

> *The first thing to be properly grasped is that in substances, including created ones, force is absolutely real in a way in which space, time and motion are not… Motion as we experience it is nothing but a relation. – Gottfried Wilhelm Leibniz*[1]

11.1. Introduction

The growth and development of articulated networks as introduced in the previous chapter has been associated with the emergence of striated space. The levels of perceived order in such spaces are only maintained with increased expenditures of matter and energy in an effort to maintain or increase the information level of the system, that is its predictability. While predictable flows of matter and energy are advantageous in many contexts, such systems lose resiliency, redundancy, and a capacity for innovation. A counter tendency in all systems is a trend towards increasing levels of connectivity, which in information theory is considered to reflect higher levels of disorder and entropy. Apparently anarchic systems, however, are not without form and structure, and such systems reveal a certain signature and produce characteristic patterns. In previous chapters, such highly connected networks were identified with the category of smooth space. Such spaces are characterized by vectors of movement, gradients of interaction, and fluid topologies. The topologies here tend to be *meshworks,* not *trees.* If striated space is best described by Leibniz's gardens, smooth space is best described by Leibniz's ponds, and the fish inhabiting them.

Figure 11.0: (*page opposite*) Water at a river weir changing from a smooth and calm state, to a laminar flow over the weir itself, to a turbulent flow at the bottom.

This is the first of two chapters examining algorithmic paradigms for describing and creating some of the forms of smooth spaces. In general because of the high degree of entropy in smooth spaces and their topological variability, smooth systems tend to be significantly harder to describe computationally than striated systems. Also, since indeterminacy plays a bigger role, the predictive capacity of algorithmic models of smooth spaces cannot be as accurately relied upon. In the first of the two chapters, properties of smooth spaces are described in terms of the forces of mechanical and deterministic interactions—the fundamental forces described by mechanics—Leibniz's "pond". In the next chapter, forces and flows are described in terms of *agents*—animal forces with varying degrees of intelligence and agency—Leibniz's fish. Both share many properties, but also introduce unique challenges. In general, the algorithms in the next two chapters describe systems that are largely liquid in nature, either in actuality or metaphorically, in contrast to the crystalline, rigid structures, or the garden-like plants that characterize and describe striated space.

11.2. Dynamic Systems in Art and Science

All forms in nature are interesting on some levels, but two categories have been especially persistent as objects of study and wonder in human thought and culture. The first category are forms exhibiting a high degree of symmetry, regularity, or mathematical order. The phyllotaxic spirals of plants, the regular structures of crystals, or the complex, but characteristic branching of trees, as described in the previous chapter. The second category are the dynamic forms at the edge of chaos, the constantly changing forms on a sheet of moving river water or the clouds in the sky. These forms can be intuitively grasped and even somewhat predicted from one moment to the next, with somewhat stable structures forming for a time, only to fade away in a later instant. Schwenk describes this, borrowing a term from Novalis, as *das sensible Chaos,* the title of his book exploring the forms of water and other “liquid” manifestations through the two divergent lenses of art and science[2]. It is almost required to approach this topic from both of these angles. Because of its ephemeral nature and its lack of form in the traditional sense, it is an immense challenge for artists, including landscape architects, to design systems incorporating water without an understanding of the kinds of transient forms and structures it creates and the patterns which it follows. On the other hand, a purely scientific approach to hydrodynamic systems is equally elusive, with attempts to scientifically describe the turbulent flows of water and air being described as the “graveyard of theories.”[3]

Figure 11.1: (*above*) A study of water from Da Vinci‘s sketchbooks along with a drawing of a woman‘s hair.

It is for this reason that many explorations of the science of water begin not with a scientist in the purest sense, but with the Renaissance polymath Leonardo da Vinci.[4] Da Vinci is equally known today for his contributions as an artist and a scientist, and he was only able to reach his high achievement in both fields because of his careful observational and projective skills on the one hand, and his ability to represent his observations artistically on the other. Ball presents a study of da Vinci’s notebooks, where his sketches of water flowing in a river occur next to sketches of a flowing woman’s hair. It is unclear if he used the sketches of water to understand the flows of hair, or the flows of hair to understand water, but perhaps there is no priority, it is rather a dialogue. Da Vinci himself remarks: “Observe the motion of the surface of the water which resembles that of hair, which has two motions, of which one depends on the weight of the hair, the other on the direction of the curls; thus the water forms eddying whirlpools, one point of which is due to the impetus of the original current and the other to the incidental motion and return flow.”[5] (Fig. 11.1) This dialogue of juxtaposing intuitive linkages across various fluid systems, and of informing rational mathematical orders with artistic explorations, is also seen in the work of designers who have made productive contributions to designing with and around water, such as Herbert Dreiseitl or Lebbeus Woods, (Fig. 11.2) both of whom switch frequently between freehand representation on the one hand and rigorous scientific, engineering, and computational models on the other.[6] [7] In approaching dynamic fluid systems algorithmically, it is imperative to allow the artistic and the scientific to work together holistically, while at the same time recognizing the distinction between the two and the limitations of each approach, and most importantly that just because an algorithmic simulation *seems* scientifically plausible, it may well be nothing of the sort.

11.3. Overview of Fluid Systems in Mathematics

Fluids are substances whose molecular structure is unable to resist any external forces without being deformed, and although liquids such as water and gases such as air have very different physical properties, the same laws of motion apply to both states of matter.[8] The modern understanding of dynamic systems on a mathematical level starts with the invention of infinitesimal calculus by Leibniz and Newton, and especially with Newton’s description of the fundamental laws of motion, and Leibniz’s observations on the continuity of matter and its infinitely divisible nature. Even as liquids can be considered in some respects as substances consisting of discreet individual molecules and atoms, they are described by equations as continuous fields divisible in an infinitesimal manner.[9] To describe the properties of liquid matter, Newton's point forces and Leibniz's notion of the continuous field of forces are often combined in a single mathematical abstraction known as the vector field. A vector at a single point in a vector field is the sum of all the forces acting on a point in space. A vector field abstraction only displays some of the vectors in the overall field, usually in a grid, but this does not mean other vectors are not present and acting in the spaces between the displayed points. In the intermediary points, it is assumed that vectors vary continuously in a manner as defined by the neighboring points. (see §A11.1) A common way to imagine a vector field is as a wind map as often used by weather forecasters. Lines of wind direction show the overall pattern in a simplified manner, but the observer intuitively understands local variations always happen between the broad strokes of the map. (Fig. 11.3)

The vectors in a vector field can be structured or altered by a combination of user defined inputs, with either a scientific or artistic rationale behind these inputs, or both. When governed by scientific principles, two series of equations are often used to structure fields. The first are the Maxwell equations, four equations describing electromagnetic interactions, or precisely how charges produce fields.[10] Apart from gravitation, all forces experienced at scales above the atomic level are ultimately electro-magnetic in origin.[11] These types of fields are further explored in the second algorithmic example at the end of this chapter. (§A11.2) Despite the fact that most forces are ultimately electromagnetic in origin, these equations from electrodynamics are not used to describe the macroscopic behavior of most molecular fluids, which are studied in the fields of hydrodynamics and aerodynamics. In such equations, the fundamental electromagnetic elements such as electric charge and charge decay lose their descriptive potential, and instead the fluid is described in terms of velocity vectors, pressure, density, and viscosity. Equations to model fluids such as water and air may be of greatest interest to landscape designers.

The precise relationship between the variables used to describe fluid flows are described by a series of equations derived first by the mathematician Leonhard Euler (and admirer of Leibniz who also played a pioneering role in the foundations of the mathematics of topology) and elaborated in the nineteenth century by Navier and Stokes. Now known as the Navier-Stokes equations, these equations are the best tool for describing the behavior of fluid systems from thin gases on the one extreme, to water, to oil, to syrup, and even to highly viscous fluids such as ice and glass on the other. The only problem is the equations are nearly impossible to solve, at least for real world practical applications, and especially once a fluid changes from laminar flow, which is flow characterized by one overall vector of movement, to turbulent flow, where backflows and vortices make predictive equations incredibly difficult to solve. Ball describes this difficulty, explaining how "fluid motion is…totally interdependent: the movement of each little 'piece' of fluid depends strongly on that of all the surrounding pieces…Every detail matters. So the problem is difficult not because we don't know what the ingredients are, but because those ingredients are too mixed up to make sense of them."[12] In addition, the process of solving the equations themselves—at least by hand—is a process that even the most devoted mathematicians would find too painfully tedious to perform except under the simplest cases. They must be iteratively solved for hundreds or even thousands of points in space, again and again until finally a solution is converged upon. And if a single initial variable changes the equations must be solved again from the beginning.

Figure 11.2: (*above*) Two drawings from Lebbeus' Woods "Slipstreaming Series" (2010).

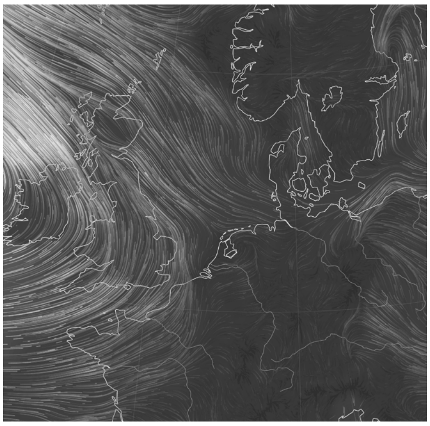


Figure 11.3: (*above*) Fields generated from realtime weather data in April 2018.
Image courtesy of earth.nullschool.net

Von Neumann, who was the foremost expert on hydrodynamics in his day, was intimately acquainted with the power but also the difficulties of nonlinear equations. To devise a tool capable of solving these equations was a primary motivation for von Neumann the mathematician to become von Neumann the computer scientist, who saw in the computer the possibility, at last, to make real use of nonlinear models such as the Navier-Stokes equations in the difficult cases such as turbulence.[13] After using early computers to solve equations to model hydrogen bomb explosions, he turned his attention to the weather as described in chapter five. Von Neumann's dream has only been realized in fits and starts, partly because of the shear complexity of the math and the computational demands required, but also because of the difficulties in defining the inputs into the equations, including the constantly changing and highly variable dimensions of fluid systems in the real world. Von Neumann's dream remains alive, however, and computer hardware and software are at last beginning to reach the point where computational fluid dynamics (CFD) can begin to describe phenomena in complex real-world situations, especially of the nature worked on by landscape engineers and architects. Significant computational and technical challenges remain, but significant hurdles remain, especially in the user's ability to conceptualize and define problems in a way that will give scientifically justifiable results.

11.4. Computational Fluid Dynamics

Computational fluid dynamics as a design and engineering tool has only a brief history with the earliest successful applications stemming from the aerospace industry in the late 1970s.[14] Its routine use remains largely confined to industries such as aerospace engineering and automobile design, and is only beginning to make an impact in engineering disciplines more closely related to landscape architecture, such as civil engineering.[15] Most CFD software is based at the core level on the Navier-Stokes equations as described in the previous section. Typically, engineering students were only introduced to these equations at the end of their undergraduate studies, and only would begin to really work with and understand them in specialized graduate programs.[16] Software packages are working to make this specialized and computationally labor-intensive field open to a broader range of users, and an increasing number of landscape architects, especially in academia, are experimenting with these tools. For landscape architects, the most obvious potential applications of CFD to projects include wind studies and water studies.

Wind studies performed in CFD can help inform decisions at a variety of scales and help improve the performative as well as experiential quality of exterior spaces. Zhou et al. used CFD methods to model flows of pollutants in Liaoyang, China, and to propose a plan for new urban green spaces to respond to the information from the model,[17] but extensions of this model to see how new buildings or new vegetation masses will either amplify or increase wind turbulence in urban green spaces is conceivable. CFD models are also helpful in landscape planning studies surrounding wind power projects, where potential energy yields in relationship to potential landscape changes such as adding or removing plantings can be modelled.[18] A much more subtle application of CFD methodologies in a specific landscape design project is found in Catherine Mosbach and Philippe Rahm's winning competition entry for the Taichung Gateway Park in Taiwan. (Fig. 11.4) Here the landscape architects in close collaboration with the German engineering firm Transsolar developed a CFD model informed by weather

Figure 11.4: (*below*) Plan detail of Mosbach and Rahm's winning entry for the Taichung Gateway Park.

data collected around the site to identify various atmospheric effects, such as temperature, humidity, wind speed, and pollution, and to manipulate these in turn through various interventions to create a tapestry of microclimates to structure the programmatic experience of the park.[19]

CFD water simulations have also been experimented with by a number of practices and academics. Notable examples include M'Closkey and VanDerSys' PEG office of landscape + architecture, whose 2011 *Edaphic Effects* simulated the effect of water flowing across a small test site populated with geo-cells, with the size of the cells themselves, and the distribution of grass vs. water in the cells, informed by patterns observed in the simulation.[20] M'Closkey and VanDerSys have carried out further experiments with CFD software both in their office and in several design studios and seminars at the University of Pennsylvania, modelling the dynamics of rivers and bays, and proposing interventions based on the patterns observed.[21] Chris Reed is also known to have integrated CFD simulations into his design studio curriculum, with the cover image of his recent book *Projective Ecologies* representing a model of a turbulent flow using the software Aquaveo, but without further information it is hard to ascertain whether such images represent actual site dynamics, or whether they are only compelling visual imagery.[22]

Figure 11.5: (*below*) Pavement "vectors" on the Plaza del Torico in Teruel, Spain.

11.5. Computational Fluid Dynamics Applied – Promise and Problems

The question of relationship between the form-giving system and the layers of information present on the site, its *isomorphism* as described in §2.6, is of special interest with the application of CFD methodologies in landscape architectural progress, or as introduced in §6.9, are these algorithms ontogenetic or teleological in nature? It is possible to apply the principles of vector fields in a purely aesthetic manner to create interesting patterns which are not pretending to performance. Two notable examples include a plaza design by Idealice at the Innsbruck Olympic Village in Austria or the Plaza del Torico by b720 Arquitectos in Teruel, Spain. (Fig. 11.5) It is likely more such aesthetic interpretations of complex algorithmic patterning will be seen in projects in the coming years.

Will such models, however, help improve for example, the design of rivers? In some senses, optimism might be called for. Complex computational tools make it possible for engineers to analyze complex river morphologies in ways impossible with traditional methods. Perhaps the modernist engineer's habit of simplifying landscape morphologies in order to simplify the calculational process is a thing of the past. On the other hand, the shear complexity of hydrological systems might advocate for a more subdued approach. In contrast to the geometry of automobiles being tested in the CFD simulations of the past, the geometry of landscape is infinitely more complex and despite constant advances in information gathering abilities, incredibly hard to describe in terms of the discrete and fixed meshes required by CFD software to model boundary conditions, along with the precise inputs and outputs which need to be measured before a CFD simulation can be run. Another important consideration is the current cost of such systems. While in the future prices might come down, commercial licenses for CFD software are very high and purchasing this software might not make financial sense at this time for most landscape design offices.[23] Academics can sometimes obtain discounted licenses or short-term trial versions of the software, but any long term research commitment will require a considerable investment in purchasing and maintaining the appropriate licenses.

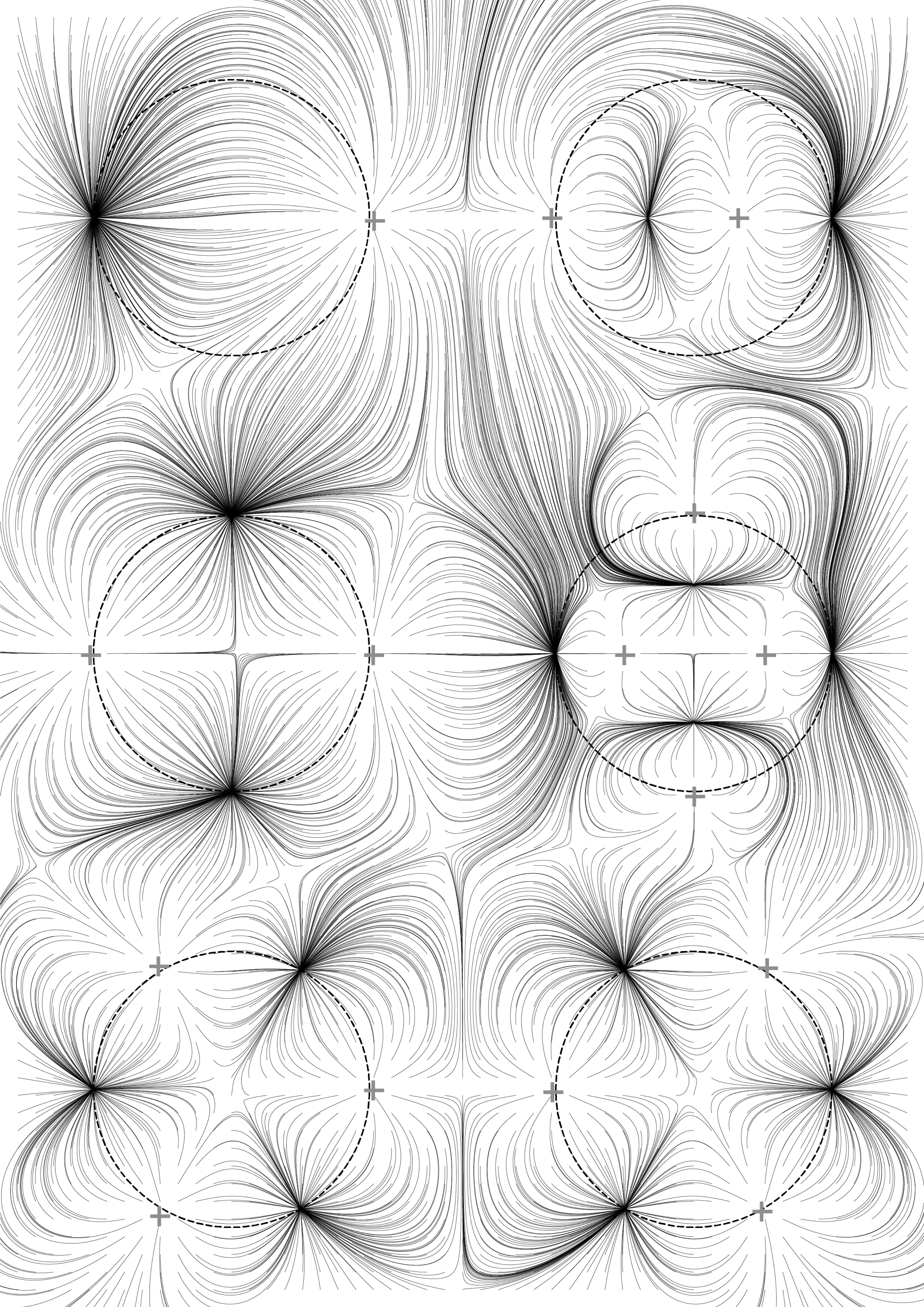
Even should the difficulties with learning the software and obtaining reliable datasets with which to work be overcome, it is also unclear if the

Figure 11.6: (*above*) Drone based photo of George Descombes L'Aire River Restoration project showing erosion as the water channel finds its own ideal course.

designer will be able to, with the help of complex hydrodynamic algorithms along with optimization algorithms, be able to match or surpass the optimization power of nature. In Leopold's important geomorphological study of river geometry, *A View of the River,* the author notes how "each cross section, on any river, has been shaped and dimensioned over time to accept a range of flows. There is a consistency from one river to another, and from one cross section to another, in the way the hydraulic parameters change from low flow to high flow."[24] The difference between low flow and high flow can be on the order of more than 1000 x more water between high and low flows in some rivers.[25] At the same time, the parameters for these cross sections tend to fall within a fairly limited morphological classification system. Would it be more productive for designers to try and understand the general rules for the behavior of fluid systems, and in the end, advocate for measures that define a broad field of possible futures rather than one specific outcome—in effect giving dynamic systems the space in which to find their own way? This was the strategy of George Descombes on the River L'Aire near Geneva, who after 11 years of intense interdisciplinary study of the stream in connection with an ambitious restoration scheme, proposed a diamond-like grid of cells through which the river could in effect choose its own path, and over time, optimize its own form.

11.6. Summary Conclusion

This chapter has introduced some of the complexities and potentials associated with the design of landscapes in the presence of dynamic and elusive fields of energy, matter, and information. The study of systems of dynamic movement—either that of non-living agents such as water or air, or as will be explored in the next section of living human and animal agents—is a rich source of formal and potentially performative inspiration for projects. Computational and algorithmic methods introduce new ways to understand and interrogate dynamic fields in the design of projects. Care must be taken, however, to not oversell such approaches as scientifically tested or engineered, and artistic vision and the intuition of the designer informed through careful study and observation can still play a role. Where stronger performative outcomes are required, landscape architects should devote a considerable amount of energy to understanding the potentials and limitations of the software and algorithms they are working with, and ideally this should be done in close interdisciplinary collaboration with experts from engineering disciplines.



Algorithm 11.1 – Field Lines Generated with Grasshopper

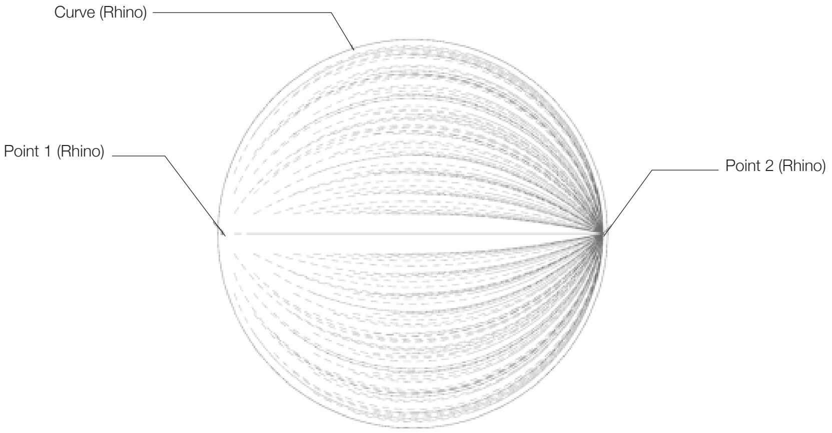
Two major series of equations exist for explaining interacting fields of forces in nature, the Navier-Stokes equations for describing the force interactions of almost any fluid substance, and the Maxwell equations for describing the movement of forces in electro-magnetic fields. As explained in the previous sections, algorithmic descriptions of the Navier-Stokes equations have been integrated into a number of software packages but the workings of these equations are highly complex and beyond a simple description. The Maxwell equations, on the other hand, were recently integrated into a series of Grasshopper "Field" components which make modeling these electromagnetic fields, at least in conceptual terms, rather simple. These components are often used in turn, to represent the movement of some types of fluids in *ontogenetic* algorithmic models of physical fluids such as water and air, although in such cases, care needs to be taken and such descriptions should not be taken as a scientific model of fluid movement.

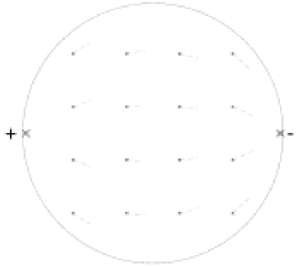
A fascinating mid-20th century book on the properties of fluid systems with a wide-range of figures describing the forms of force is Theodor Schwenk's *Das sensible Chaos* (English: Sensitive Chaos: The Creation of Flowing Forms in Water and Air). An image in the book that attracted the author's attention early in this research was one which describe five basic types of "fields" which can be observed in a circular dish of water when it is gently oscillated with various rhythmic processes (Fig. 11.10, black and white diagrams) Based on these fields, a series algorithms were created to describe these fields individually, and then to speculate on how they might interact with each other. The results of using a series of positive and negative point "charges" to model these fields yielded results which closely approximated these movements in water (Fig. 11.10, blue line diagrams).

Since these components represent a kind of computational "black box" where the exact equations are hidden from the user, no thorough description of the algorithm is given here. By combining these point charges with spin and other types of field forces, however, the complex movement of many fluid systems can be approximated in purely formal ways. Again, these diagrams do not represent a truly *teleological* algorithmic approach, but can serve as a useful artistic tool when other forms of complex fluid modeling are not available.

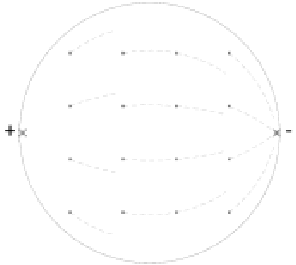
Figure 11.7: (opposite page) Flow lines derived from Grasshopper Field components, which compute forces based on Maxwell's equations.

Here, a series of positive and negative charges are arranged on the edge, and in one case also inside, six circles. Lines move away from areas with positive charges as indicated in the image, and towards negative charges.

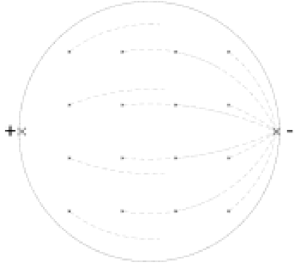




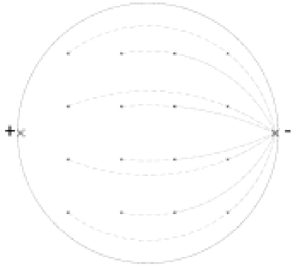
Field Lines Starting at 16 points in Circle
Line Length: 250 Iterations



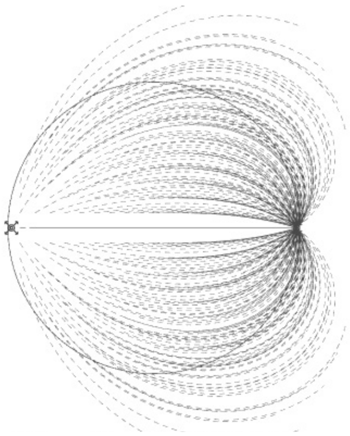
Line Length: 500 Iterations



Line Length: 1000 Iterations

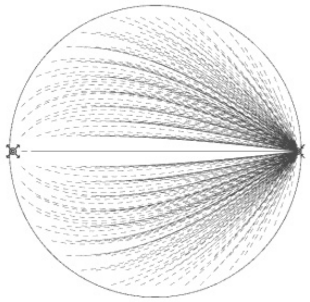


Line Length: 3000 Iterations



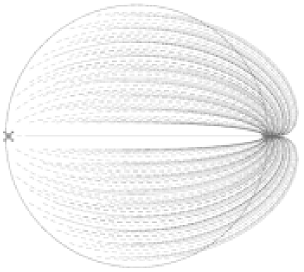
Left Point Charge: +2.0
Right Point Charge: -1.0

Decay Rate = 1.0



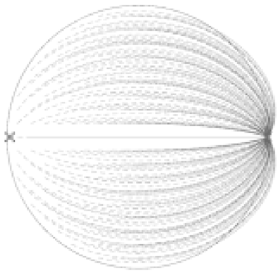
Left Point Charge: +1.0
Right Point Charge: -4.0

Decay Rate = 1.0



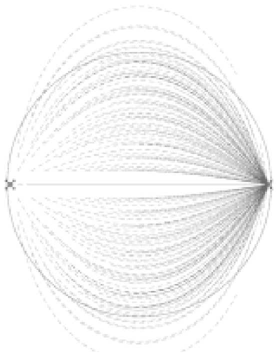
Left Point Charge: +1.0
Right Point Charge: -1.0

Decay Rate = 0.1



Left Point Charge: +1.0
Right Point Charge: -1.0

Decay Rate = 0.5



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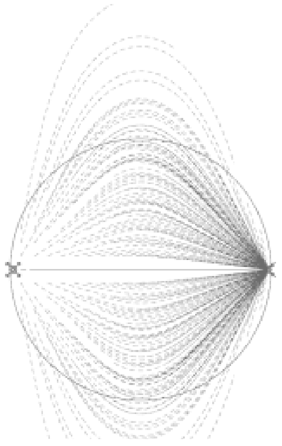
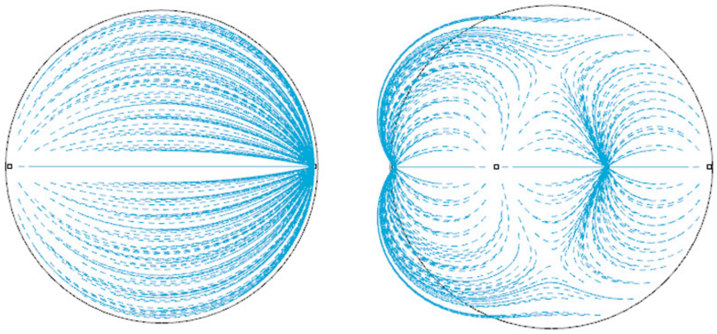
Right Point Charge: -1.0

Decay Rate = 2.0



Left Point Charge: +1.0
Right Point Charge: -1.0

Decay Rate = 5.0



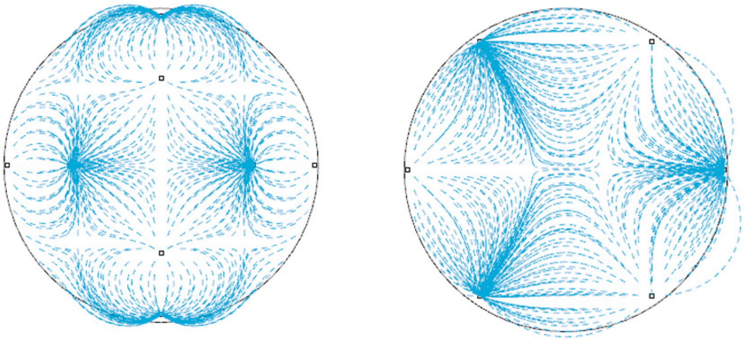
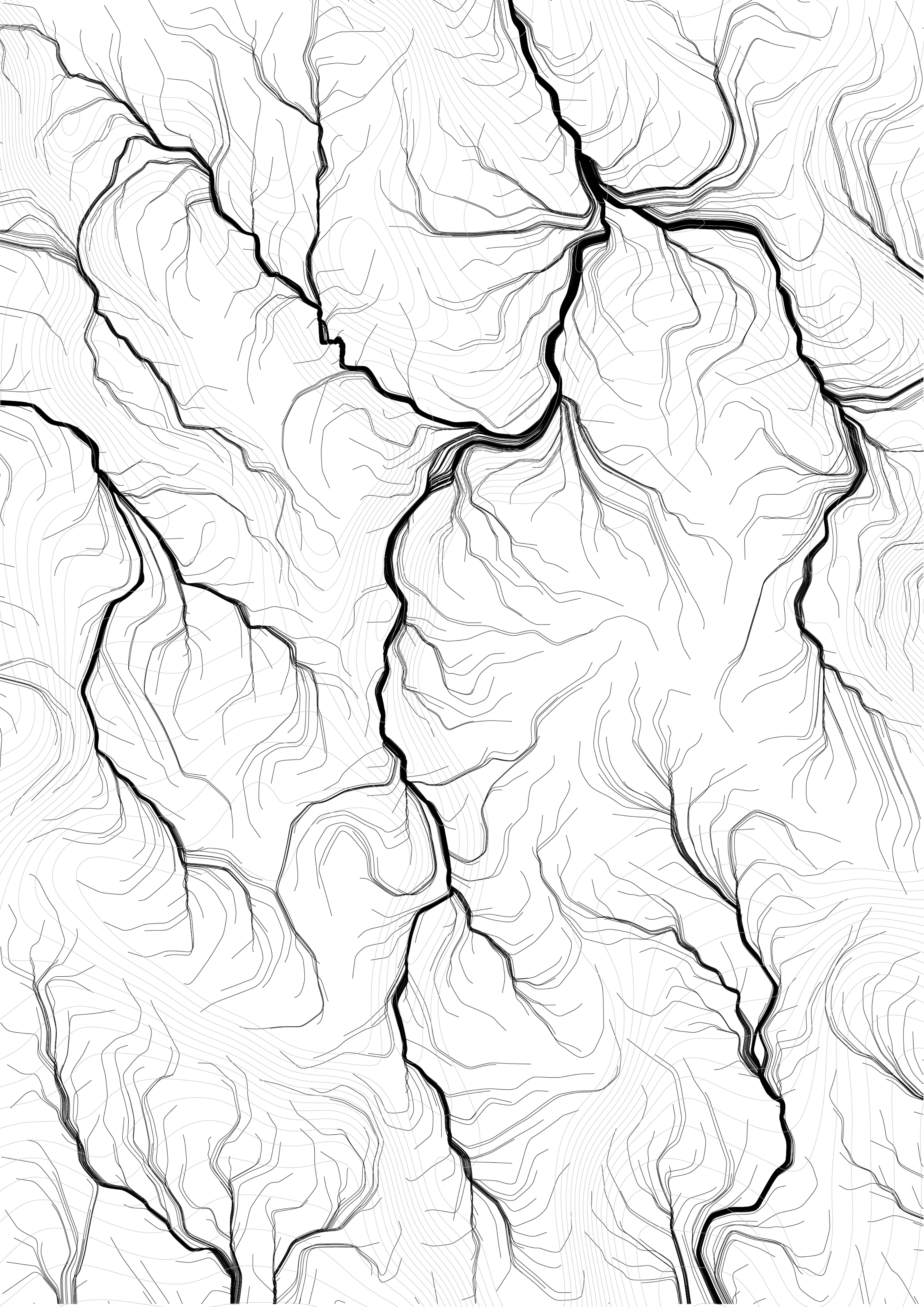


Figure 11.9: (opposite page) Description of algorithmic setup of point charge fields in Grasshopper.

Figure 11.10: (this page) Drawings of patterns of water oscillation based on patterns from Schwenk and Parlenko, along with algorithmic adaptations of the pattern.



Algorithm 11.2. – Flow Field with Noise Functions

This first example illustrates some basic principles of vector fields, in this particular case one reflecting elements of random variation or "noise" based on the principle of continuity expressed by Leibniz and apparent in fluid systems. The algorithm also shows how form and structure can emerge from a continuously varying field.

In many of the previous examples, the algorithm has started with a random assignment of values to points or cells with no initial relationship to neighbors. Values can either converge or diverge through time based on relationships to neighbors or various form-giving processes. Another common approach to describe initial randomness is to apply a "noise" function—Perlin Noise being perhaps the most famous example—where random values are not separated by sudden jumps, but where variation is separated by intermediate steps of continuous values between one point and the next—in other words, random values in a noise function are influenced by the history of prior random values. Figure 11.12 shows examples of 1-dimensional graphs showing the difference between pure randomness and the continuous randomness expressed by Perlin Noise.

In this example, noise is applied to vectors in a two-dimensional grid through a progressive series of rotations. This is done first in the X direction, where values are varied from one column to the next in a series of progressive random rotations from column to column. In each column there is a chance that the vector from the previous column will be rotated +/- the value of a parameter *R*. If *R* is 15° for example, and the vectors in row 1 are 40° from the X axis, the next row of vectors will be rotated such that they can have a value between 25° and 55° from the X axis, and so on. The results of the progressive random rotations are seen in Fig. 11.13 in the bottom left diagram. A similar operation is then repeated in the Y direction, with values now being progressively rotated moving from row to row, also based on a range of values determined by *R*. The progressive rotations of the initial vector in both the X and Y directions are then summed together to create an abstract vector field. These vectors will then be used to steer the movement of "particles" through the field. (Fig. 11.13, bottom right diagram)

To describe the field with particle motion, a series of field lines starting at random points are generated at random points within the vector field, with the density of particles able to be changed by the user. The field lines grow by small increments with the current vector of the growing lines determined by the average of vector of the nearest "steering vectors" associated with the XY grid. What is surprising about this algorithm is that despite this initial randomness, the field lines organize into a network of subtle beauty reminiscent of the flow of water in a watershed. What is also surprising is whatever the value of *R,* the field lines find their way to the edges of the initial XY grid, much in the way rivers tend to find their way to the ocean. (Fig. 11.14)

As a quick experiment in pure formalism, a second algorithm was devised to take the flowing field lines and generate a topographical surface which would cause water to flow across it in the way suggested by the randomly generated field lines. (Fig. The results of one of these topographical extrapolations is incorporated into Fig. 11.11.

Figure 11.11: (opposite page) Field lines through a vector field generated according to the principles described here. Contour lines are generated from a hypothetical surface which might drain water in a way similar to the indicated field lines.

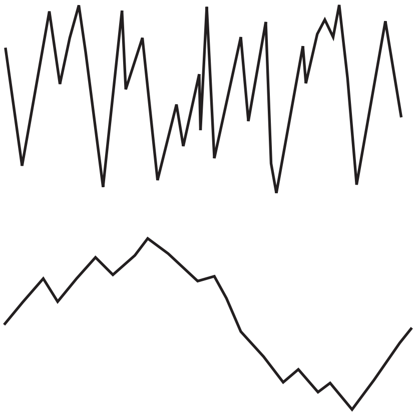
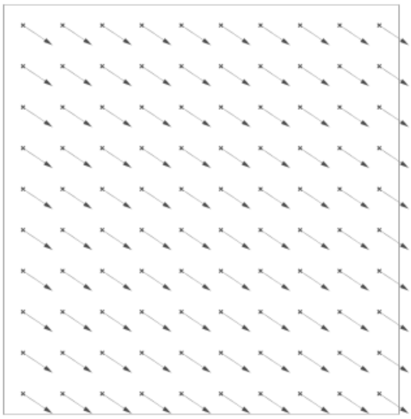


Figure 11.12: (above) A line governed by pure randomness above, and a line exhibiting properties of noise, below.

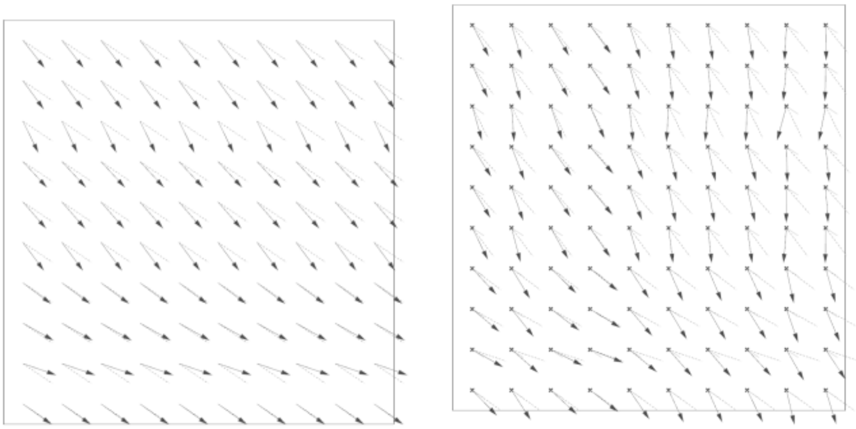
Figure 11.13: (right) Process for initial setup of the vectorfield, where vectors with a uniform initial direction are rotated according to the principles described in §A11.2

Figure 11.14: (opposite page) Variations of the field with variations in the initial input parameters.

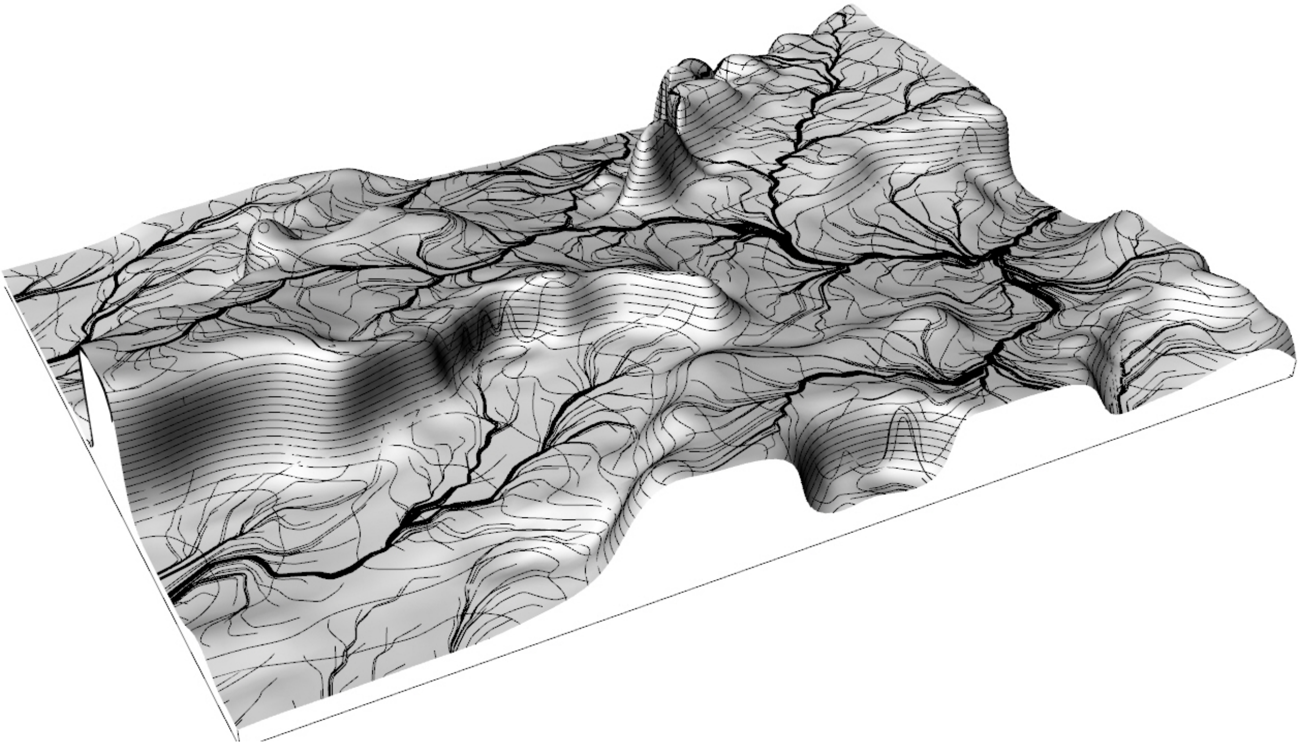
Figure 11.15: (below) One of many possible topographies which could produce the field lines shown in Fig. 11.11. This reverses the typical process wehre a topography is first generated, after which the pattern of flows follows the topography afterwards.

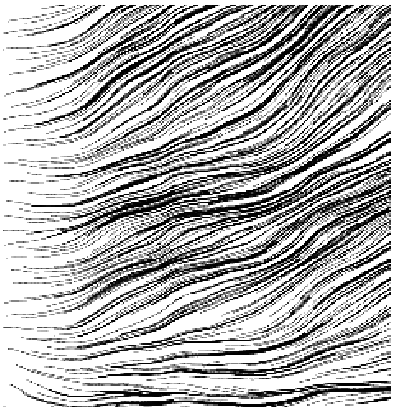


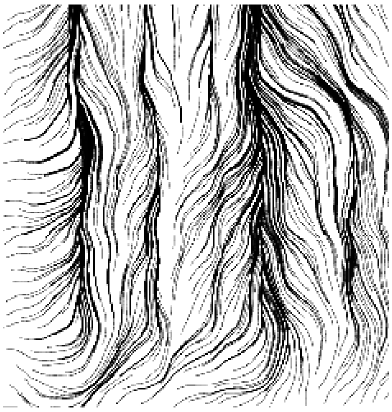
Initial Vectors

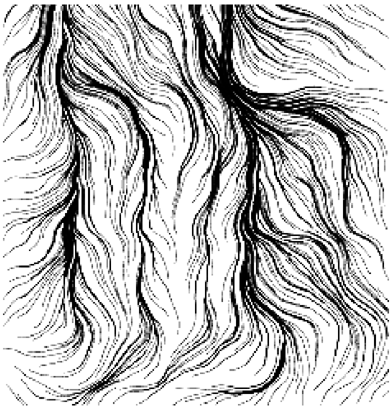


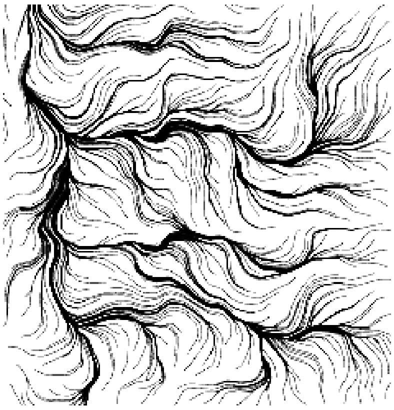
Initial Vectors Rotated

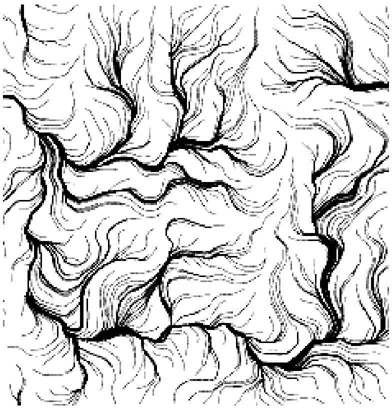


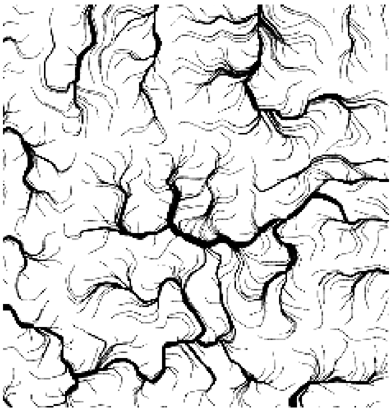


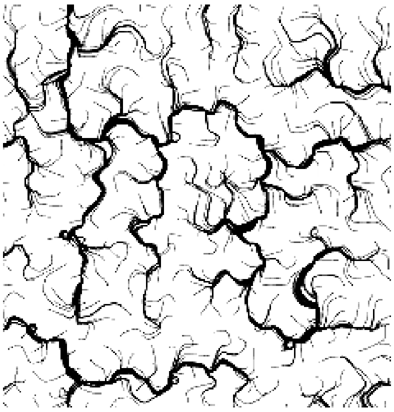


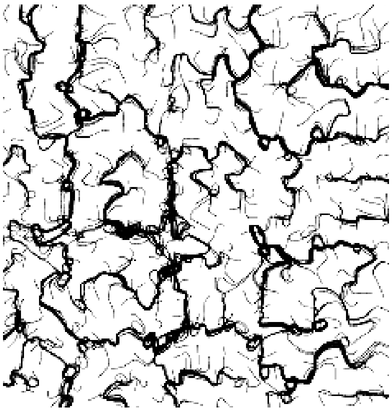


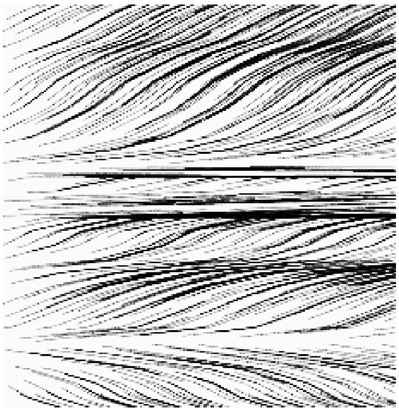


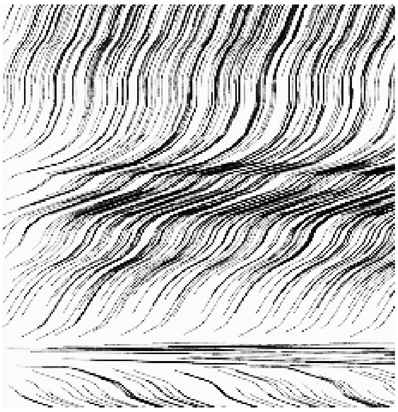


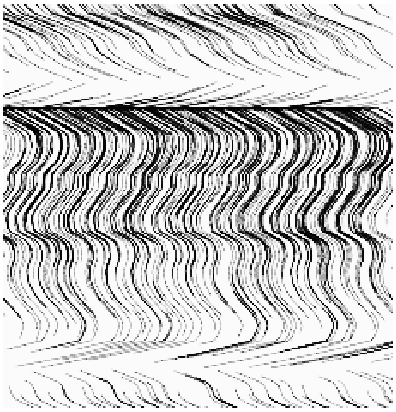


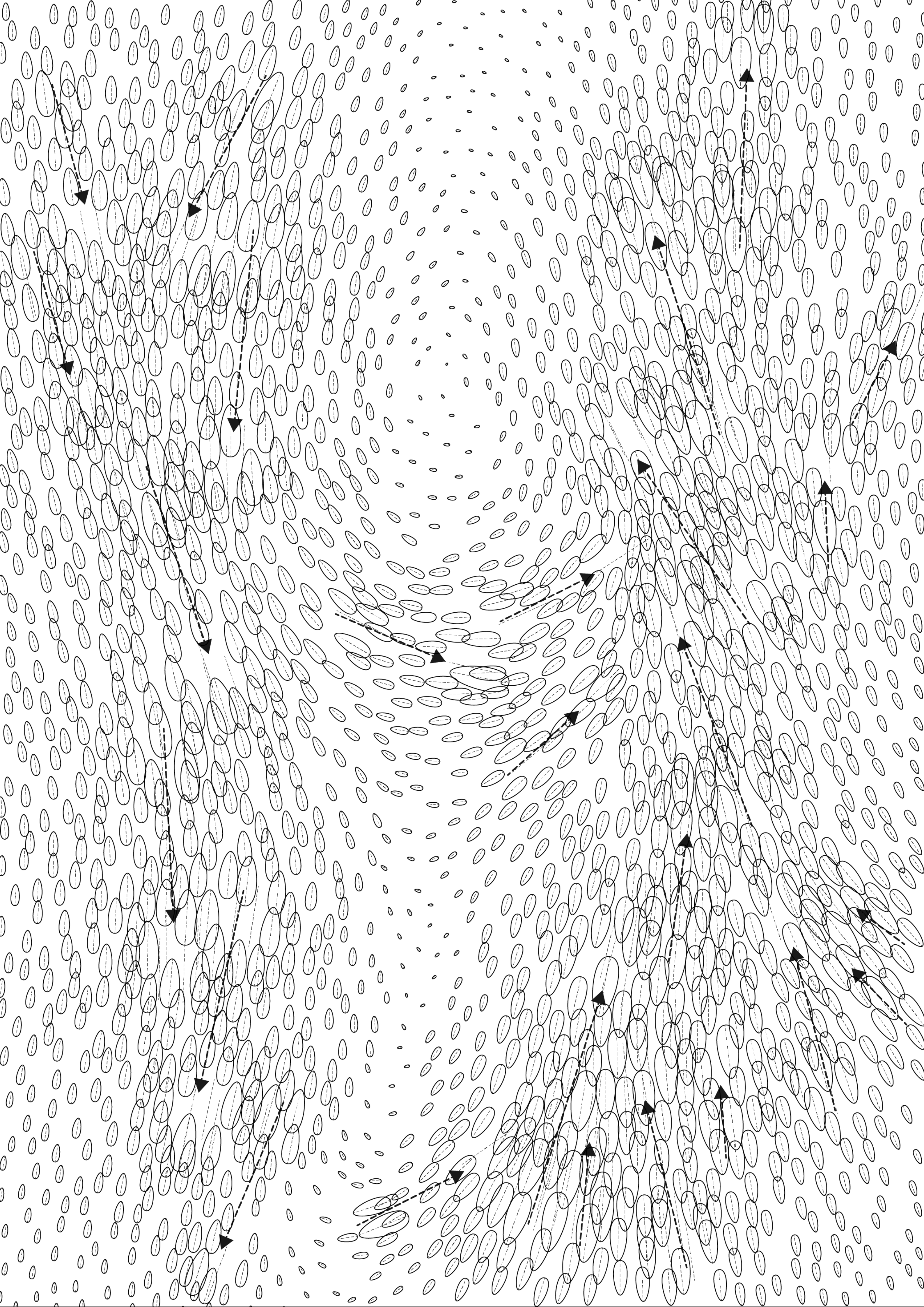












Algorithm 11.3. – Vector Field with User Defined Inputs

Vector fields can be derived from physical laws, such as the Maxwell equations as demonstrated in §A11.1, from an algorithmically generated rule set not grounded in natural laws, but producing form resembling natural structures as in §A11.2, or from user defined inputs. This third method may be of most interest and utility to designers interested in integrating vector fields into a design process which is not necessarily trying to simulate the actions of natural processes, but which seeks to exploit the form giving potentials of vector fields in an iterative design process with a number of requirements and constraints.

The logic here is very simple to that presented in algorithm §A11.2, but instead of using a noise function—rotating random vectors in a grid—the user draws a series of lines that describe and define movement at specific points. It is up to the designer in this case to determine the rationale behind the directions and intensities (as determined by the length of the line) for these flows.

Figure 11.16 (page opposite) - Forms arranged in a vector field determined by the white, user drawn lines.

Once the vector field is established, a number of secondary steps can be used to represent the results artistically. The image to the left shows a series of oblong shapes based on the direction and intensities of the vectors. In some ways, these resemble a drumlin swarm, a topographical landform often left in the wake of glacial retreat, with the vectors of the drumlins representing the dynamic movement of the glacier, while the oblong form is also an expression of a directional force. Variations of this field are shown in Figure 11.19.

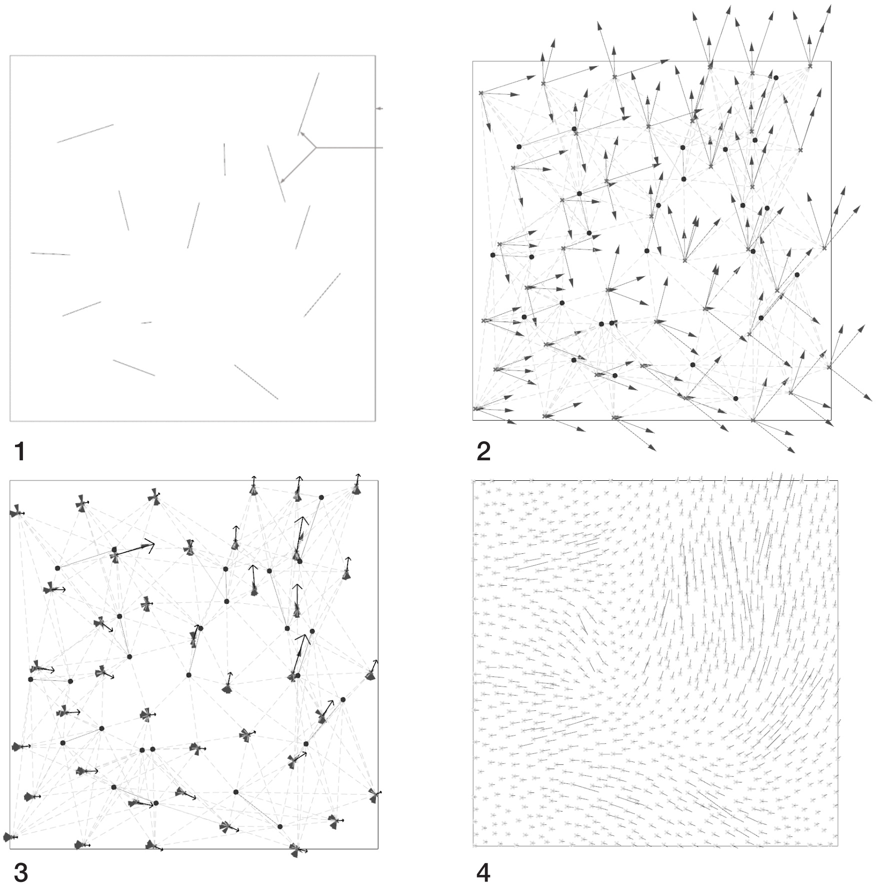
A second strategy to represent the field is to trace lines of particle movement, in a manner similar to the movement demonstrated in §11.1. This is done by drawing a very short line, and incrementing the line in very small steps adjusting its heading to align with the nearest vector or vectors. Results of this method are shown in Figure 11.20.

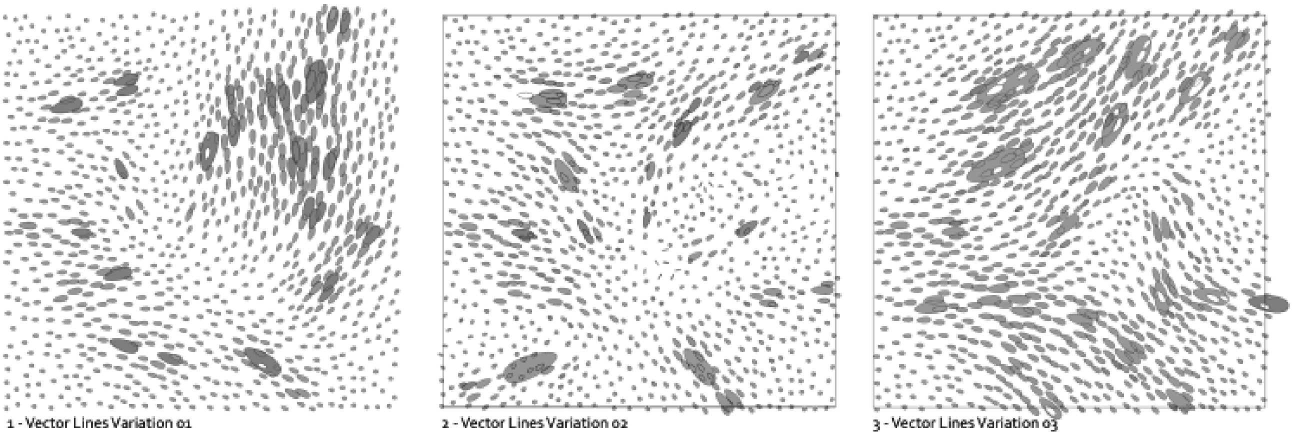
Figure 11.17 (left) - The drumlin swarm landform arranges itself in a vectorfield tracing glacial movment and forces.

Figure 11.18 (right) - The four steps to create the vector field. The user defines lines in Step 1, from here, vectors are determined for each point by summing the vectors of nearby lines, scaled based on their distance from the line (Step 2 and 3). From this, the final vector field is drawn.

Figure 11.19 (below) - Once the field is defined, „drumlin-like“ shapes are created.

Figure 11.20 (opposite page) - An alternate method is to trace particle paths through the field, creating interesting forms in the process. These are regenerated quickly so can be part of an iterative design process.

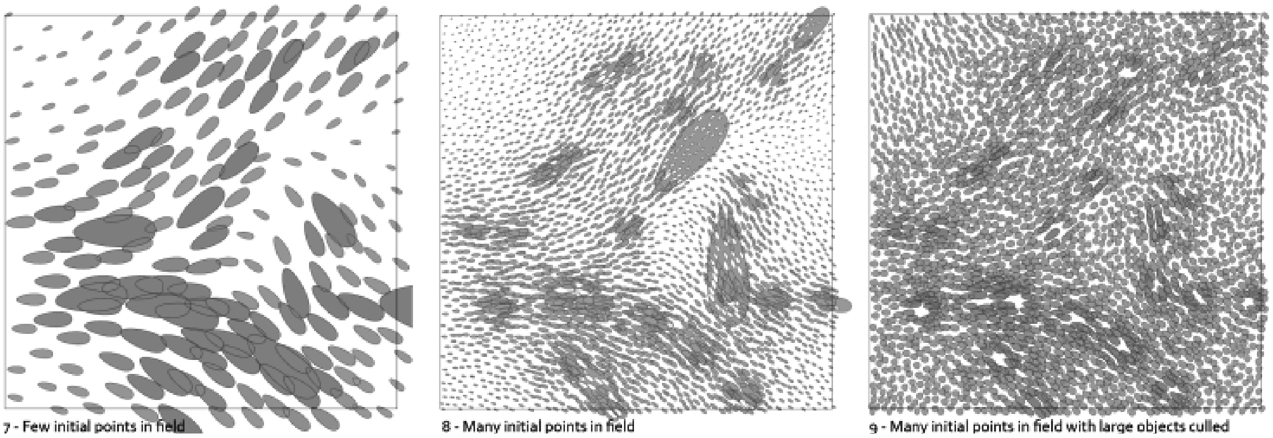




1 - Vector Lines Variation 01

2 - Vector Lines Variation 02

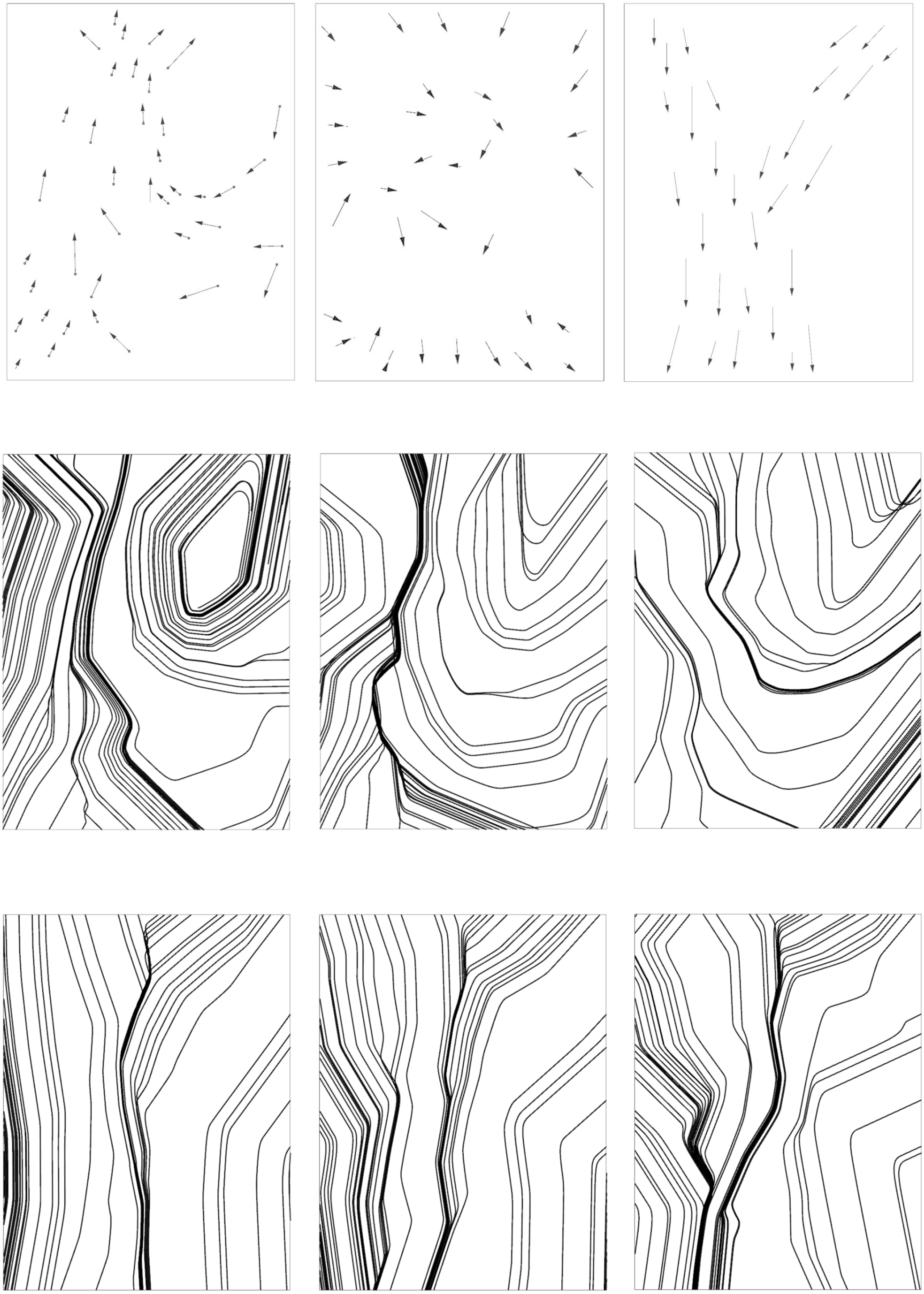
3 - Vector Lines Variation 03



7 - Few initial points in field

8 - Many initial points in field

9 - Many initial points in field with large objects culled



Endnotes

1 Gottfried Leibniz, “Essay on Dynamics: showing the wonderful laws of nature concerning bodily forces and their interactions, and tracing them to their causes.” Trans. Jonathan Bennett, (2006), 12.

2 Theodor Schwenk. *Das sensible Chaos.* (Stuttgart: Freies Geistesleben, 2010), 7.

3 David Ruelle as cited in Phillip Ball. *Flow: Nature's Patterns A Tapestry in Three Parts* (Oxford: Oxford University Press, 2009), 166.

4 Mandelbrot, Schwenk, and Ball all begin their examinations of the subject of flow and turbulence with da Vinci. See Schwenk, 7. Ball, 1-20, Benoit Mandelbrot, *The Fractal Geometry of Nature,* C2-C3.

5 As quoted in Ball, 9.

6 Herbert Dreiseitl. “In conversation with Herbert Dreiseitl,” *Journal of Landscape Architecture* (Autumn 2013), 74.

7 Lebbeus Woods and Clare Jacobson, *Slow Manifesto: Lebbeus Woods Blog,* Clare Jacobson, ed. (New York: Princeton Architectural Press, 2015).

8 Joel Ferziger and Milovan Peric, *Numerische Strömungsmechanik* (Berlin: Springer, 2008), 2.

9 John Anderson, *Computational Fluid Dynamics: The Basics with Applications* (London: McGraw Hill, 1995), 42.

10 David Griffiths, *Introduction to Electrodynamics,* 4th ed. (Amsterdam: Pearson, 2013), 332-338.

11 Ibid, xiv-xiv.

12 Ball, 166.

13 Von Neumann, *Self-replicating Automata*, 33-34.

14 Anderson, 4.

15 Casimir Katz, “Use of Computational Fluid Dynamics in Civil Engineering.” Seminar Notes 23 April 2012, Pdf file <www.sofistik.eu/fileadmin/FILES/Produkte/statik/cfd/english/V13_KatzKrus.pdf>, Accessed 12 Mar 2018.

16 Anderson, xix.

17 Yuan Zhou, Tiemao Shi, Yuanman Hu, Chang Gao, Miao Liu, Shilei Fu, Shizhe Wang. “Urban Green Space Planning Based on Computational Fluid Dynamics: Model and Landscape Ecology Principle: A Case Study of Liaoyang City, Northeast China.” *Chinese Geographical Science,* 21:4 (2011), 465-475.

18 Zhuo-dong Zhang, Ralf Wieland, Matthias Reiche, Roger Funk, Carsten Hoffmann, Yong Li, Michael Sommer, “A computational fluid dynamics model for wind simulation: model implementation and experimental validation.” *Journal of Zhejiang University-Science A (Applied Physics & Engineering)* 13:4 (2012), 274-283.

19 Jillian Walliss and Heike Rahmann, *Landscape Architecture and Digital Technologies: Re-conceptualising Design and Making* (London: Routledge, 2016), 47-60.

20 Karen M’Closkey and Keith VanDerSys, *Dynamic Patterns: Visualizing Landscapes in a Digital Age* (London: Routledge, 2017), 68, 70-72.

21 *Ibid*, 36, 65-69.

22 Tomás Folch and Chris Reed, after Tomás Folch, Amna Chaudry, Lauren McClure, and Sara Newey. Oyster Reef Flows, 2011. In *Projective Ecologies,* Chris Reed and Nina Marie Lister, eds. (Barcelona: Actar), 286-287.

23 Aquaveo at the time of this writing costs USD 2900 for the basic Riverine modelling suite, while the addition of coastal modelling capabilities brings the price to USD 9250, with the CoastalPro version costing USD 24800. While these prices are in line with many other professional software packages, clear goals and workflows need to be established before making such an investment. < www.aquaveo.com/software/sms-pricing>, Accessed 12 Mar 2018.

24 Luna Leopold, *A View of the River* (Cambridge, MA: Harvard University Press, 1995), 168.

25 *Ibid*, 169.

Chapter 12 Agents & Automata

"In some ways, cows are better designers than people. At least they're not confused about who they are and what they are and where nature is and whether they're a part of it or not." James Rose[1]

12.1. Introduction

The last chapter introduced methodologies for algorithmically describing vector dominated smooth spaces based on some of the principles of mechanical interaction between non-living forces as observed in electromagnetic fields or in fluid (liquid or gas) systems. These systems can increasingly be described through advanced hardware and software that have the capability of solving the highly complex nonlinear equations needed to scientifically describe such systems. A second important paradigm which has emerged in the last decades, and which deals with vectors or movement in space is what is broadly termed agent-based modelling. An agent-based model makes use of computational artificial intelligences that often stand as a proxy for living, usually animal-like organisms in the real world, although agents can also stand for non-living, dynamic actors. These agents are not necessarily tasked with simulating reality, but with analyzing physical space to discover underlying patterns, behaviors, and interactions that may be of interest in a design context. Like computational models of mechanical interactions, agent-based models can range from the very simple to the very complex, and while many can be programmed with very simple algorithms, more developed software packages can facilitate the implementation of agent-based models in various landscape architectural design contexts. While agent-based models can be used in a variety of contexts and are not always based on vector motion through space, the focus of this chapter is on the use of agent-based models to reveal patterns of movement.

Figure 12.0: (*page opposite*) A flock of birds. By paying attention to only local interactions with their immediate neighbors, complex self-organized forms become apparent.

12.2. Elements of an Agent Based Model

Before describing the advantages and potential applications of an agent-based model, it is helpful to define what they are. Agent-based models themselves can range from the very simple to the highly complex. A succinct description of agent-based modeling is given by Kinney, who describes how: "the agent paradigm… is based upon the notion of *reactive*, *autonomous*, *internally-motivated* entities embedded in changing, uncertain worlds which they perceive and in which they act."[2] These notions are also present in Macal and North's description, where they define the three important elements of typical agent based models as follows:

> "1. A set of agents, their attributes and behaviours.
> 2. A set of agent relationships and methods of interaction: An underlying topology of connectedness defines how and with whom agents interact.
> 3. The agents' environment: Agents interact with their environment in addition to other agents."[3]

A more complete description of these three elements is helpful. The next three paragraphs will describe first the agents and their internal structure, secondly the agent's environment with its embedded layers of information, and thirdly the performative field of agent relationships and interactions. They are described in this order because of the close conceptual correlation with the form, information, performance relationship that was developed in part I of this thesis.

The agents themselves, and as hinted at in Kinney's description of agents as autonomous and internally-motivated entities, can be helpfully conceptualized in terms of Leibniz's monads, unique "souls" with internal motivations, goals, and potential behaviors. Agents may reveal unexpected patterns through their interaction with their environment, and depending on the simulation may reveal a degree of adaptation, but their internal structure is largely immutable and also non-reducible. From a mathematical standpoint, the agent is composed of imbedded formal relations and internal axioms defining actions taken under specific circumstances. From a programming perspective, they are best treated as discrete, identifiable, and distinctive "objects" using the object-oriented programming paradigm, and while they share attributes and potential behaviors with other members of their class, they always remain unique expressions of this class.[4] This is in contrast to the way in which fluids were described in the last chapter, where the constituent parts of a fluid, its molecular structures, were disregarded, and where the fluid was modeled as an infinitesimally divisible continuum. While the example algorithms described at the end of this chapter will keep the internal attributes and behaviors very simple, in advanced simulations, these can become very complex. Agents can have "beliefs" about their environment, "goals" which they seek with varying degrees of intensity, as well as "plans" or tactical plan sets to achieve their goals. The programmer in such complex cases needs to embed the agents with execution properties that ensure "that beliefs, goals, and intentions evolve rationally."[5]

Macal and North's third component of agent-based models, which is described here secondly, is the environment. Again, the environment can be extremely simple or complex. Examples included bounded and unbounded 2D or 3D Euclidean/Cartesian spaces, cellular automata, networked topological structures, geographic information systems, or even aspatial models.[6] In general, the environment contains objects and information with which the agents can interact either directly or indirectly. As described by Johnston: "unlike agents, the environment does not make decisions. However, it is nonetheless interactive in that it can evolve and change over time. It can also provide a form of memory or information storage for the consequences of past agent behaviors that can influence future agent decision making."[7] In applications to landscape architectural projects, the description of the environment in which the agents act may take on higher importance than in other applications. Care should be taken, however, to describe the environment largely in terms with which the agents can interact. Extraneous information may be more distracting than helpful in such simulations.

Finally, the performative field of interaction between the agents and their environment needs to be defined. The relational space is not defined separately from the internal structure of the agents themselves and the environment, but stands in dialogue between the two. Agents can relate to or interact with either themselves or other agents, but these interactions are always *local*. In Chapter 6 the concept of the neighborhood for cellular automata was introduced (§6.13), but local neighborhoods exist in all other spaces as well. Different interactions can also have different neighborhoods. What is important is that the agent does not have a global picture at any time, and that it makes its decisions always based on local interactions.[8] These interactions can take many forms, and can be deterministic or probabilistic. In many ways these interactions can be thought of as von Neumann's games, where actors make decisions based on a perceived cost-benefit matrix. Advanced artificial intelligent agents also usually have some kind of bounded rationality, where they must make their decisions, like real actors, in a timely manner.[9]

12.3. Intelligent Networks from "Unintelligent" Agents

Part I of this thesis explored the notion that landscapes can be read as the memory of countless small interactions that through time have shaped the broader environment. Before the modern period, the vast majority of these local interactions took place in a non-discursive space, with no overarching master plan guiding the development of cultural landscapes, of local transportation networks, or the form of many cities, villages, and towns. Much of the built environment still carries these ancient traces. Considering only paths of movement, the logic for the formation of road networks, which in turn fostered the development of trade networks and paths of cultural diffusion, was for much of history an emergent phenomenon springing from the interaction between countless actors and their environment. The traces of this legacy still affect the urban fabric of modern cities; two examples familiar to the author include Broadway in New York,[10] or Peachtree Street in Atlanta,[11] both of which have their roots in customary Indian trails which predate European settlement, and which in turn may have had their origin in the movements of large animals through the landscape since time immemorial. (Fig. 12.1) As expressed nearly a hundred years ago by Turner: "the buffalo trail became the Indian trail, and this became the trader's 'trace;' the trails widened into roads, and the roads into turnpikes, and these in turn were transformed into railroads."[12]

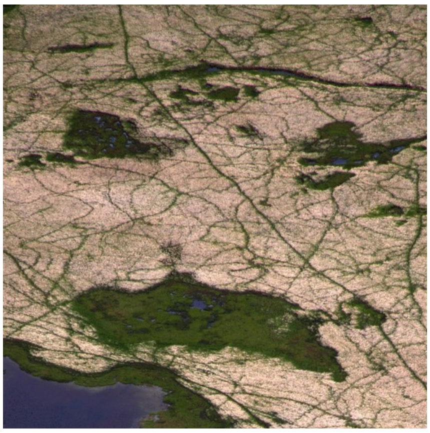
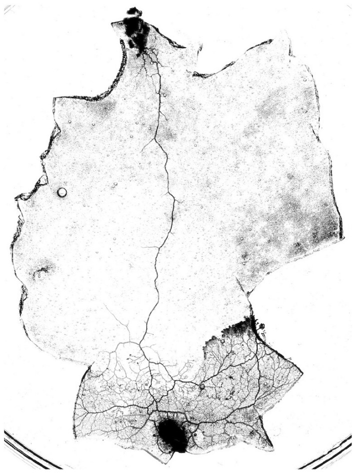


Figure 12.1: (*above*) Animal trails emerge through interaction between animals and their environment over generations of time. Even "pristine" wild landscapes are structured by these paths of movement.

If this "wild animal path" hypothesis for the origin of the first roads is true,[13] should such traces be considered as random, inefficient, and something to be erased? Interestingly, the modernist architect Le Corbusier, while deriding what he calls "the pack-donkey way" recognizes its utility as perhaps the most efficient line of movement through the landscape. In *The City of Tomorrow and Its Planning,* he contrasts the genius of man's way with this pack-donkey way, observing that:

> "Man walks in straight line because he has a goal and knows where he is going; he has made up his mind to reach some particular place and he goes straight to it. The pack-donkey meanders along, meditates a little in his scatterbrained and distracted fashion, he zigzags in order to avoid the larger stones, or to ease the climb, or to gain a little shade; he takes the line of least resistance. But man governs his feeling by his reason…he rules the brute creation by his intelligence. His intelligence formulates laws which are the product of experience…the laws of experience must be obeyed. Man must consider the result in advance. But the pack-donkey thinks of nothing at all, except what will save himself trouble. The Pack-Donkey's Way is responsible for the plan of every continental city; including Paris, unfortunately."[14]

While Le Corbusier's critique of the historic city and its emergent nature appealed to generations of modernist planners, the pendulum in urban design theory has shifted away from the monomaniacal vision expressed in so many failed post-war planned cities, with emergent urban fabric of historic cities being recognized as a perhaps more humane expression of urbanism. While a full critique of Le Corbusier's thinking is beyond the scope of this chapter, a glaring flaw in Le Corbusier's reasoning should



(b)

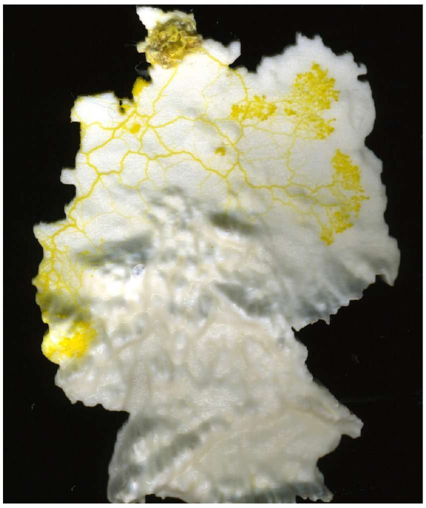


Figure 12.2: (*above*) Slime molds growing across a physical model of Germany revealing optimized corridors of movement. Images courtesy of Adamatzky (2012), 5.

be obvious: a straight-line might represent an optimized path for a single, rational individual, but what about for a collection of tens to hundreds of thousands of individuals in a typical city? The "pack-donkey way" on the other hand does not represent the path of least resistance for a single, lazy donkey, but for all the countless, donkeys, cows, goats, children, traders, and armies that might use the path. Emergent paths tend to represent a certain optimized condition, and this can often be ascertained without any rational "intelligence."

This hypothesis is demonstrated rather convincingly in a fascinating series of experiments by propagating slime molds on 3D-printed terrains of the United States and Germany. (Fig. 12.2) In a series of experiments by Adamatzky, slime molds with no central brain or nervous system were able to grow in networks that closely approximated the longest autoroutes in those two countries. The slime molds were only slightly longer than their real-world counterparts (1.095 and 1.158 times longer respectively),[15] but the efficiencies gained in the planned road network may simply be a result of the fact that engineers were allowed to dig tunnels while slime molds could not.[16] Other experiments point to the fact that the unintelligent slime mold "does not compute a shortest path per se, but the path optimal for the amount of resources involved."[17] Likewise, the emergence of "buffalo trails," "pack-donkey trails," and "cow paths" which characterized many pre-modern transport networks could be based on factors such as the complexities of the underlying topography, the availability of resources, and the history of prior movements of still other animals. The English word "highway" contains the memory of the relationship between corridors of movement and underlying topography, where major roads tended to follow high topographic ridges to avoid areas of excess water accumulation at lower points, which could significantly hinder travel. Not only humans, but also animals have instinctively identified these relationships. The major ancient route from Hamburg through Flensburg to Viborg in central Denmark runs along the Jutland watershed between the North and Baltic Seas, and is called the *Ochsenweg* in German, but *Haervejen*, translated as army road, in Danish.[18] This points to the optimal use of the route as both a route for animals and armies. The Spanish word for street also maintains these animal origins, the word *calle* deriving from the Latin *callis,* "a path for cattle."[19] Once derided as a metaphor for inefficiency, the phrase "paving the cow paths" has taken on a positive connotation in recent years, and designers in fields from software engineering to landscape design are experiencing a paradigm shift where "desire paths" (German *Trampelpfade)* are no longer seen as something to fight against, but as a manifestation of collective intelligence which designers should work with, not against.[20] Like slime molds following a simple set of "mindless" recursive rules, algorithmic simulations with agents following simple behavioral parameters can often reveal unseen patterns and bring them into the discursive realm of design. This is ultimately the goal of agent-based models in a design context.

12.4. Swarms and Coordinated Behavior

Agent-based models can not only reveal optimal patterns by interrogating the relationship between agents and their environment, but also by exploring the relationship of agents to other agents. The behavior of large groups of animals has long fascinated thinkers, as hinted at by Leibniz's musings on the apparently chaotic behavior of schools of fish. Agent-based models have also pointed to how such coordinated, collective behavior emerges. An early proponent for the use of agent-based models in the spatial design disciplines was the architect Stan Allen, who described the emergent patterns created by simple computer agents known as "Boids" in *From Object to Field* (see §2.11,

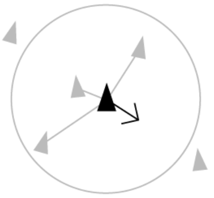
§9.5, §A12.1). The "Boids" model, developed by Craig Reynolds in 1986 and which is described in more detail in the algorithmic examples at the end of this chapter, represented an early success in computationally describing types of coordinated behavior observed in flocks, swarms, and crowds, in ant colonies and in schools of fish. Reynolds model proposed and demonstrated that by adhering to simple rules of *local* interaction, overall group behavior emerges. (Fig. 12.3)

Such unspoken rules of collective behavior happen in everything from simple bacteria to large crowds of humans. What is observed in nature is reflected in various "self-propelled particle" models, where individual agents are given a random vector of movement, but where vectors are slightly adjusted based on the vectors of other nearby "particles." At low densities, the overall randomness of the vectors remains, but at high densities, group behavior emerges. [21] This can be seen in human keratocyte cells responsible for reforming damaged tissue, to swarms of locusts, who normally exhibit uncoordinated behavior in small groups, but who after achieving a critical density, form enormous, destructive swarms.[22] This is also experienced in our everyday experiences negotiating space. When the density of people navigating a space is low, we are generally free to choose whatever path best suits our current aims and needs. In a crowded space, such as at a concert, sporting event, or nightclub, humans without any verbal agreement organize flows through the crowd. Problems only arise when someone violates this unspoken crowd order, or when an unexpected event causes a crowd panic, leading to potentially fatal and unmanageable consequences.[23] Computational models of crowds and crowd behavior can be used to study how changes in the configuration of spaces might positively or negatively affect flows of human or animal actors.

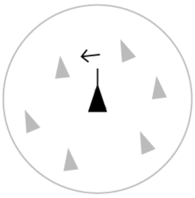
12.5. Design Applications

For landscape architects and planners, a number of potential applications of integrating agent-based models into landscape architectural practice should be readily identified. Agent models are already beginning to be integrated into GIS models, as identified by Johnston, for problems as diverse as developing connective corridors for wildlife movement, exploring patterns of land-use change, optimizing timber resource extraction in forests, or analyzing traffic patterns and producing evacuation strategies.[24] Agent-based models can enrich the static datasets common to most GIS platforms, which "focus on spatial representation, often at the expense of temporal representation,"[25] and begin to "explore the relationship between observed spatial patterns and the processes that create them."[26] They are also changing the practice of urban design; Puusepp describes how agent-based models of circulation helped inform a master plan competition entry for the Nordhavn district in Copenhagen.[27] Puusepp also sees in the work of Hillier and his computer generated settlement models, where space is treated as if it is "composed of nothing but mobile individuals" the early influence of the agent-based design paradigm, although this is not explicit in Hillier's work.[28] [29] Batty makes the utility of agent-based models explicit in his *Cities and Complexity* which expands the ideas he had introduced in *Fractal Cities*. (see §10.4)

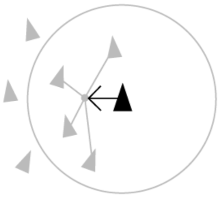
At the smaller scale of the site, there has been surprisingly little done with agent-based modeling despite significant potential. Walliss and Rahmann's *Landscape Architecture and Digital Technologies,* which is otherwise very thorough, makes no mention of agent-based models. M'Closkey and VanDerSys dedicate a chapter to "Behavioral Patterns" and introduce the importance of agents and agent simulations, but offer no in-depth examples of this at the site scale.[30] Some interesting applications have been submitted



Separation:
Steer to avoid crowding
local flockmates



Alignment:
Steer toward the average
heading of local flockmates



Cohesion:
Steer to move toward the average
position of local flockmates

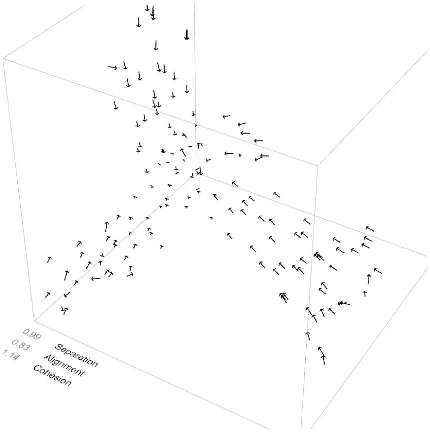


Figure 12.3: (*above*) The three behaviors of Craig Reynolds' Boids, with a representation of the flocking behavior shown below.

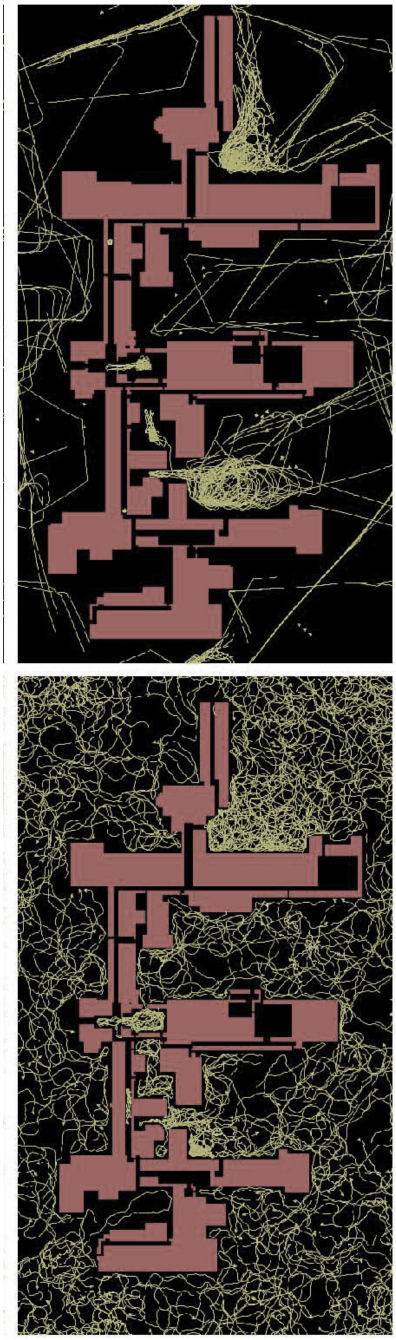


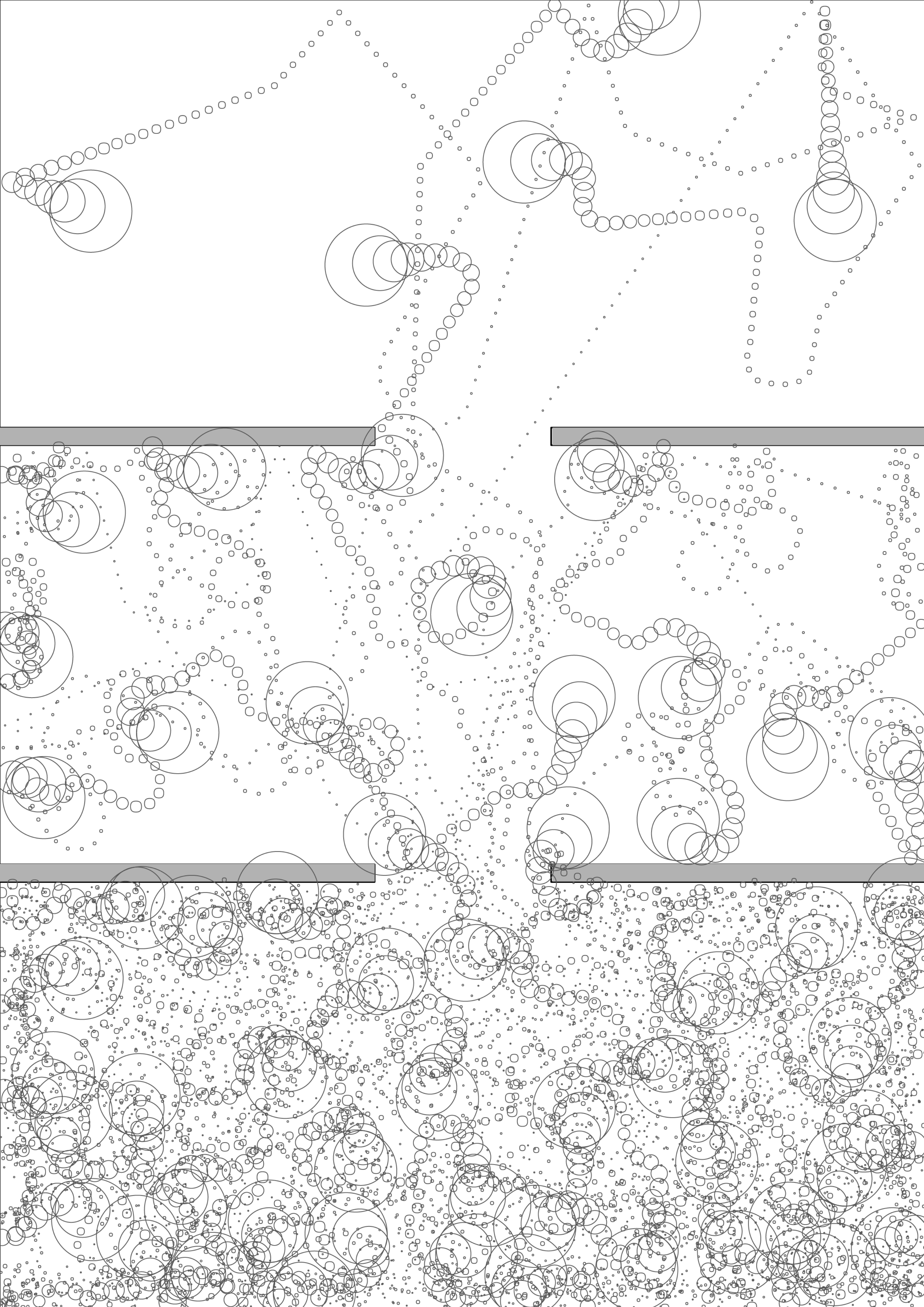
Figure 12.4: (*above*) Various “flocking scenarios“ near a building studying potential paths of movement.

by Nikolay Popov at Unitec in New Zealand using the NetLogo software, a simple programming environment that specializes in agent-based simulation. He proposes using such simulations to study movement through exterior spaces, how new buildings, entryways, and obstacles in exterior space can change the flows of actors, as well as how objects can change the underlying hydrology of sites. (Fig. 12.4) Popov also uses agent-models to model ecological processes of growth and stochastic disturbance.[31] Perhaps because of the poor graphic capabilities of the NetLogo software and the difficulty with interacting with other types of design drawings, however, little follow-up work to Popov’s proposals has taken place. The addition of agent-based scripting capabilities to Rhino and Grasshopper, especially with the excellent user-friendly plugin Quelea, may make developing such models much simpler and more accessible.

Ultimately, agent-based models offer a potentially productive approach to site-scale design, especially with the key task of delimiting sequences and systems of movement. As the pattern of walks and ways is often, at least in plan view, the most distinctive and characteristic element of a landscape composition or style—as reflected in the meandering paths of the English garden vs. the axial geometries of the Baroque—the adoption of bottom-up, agent-based design approaches in the coming years may have a significant impact on landscape architectural design expression. Agent-based models may also help landscapes to perform better. The imposition of an incompatible system of geometries onto a site, for example, can often lead to problems, especially when the subtle structures of the existing landscape are not adequately accounted for. Paths going through low-lying areas often fall victim to chronic drainage problems and in other landscapes, as previously discussed, the system of paths as envisioned by the designer fails to correspond to how users actually navigate the landscape, as evidenced by the emergence of “desire paths” in many parks, gardens, campus, and urban spaces. Agent-based models may help designers earlier in the process recognize potential conflicts between their design intentions and the agent dynamics around the site. Agent models may also help address certain technical issues. On steeper sites, for example, it is also possible that the intended composition of the landscape architect does not allow for accessible paths of movement, and when considered late in the design process the problem can sometimes only be resolved with zigzagging ramps with unsightly and expensive railings, and additional paths which do not conform to the overall design concept. Agent-based models can be used to reveal potential paths of movement through a site early in the design process, favoring certain types of movement, while avoiding others, and thus become an integral part of a discursive and iterative design process. (see §A12.2)

12.6. Summary Conclusion

The agent-based paradigm stemming from developments in the computer science of artificial intelligence can be a relatively simple, yet powerful way to conceptualize how global forms and patterns in the built environment emerge from discrete, local interactions. Agent-based modeling offers significant potential to understand and work with the dynamic web of agent and actor interactions on sites. Well-constructed models will reveal patterns perhaps invisible to the designer, but which can have a significant long-term impact on a project's long-term success or failure. This thesis has not touched upon concepts from Actor Network Theory, an influential paradigm in the social sciences advocated by Latour and others, but a potentially powerful relationship between computational agent-based models and this rapidly evolving field of research exist, and represents another potentially productive avenue of future landscape architectural research.



Algorithm 12.1. Agent with Avoidance Behavior

To demonstrate how an agent with only a single "behavior" can leave a powerful spatial footprint, this example demonstrates the movement of an agent through an enclosed field where the agents adjust their movement when coming into proximity of another agent and attempt to "avoid" contact with that neighbor. The agents in general will always "walk" in a straight line. This "walking" movement is represented by a very small step in a particular vector or direction of movement. Before engaging the "behavior," the only thing which alters the agents path is encountering an obstacle, in which case much like a billiard ball, the agent will be "reflected" based on its current heading. While this is not considered a "behavior," this is required to keep the agents in a contained space. (Fig. 12.6) More nuanced "behaviors" at the edge conditions can be coded by a designer as needed.

The behavior itself is illustrated in the diagrams in Figure 12.7. The steps can be described as follows:

Figure 12.5: (*page opposite)* Agents moving through a field divided into three "rooms." Here all agents start in the lower room and move upwards. Due to the programmed "avoidance behavior," the Agents crowded at the bottom and in the top seem to exhibit more "nervousness" while the ones at the top seem more "confident."

Step One: The algorithm draws a circle with radius R at each agent point. (Indicated in Figure xxx, Image 1) This is the radius at which the avoidance behavior will be engaged. Agents with no neighbor inside their circle (or comfort zone) will continue moving in a straight path. These agents are indicated in Image 2 by white circles. The shaded circles in Image 2 indicate agents with at least one neighbor in their circle, and for whom the avoidance behavior will be engaged.

Step Two: The agent calculates the vector between its position and its nearest neighbor. (Fig. 12.7, Image 3) It then multiples together 3 quantities. Its current heading V_C, the vector between it and its nearest neighbor $V_{N,}$ which is then reversed to $-V_N$ (since it wants to move away, not towards its neighbor) and a parametrically variable "avoidance strength" quantity A. If A is very low, the current heading will be prioritized. If A is very high, the agent will turn to move away from this neighbor very quickly. The sum of this equation, its updated vector is V'. The equation then looks like this:

$$V' = V_C + (-V_N * A)$$

Step Three: The agent then moves a small amount equivalent to the simulations "step size" in the heading of the new vector V'. The process will then repeat in in a similar fashion for as many rounds as need to be modeled.

In this particular example, the current position of agents are shown by large circles, while previous positions are shown by incrementally smaller circles, creating disappearing "footprints" in the field. These footprints are only shown for representational purposes and agents do not interact with them in any way.

Figure 12.8 shows the affect of adjusting the parameters A and R.

Where R *is* low, and A is high, agents develop a jerky type of behavior.
Where R *is* low, and A is low, agents are non-chalant.
Where R *is* high, and A is low, agents are smooth operators.
Where R *is* high, and A is high, agents are paranoid and nervous.

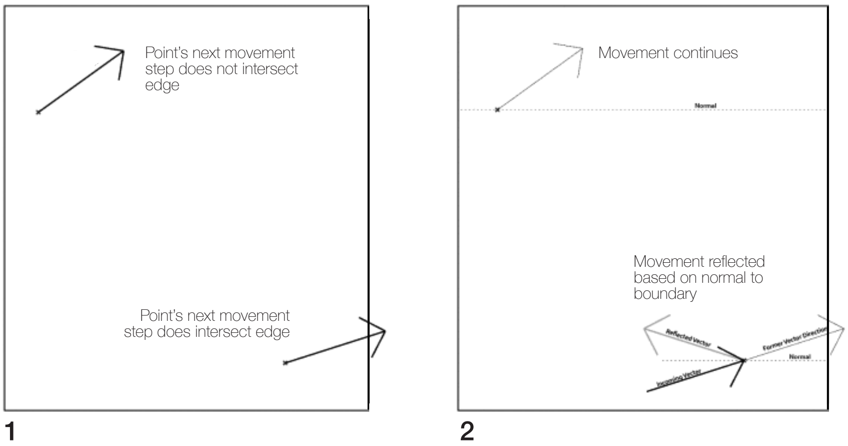


Figure 12.6: (*right)* Agent reflection rules.

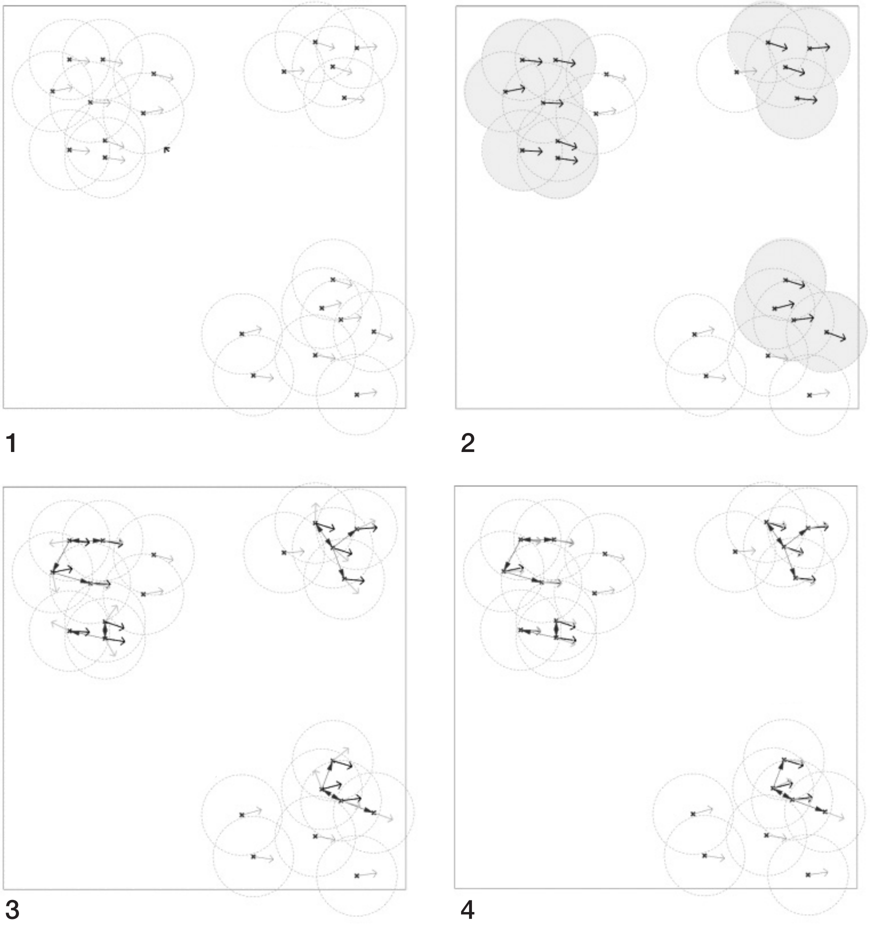


Figure 12.7: (*right)* Agent avoidance rules.

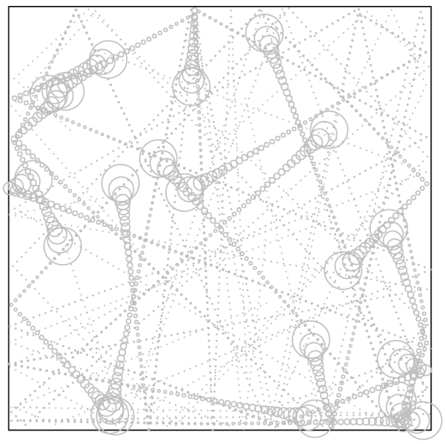
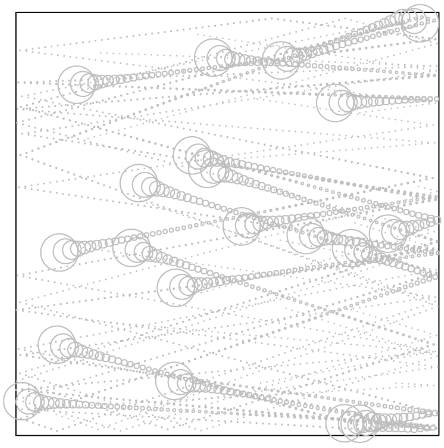
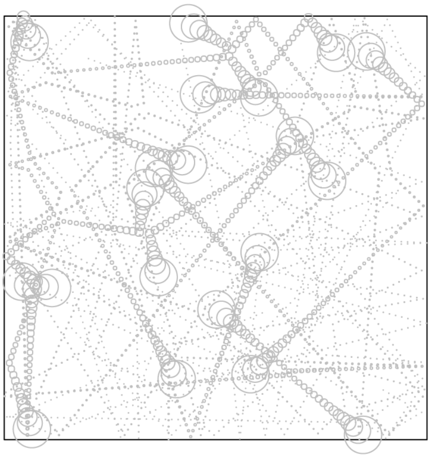
1. Determine radius of effect

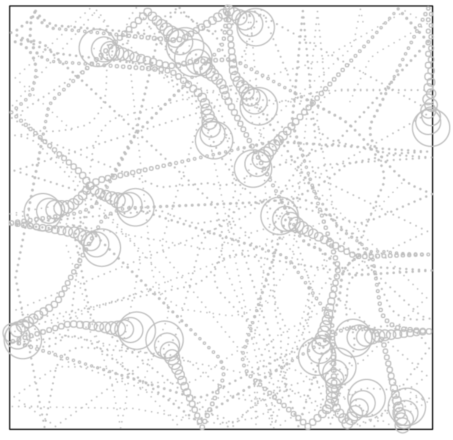
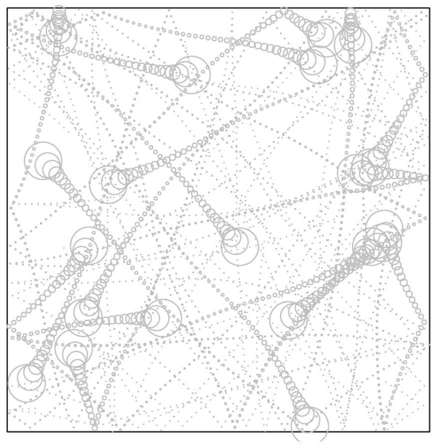
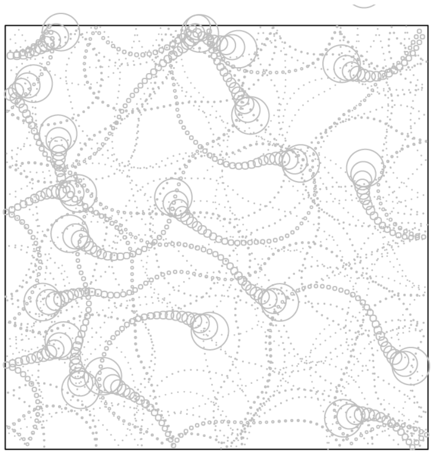
2. Shaded circles have a neighbor in their radius of effect and will engage avoidance behavior. Agents with non-shaded circle continue on their current vector.

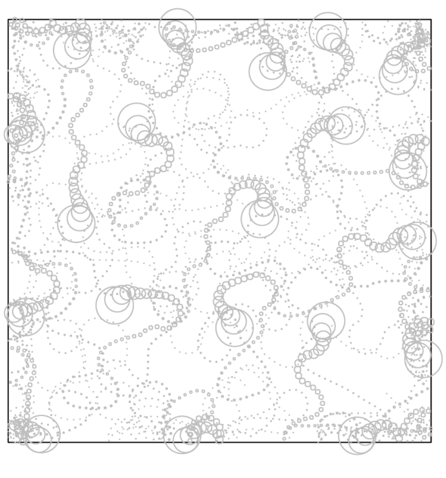
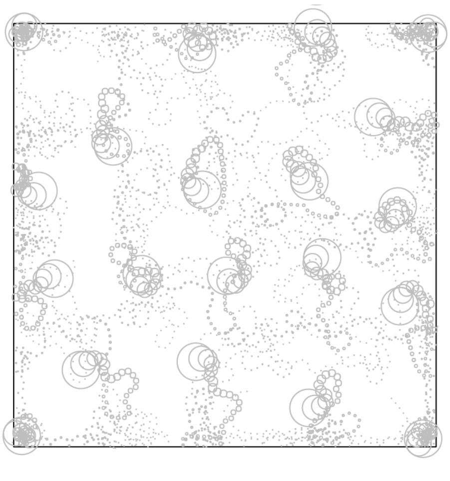
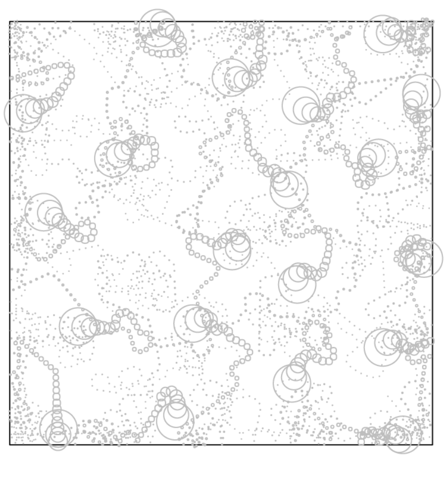
3. Vector of agents with engaged avoidance behavior is moved slightly away from neighbor's vector of movement.

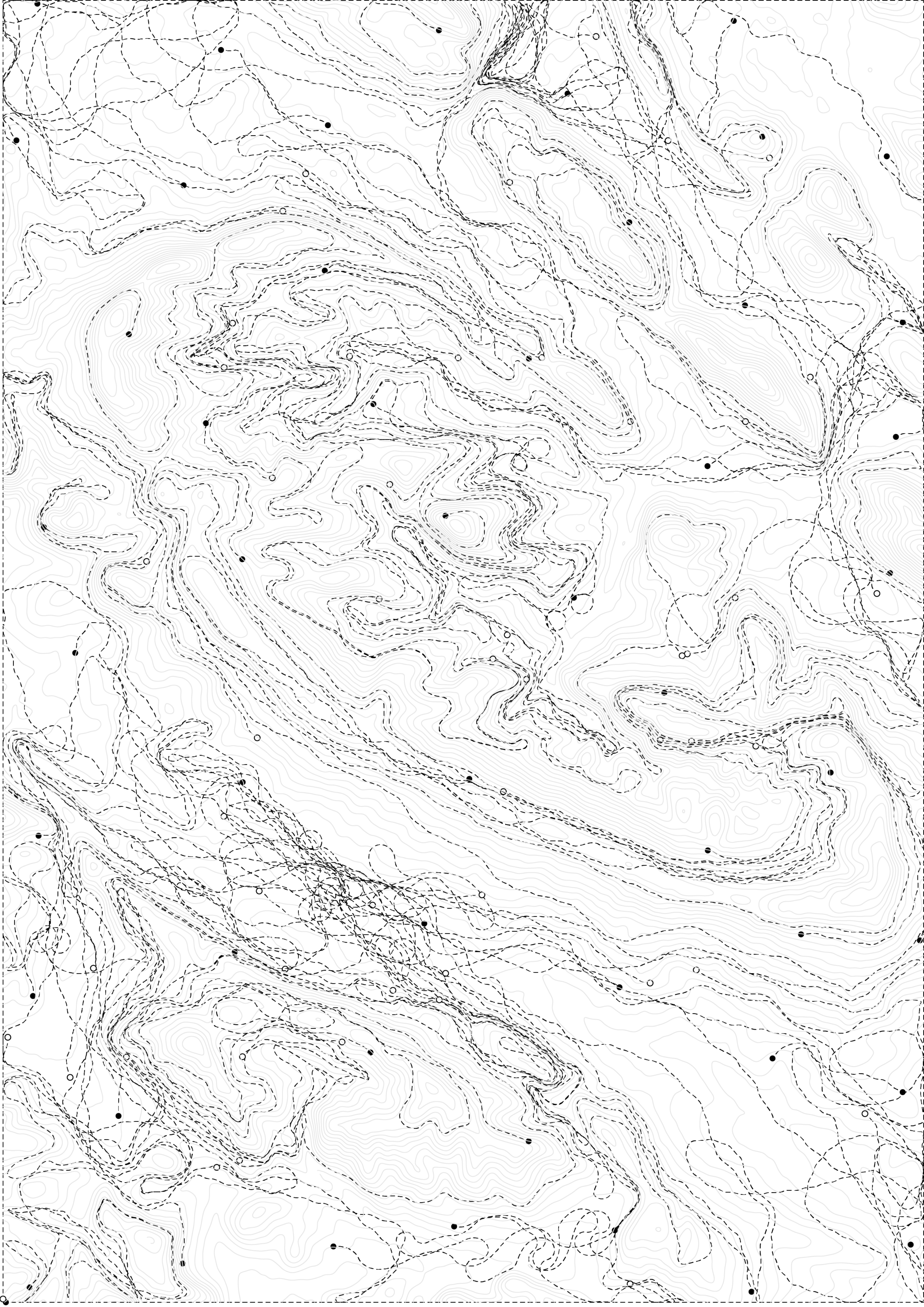
4. New vector for each agent is established.

Figure 12.8: (page *opposite)* Various agent patterns created by adjusting the area of affect (*R)* and the strength of the avoidance (*A)*



Algorithm 12.2. Agent Scouting of Topography[32]

In this example, a simple agent-based approach is used to analyze the topography of a site to reveal potential paths of movement that do not exceed a maximum allowable slope. The most practical use of such an analysis is for the design of a network of paths that meets jurisdictional requirements for accessibility, but such an approach also can insure that the greatest number of users can traverse a path network comfortably. As described previously, agent-based models generally contain an environment, rules for interaction with other agents, along with rules of interaction with their environment. In this example, the environment is a 3D topographical surface modeled in Rhino. The agents do not interact with other agents, but only with their environment, based on a few rules defined using the scripting engine Grasshopper with the looping plugin Anemone.

Three very simple parameters will govern the agent's movement. The first is the maximum vertical rise or slope for a specific horizontal run that the agent is allowed to travel. For accessible paths, many jurisdictions mandate for example that the slope should not exceed 1:20, so this might be a value of interest to test in a real-world application. For other purposes, other values can be used as well. The second parameter is the amount of random deviation the agent will be allowed from its current heading. A third parameter is the step size or distance the agent travels with each iteration of the loop. Smaller step sizes will increase the accuracy of the simulation but will also increase the time needed to run.

At the start of the simulation, a predefined number of agents are randomly populated on the terrain, although these can be placed at specific points as well. The simulation then draws a cylinder with a radius equal to the step size, and with a height equal to the maximum allowable slope in both an up and down direction. (Fig. 12.10, Image 1) The simulation then performs a Boolean intersect operation between the terrain surface modeled in Rhino and the cylinder. The resulting intersection arc or arcs represent possible directions of movement for the agent. (Fig. 12.10, Image 2) The simulation prioritizes movement in the current direction with a bit of randomness by tentatively moving the agent one-half of the step-size with a vector determined by the agent's current position and previous position, with an optional random deviation slightly to the left or right. (Fig. 12.10, Image 3) The agent movement for each round is then fixed by taking the closest point on the arcs of possible movement to this tentative movement point. (Fig. 12.10, Image 4) The process is then repeated as many times as desired, with a curve drawn between the agent locations at each time step.

In the flatter areas of the site, no ideal or preferred structure may be evident, but other areas reveal clear preferred corridors of movement. Depending on the topographical surface as well as the boundaries of the site, it may also be apparent that certain parts of the site cannot be easily or practically connected with an accessible path. These may point to areas of the site where some topographical manipulation could be desirable. Additionally, the tests were run with a random population of agents, but it may also be desirable to start the agents at key points on the site, such as near existing or proposed entries to the site, or at key points on the site that need to be accessed. More complex rules can refine and improve the process further. Combined with a simulation of the water network on the site, for example, the agents could be programmed to avoid areas of excess water accumulation. In general, however, such models do not "design" the path network of the site—they only point to possibilities, and it is then up to the designer to incorporate this understanding into an understanding of the project's goals.

Figure 12.9: (opposite page) Traces of swarm of agents moving across a large (approximately 6x8 km) terrain near Dellingsen, Germany.

Figure 12.10: (right) The decision steps for a single agent.

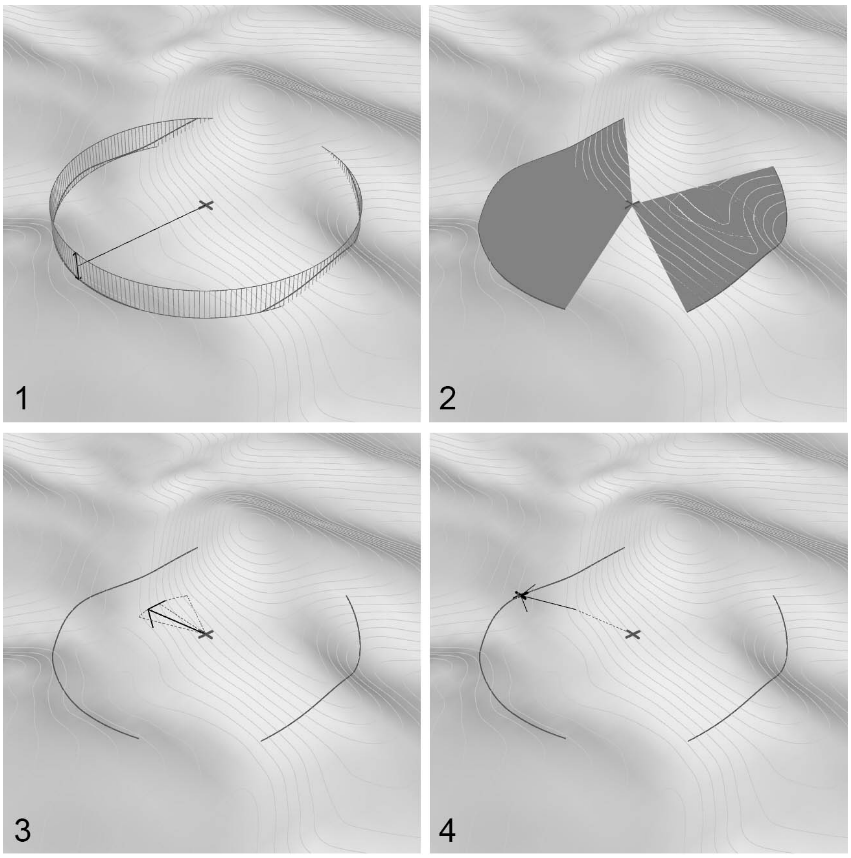
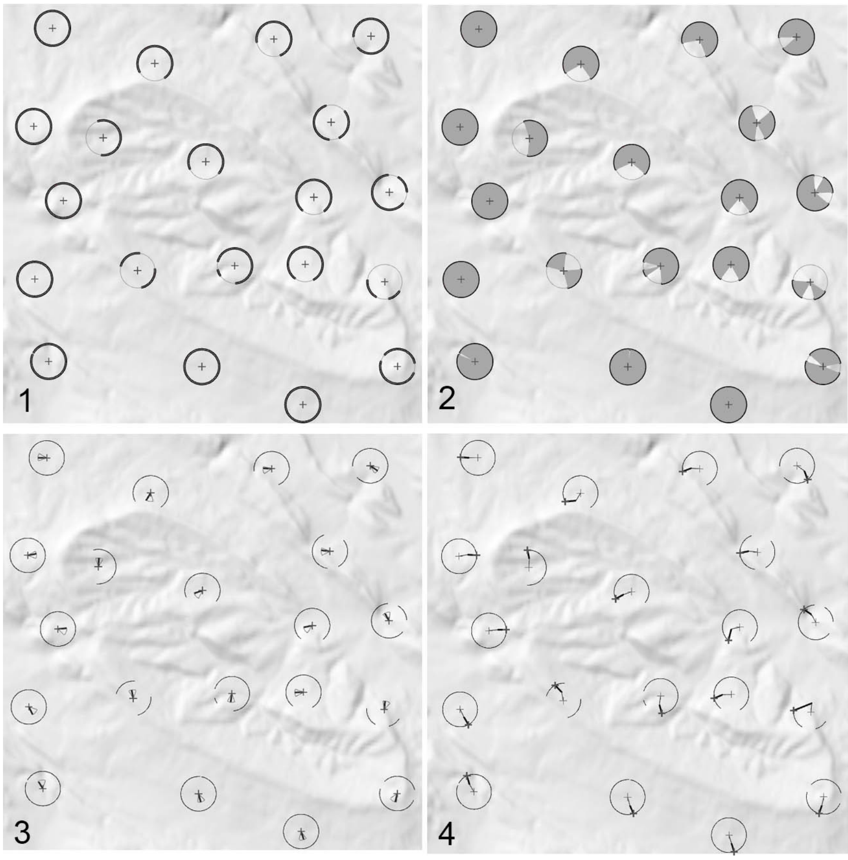
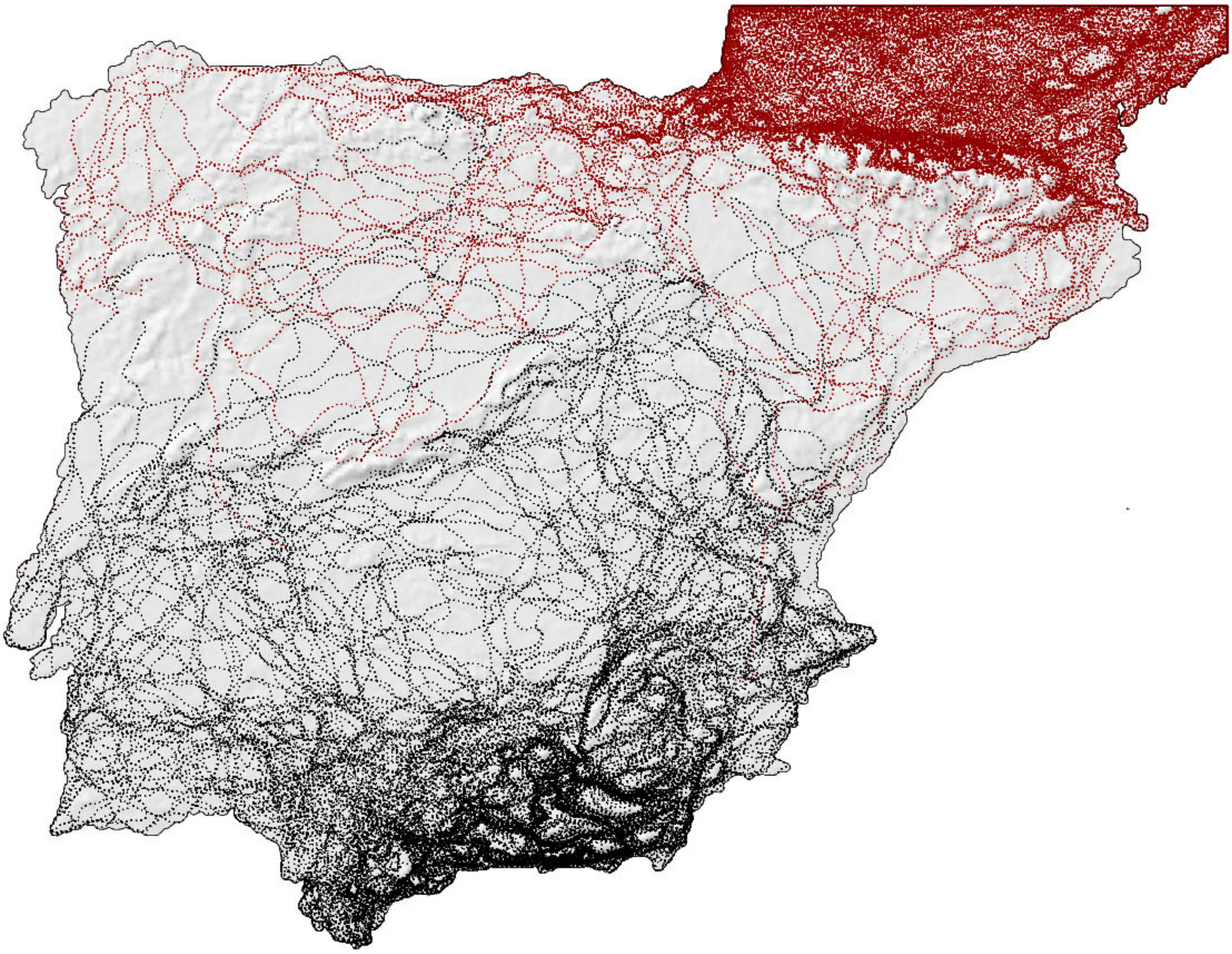


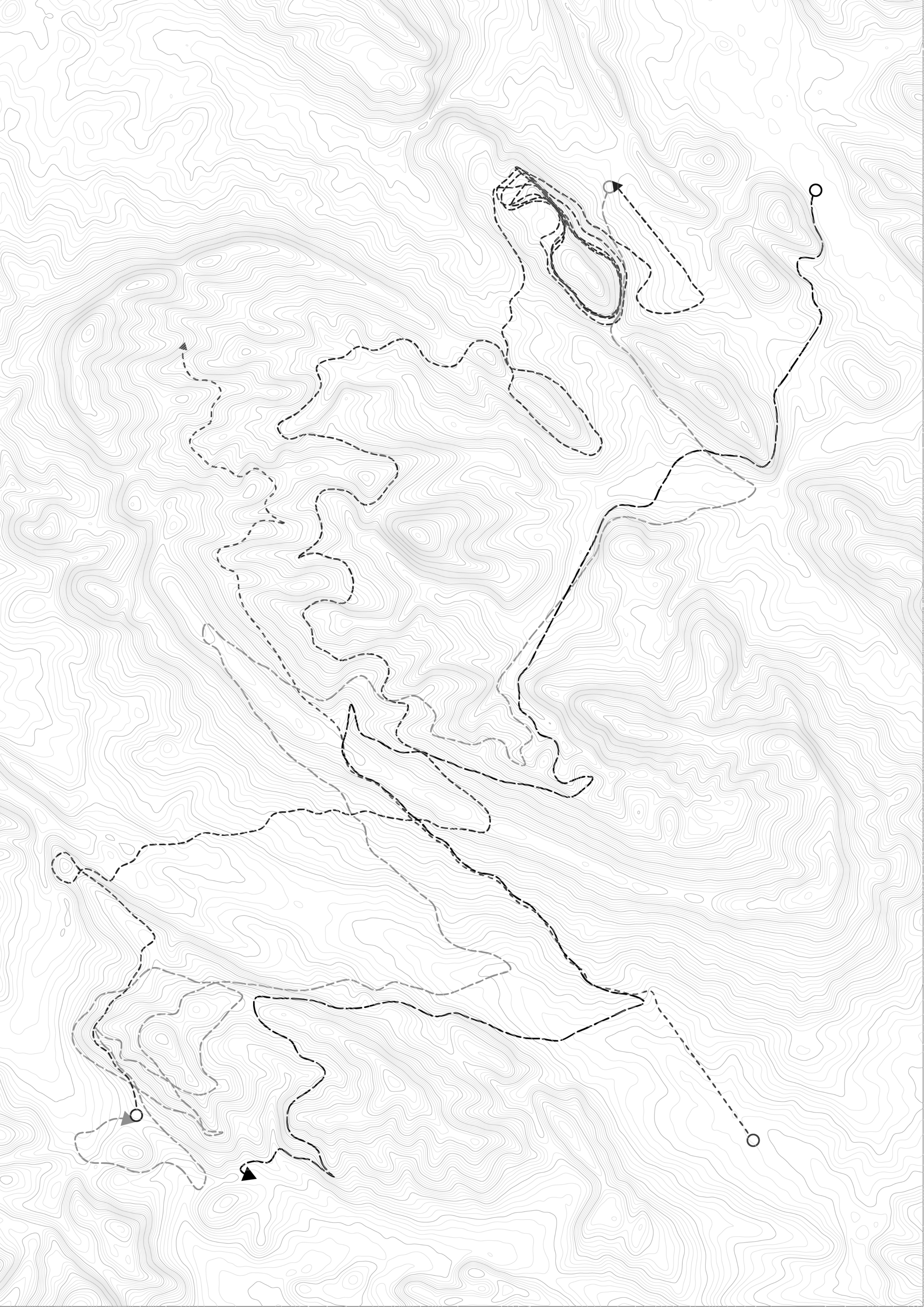
Figure 12.11: (right) The decision steps for multiple agents with each offered a varying potential range of movement based on their current local conditions.



Such a simple process, however, can reveal underlying structures in a meaningful way. As a small test, the script was run on a topographical model of the Iberian Peninsula and the south of France to speculate as to how historical corridors of movement may have formed. (Fig. 12.12) Interestingly, a clear corridor of movement emerges along the northern coast of the peninsula linking it to the south of France. Those familiar with the history of the peninsula will recognize this emergent path as the Way of Saint James, a popular pilgrimage route in the middle ages. This along with Barcelona was also the only part of the peninsula that retained strong cultural links to the rest of Europe while the rest of the peninsula was under Moorish rule with strong links to North Africa. Such models developed to a more advanced degree have been influential in the historical study of landscapes, and effects of the collective acts of actors through time.[33] Perhaps such models will also be helpful to how we understand and design the landscapes of the future.

Figure 12.12: (below) Traces of a swarm of agents moving across the Iberian peninsula, with one population in the south of France, and one starting near the straights of Gibraltar.





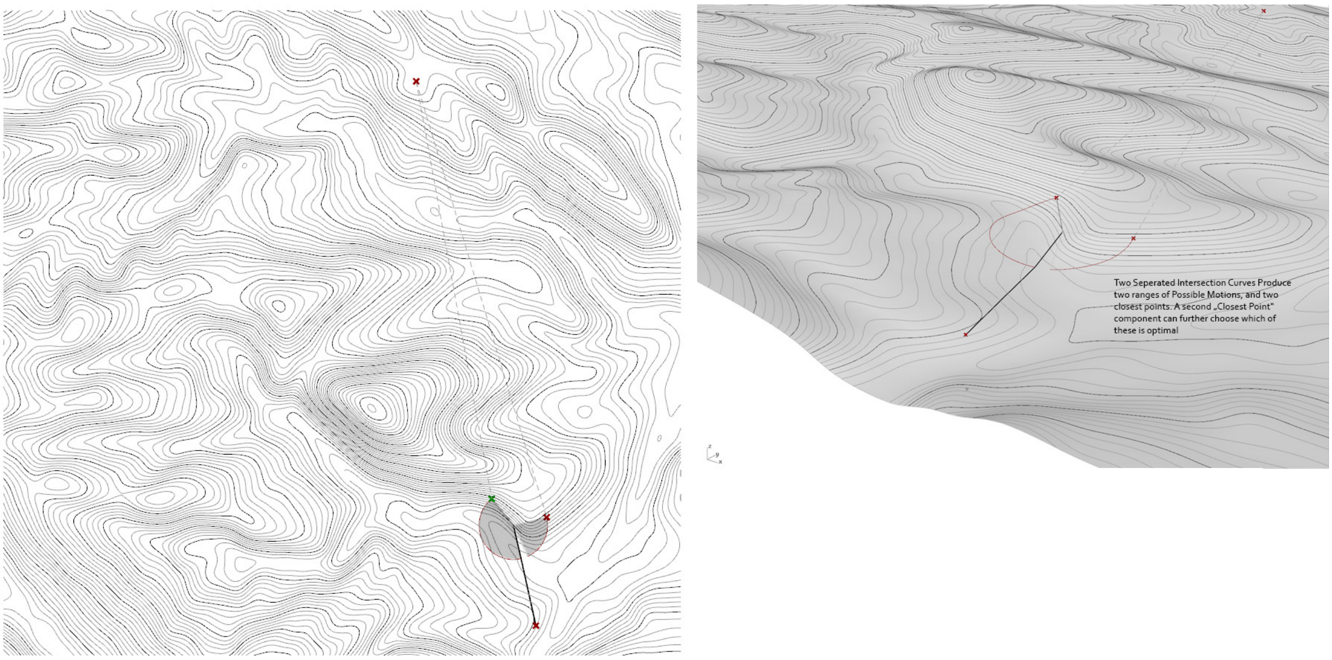
Algorithm 12.3. Agent Pathfinder Algorithm

The last example showed how agents might move across a surface reacting only to local topographic conditions but otherwise their movement is based solely on their current vector with a small amount of random movement. There is, in other words, no goal and the agents wander through the landscape aimlessly. At times, however, it is useful to provide a goal to direct the agents movement. A common task of landscape architecture is to determine paths of movement between specific fixed points. This variation of the previous algorithm provides a potential strategy to address this task, and also provides a logic which will be addressed again in §A14.3 as well as the third design case study presented in Chapter 17.

The general steps in this algorithm are almost identical to those presented in Figure 12.10, repeating the steps illustrated in Image 1 and Image 2 in an identical fashion. The decision in which vector to move, however, is made differently. Figure 12.10, Image 3 and 4 show a decision mechanism which prioritizes potential points at or near the current vector of movement. In this algorithm, priority is given to the set of possible movement which is closest to the final goal. In other words, the agent knows where it wants to go, and will steer its movement away from this goal the minimum amount possible to get there. This behavior is shown in Figure 12.14.

By adjusting the maximum allowable slope parameter, the potential paths of movement change, but in other aspects it is fairly straightforward. One drawback of this algorithm is that as an agent gets closer to its final goal, ironically it has more trouble finding an ideal path since it does not consider as broad a range of options in the larger landscape. In other words it becomes too single minded. A potential remedy to this problem is to run the simulation in both directions, starting at the goal in a second run of the algorithm, and working backwards with the starting point designated as the new goal. Between each intersection between the two paths, the designer can choose which one works best. (Fig. 12.15) By combining this with other criteria, or rules to avoid certain areas while favoring others, a rich and interesting series of movements can be conceived and implemented. Additionally, multiple points and nodes can be combined with paths to create many of the network topologies illustrated in Chapter 8, but which respond to topography in a more intelligent way.

Figure 12.13 (*left*) - Four directed agents moving between starting points, as indidcated by a white circle, and a final goal, indicated by a black arrowhead.



Two Seperated Intersection Curves Produce two ranges of Possible Motions, and two closest points. A second „Closest Point" component can further choose which of these is optimal

Figure 12.14 (*above*) - Replacing step three in the decision tree illustrated in Figure 12.10, in this algorithm the agent moves in the possible heading closest to its final goal.

Figure 12.15 (*below*) - Running the agent in two directions can help overcome problems as the agent nears its goal.

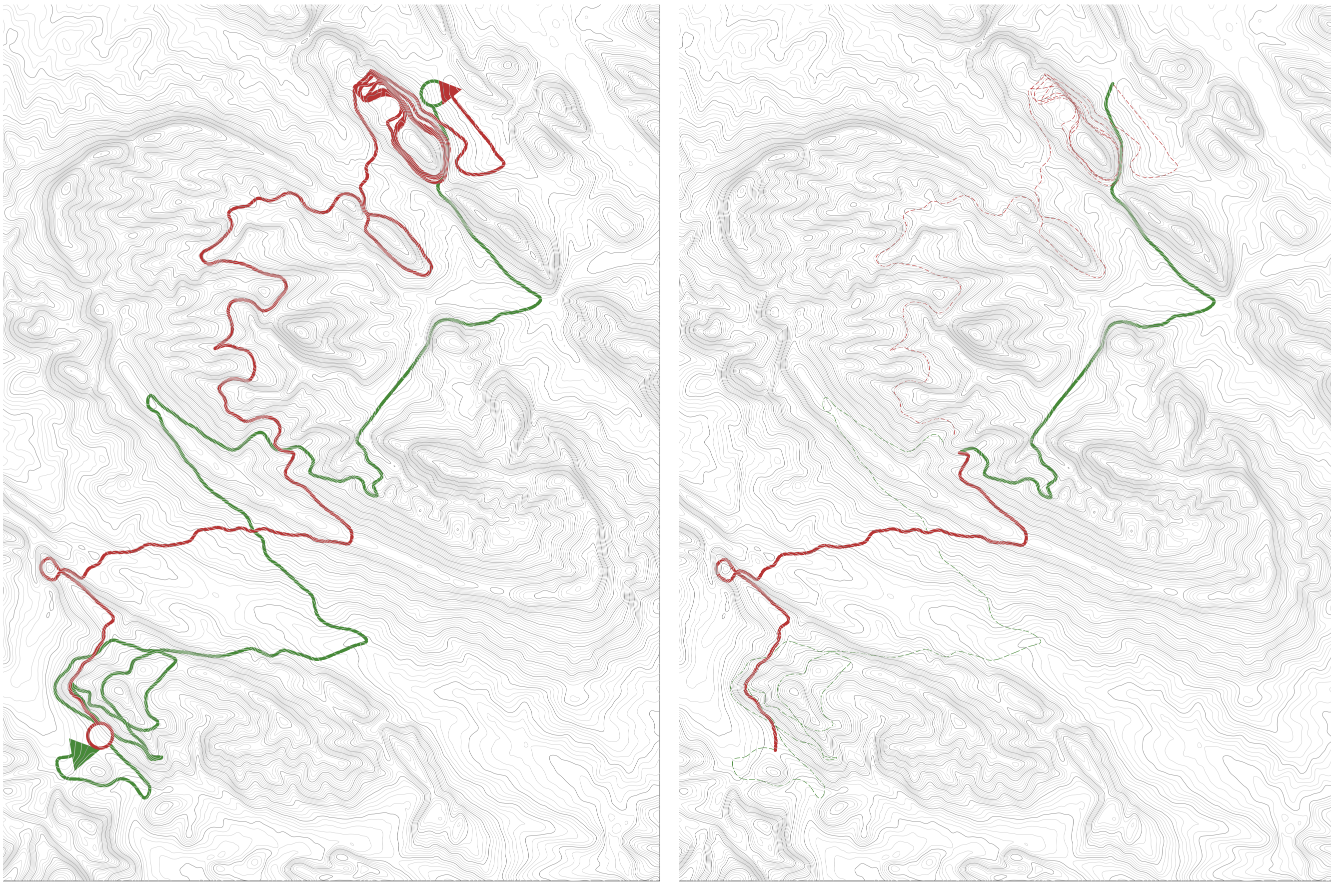
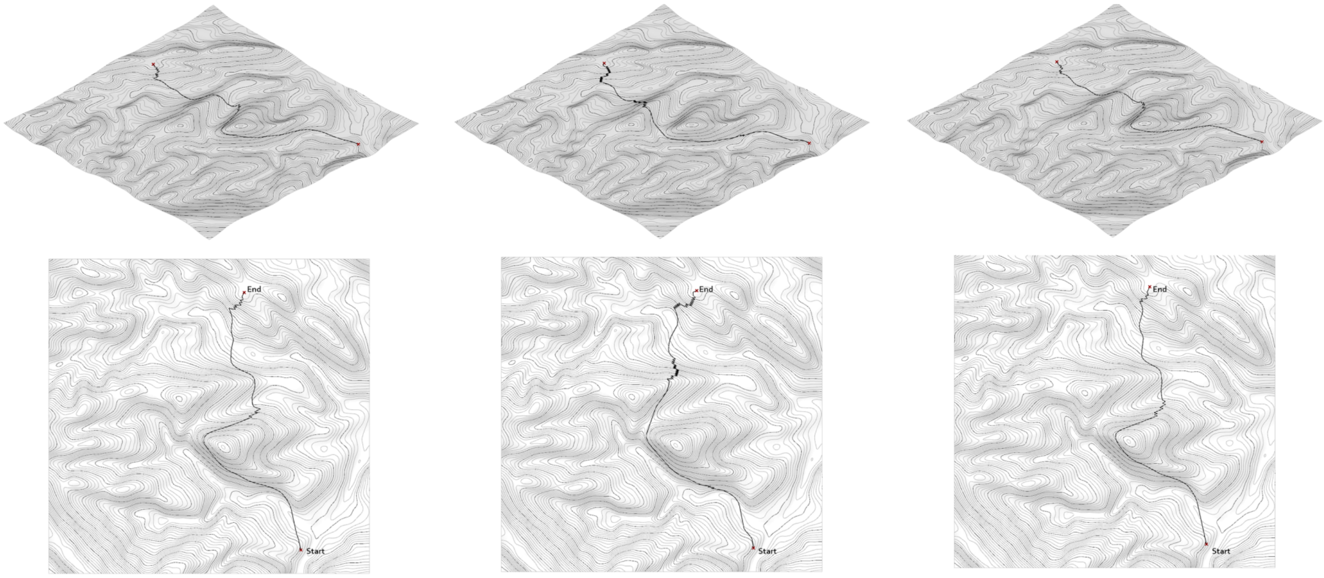


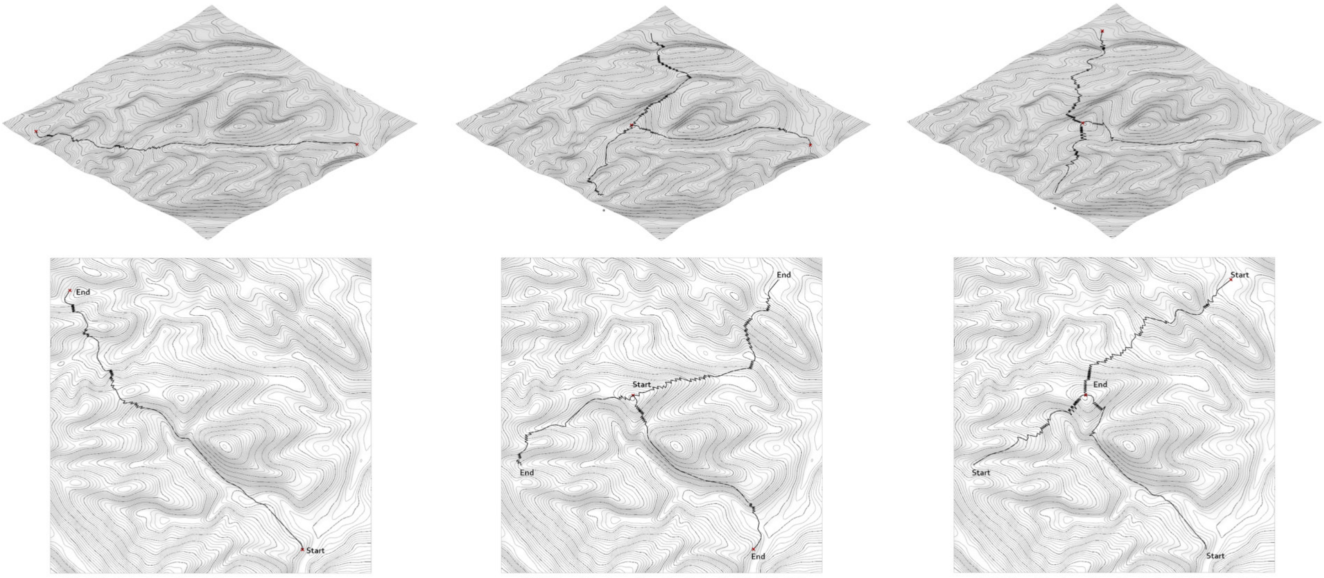
Figure 12.16 (*below*) - Various path running scenarios. Multiple points or destinations can be included when developing a more complex network.



01 - Path between two points - Maximum Slope 1:12 (8.3%)

02 - Path between two points - Maximum Slope 1:20 (5%)

02 - Path between two points - Maximum Slope 1:10 (10%)



04 - Path with Destination changed (1:20 slope)

05 - 3 Paths to Form a Network - 1:20 Slopes, Recursive Growth starts at Center Point

05 - 3 Paths to Form a Network - 1:20 Slopes, Recursive Growth starts at Outer Points

Endnotes

1 Rose, Gardens make me laugh, 30.

2 Michael Kinney and David Georgeff, "Modelling and Design of Multi-Agent Systems," *Intelligent Agents III: Proceedings of the Third International Workshop on Agent Theories, Architectures, and Languages (ATAL-96)* (Springer, 1997), 1. Emphasis added.

3 CM Macal and MJ North. "Tutorial on agent-based modeling and simulation." *Journal of Simulation* (2010: 4), 152.

4 Kinney and Georgeff, 1.

5 *Ibid,* 3.

6 Macal and North, 155.

7 Johnston, 5.

8 Macal and North, 154-155.

9 Kinney and Georgeff, 3.

10 David Dunlap, "Oldest streets are protected as landmark." *New York Times,* 15 June 1983. <www.nytimes.com/1983/06/15/nyregion/oldest-streets-are-protected-as-landmark.html>, Accessed: 13 Mar 2018.

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23 *Ibid,* 143-145.

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27 Renee Puusepp, *Generating Circulation Diagrams for Architecture and Urban Design Using Multi-agent Systems.* PhD Thesis, (University of East London, April 2011), 159 – 167.

28 *Ibid,* 23.

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30 Karen M'Closkey and Keith VanDerSys, *Dynamic Patterns: Visualizing Landscapes in a Digital Age* (London: Routledge, 2017), 86, 92-99.

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Chapter 13 – Topography & Terrain

"When the climbers in 1953 planted their flags on the highest mountain, they set them in snow over the skeletons of creatures that had lived in the warm clear ocean that India, moving north, blanked out. Possibly as much as twenty thousand feet below the seafloor, the skeletal remains had turned into rock. This one fact is a treatise in itself on the movements of the surface of the earth. If by some fiat I had to restrict all this writing to one sentence, this is the one I would choose: The summit of Mt. Everest is marine limestone." – John McPhee[1]

Figure 13.0: (*page opposite*) In tidal mudflats near Wilhelmshaven, the fluid nature of landform becomes obvious as gradual changes in the mudflat's dynamics slowly changes the patterns eroded by moving water.

13.1. Introduction

Landform is the fundamental building block of both the natural and the designed landscape and plays a key role as the substrate on which life as we know it takes place. While in the span of a human lifetime the earth might seem solid, looking at the changes in the surface of the earth in geological time reveals a much more fluid character. As eloquently expressed by McPhee, "the continents, perched on their plates, are thought to have been carried so very far and to be going in so many directions, that it seems an act of pure hubris to assert that some landmark of our world is fixed" with coordinates of latitude and longitude being "a temporary description…as if for a boat on the sea."[2] Some structures have the transitory nature of ocean waves, such as sand dunes, the slow-motion breakers of the desert. Yet in the mix of this soup, enduring structures seemingly defy constant change, such as the huge cratons, rigid shields of geologically inactive rock giving the hearts of continental landmasses their stability.[3] [4]

The complex, fluidlike character of the earth's crust belies elements of both stratified and smooth space. On the one hand, the earth's surface can be seen as a singular, continuous surface, a space whose gradual transformations and folds play a key role in the habitats and evolution of both biological organisms and human societies. On the other hand, it is a complex, bewildering, stratified and deep agglomeration, concealing as many mysteries as it reveals. Regardless, the study of landform is a key component of scientific and human endeavor, with ever revised theories to explain the complexity of the physical world. With the proliferation of digital methods, the study of landform has taken on a new dimension, and we are seeing an explosion of algorithmic studies of landform both to model and explain the emergence of these structures in nature, and to speculate as to what new structures could exist on other worlds or in the "new natures" of the digital realm. Such methods offer a fertile resource for landscape architects to shape topographies in new ways, to both create landforms which harmonize with natural and social dynamics, or to shape the ground in ways which nature never intended.

13.2. Natural Landforms

Landform in nature is always the result of dynamic processes of creation and modification and the processes that produce a particular landform or series of landforms can be read in the landform itself. Geomorphologists categorize the processes responsible for landform creation into two larger groups, *endogenic* and *exogenic* processes.[5] Subterranean forces originating deep within the earth's core and mantle are the fundamental drivers of endogenic processes, which are the processes primarily responsible for creating landform structure.[6] The endogenic processes of volcanism and igneous intrusion represent the first solidification of the plastic mantle into definite forms, such as flows of basalt, granite batholiths, and volcanic cones.[7] These shapes are in turn shaped, warped, or exposed by the endogenic processes of folding, faulting, and tectonic uplift.[8] As soon as the rock has reached the surface, it becomes subject to a new series of processes, the exogenic processes of weathering, which include erosion, sedimentation, and deposition by mechanical agents such as wind, water, ice, or chemical compounds, and by biological agents such as plants, animals, and human beings.[9] Each of these processes leaves in the landform traces of its actions and clues to its behavior, until these landforms are themselves erased by other processes, covered by miles of deposited rock, or subsumed back into the plastic mantle through deep ocean trenches. Landforms can also be categorized based on speeds of movement. While it is typical to think of the earth's crust as firm and everlasting, in geological time, the earth's solid crust behaves more like a fluid, just like the planet's liquid core or plastic mantle, but operating on a much different timescale. Key to the persistence of landforms are their size, with large continental structures lasting hundreds of millions to billions of years, while ripples in sand after formed, may only last until the next wave or gust of wind erases them forever.[10]

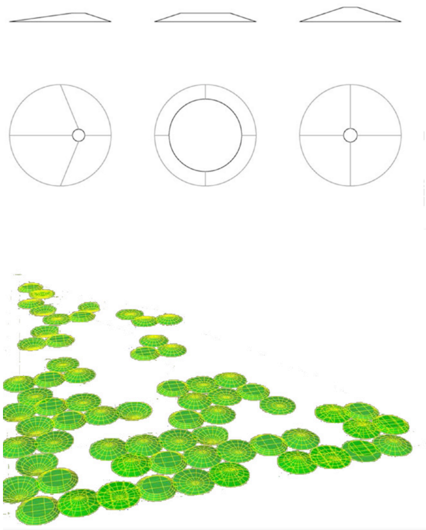


Figure 13.1: (*above*) A scripted model using Rhino and Grasshopper for the landforms in StossLU's *Bass River Park.*
Image copyright Stoss Inc.
Image coutesy of Chris Reed

The landforms created by landscape architects rarely have the dimension, power, or longevity of all but the smallest landforms made by nature, but their formal dimensions and proportions along with the logics of their production are a consistent source of inspiration for landscape architects. While computational process models do not need to be used to simulate or mimic the processes of natural landform creation in making landscape architectural interpretations of them, there are an increasing number of practices attempting to do so. An early example would be Stoss's Bass River park, where the park's landforms are abstractions of the local, hummocky kettle and kame terrain of the region,[11] a post-glacial landscape typology with small, irregularly shaped mounds of sand and gravel known as "kames", deposited near a glacial end morraine and often associated with depressions or "kettles" left after the melting of large blocks of ice.[12] Within this field of repetitive and alternating kames and kettles, the landscape architects insert various new programs, winding paths, and emergent ecologies, which are intended to provide a richness of experience for the park's various users.[13] This process was facilitated with the use of a fairly simple Rhino and Grasshopper algorithm to test variations. (Fig. 13.1) Here the computational model is fairly simple, representing an early test case, but more complex algorithmic landform studies would eventually come out of such early experimentations.

13.3. Artificial Landforms

Apart from the occasional topographic whimsy in the designed landscape, like natural landforms, landforms constructed by humans also follow a formal logic closely associated with the processes of their creation. The emergence of a vocabulary of forms based on the cumulative actions of human actors over time has led many to conclude that humanity has become essentially a force of nature, whose sculpting and transformation of the earth's surface can rival that of even the most powerful geologic processes. This realization is behind the increasing use of the term *Anthropocene* to describe our current epoch in geological time.[14] According to Lóczy, human activity can create landform through three different kinds of processes:

> 1. Through direct human processes "like construction; excavation or hydrological interventions."
> 2. Through indirect human impact on geomorphic processes, such as through "acceleration of erosion and sedimentation; ground subsidence; slope failure and earthquakes triggered."
> 3. Through indirect "human impacts on conditions influencing processes", that is by "indirectly influencing the biophysical conditions which control geomorphic processes (e.g. climate change induced by human activities."[15]

The various types of artificial landforms are too numerous to name here, but to make sense of them, Szabó proposes a "genetic classification" of manmade landforms, which similar to natural landforms, are classified according to the processes of their creation. In his classification scheme, (Fig. 13.2) landform types are associated with industrial, mining, urban, military, transportation, hydrological, agricultural, and touristic generative processes. They are further classified based on whether they are mostly excavations (cuts), accumulations (fills), or planations (balanced grading), and whether the landform is created through a primary intentionality, or if it is a byproduct of some other process. The processes of creation in such landforms should be of considerable importance to landscape architects as much of the systems related discourse of landscape architecture in recent years focuses on these types of earthworks.

Figure 13.2: (*below*) Szábo's "genetic classification" of manmade landforms (2009)

Type of intervention	*Land-form type*	*Direct product*		*Indirect product*	
		Primary	*Secondary*	*Modified in quality*	*Modified in quantity*
Montanogenic	E	—	Open-cast pits	Subsidence bowls, sinkholes	Fluvial features caused by mine water inflow
	P	—	Waste-filled valleys	Accumulation in pits	
	A	—	Spoil heaps	Bulges around tips	
Industrogenic	E	Cooling lake basins	Quarries for landfill	Mass movements on industrial raw material disposal sites	Accelerated erosion by sewage inflow
	P	Industrial parks	Sludge reservoirs		
	A	Sockles for windmills	Slag disposal sites		
Urbanogenic	E	Cave dwellings	Loam pits	Cellar collapses	Erosion by runoff from sealed surfaces
	P	Levelled construction sites	Garbage disposal sites, sanitary landfills		
	A	Tells, burial mounds, tumuli	Rubble mounds		
Traffic	E	Road cuts	Hollow roads	Slumps on embankments	Increased piping
	P	Airfields	Mounds removed		
	A	Embankment	Roadside A		A in culverts
Water management	E	Artificial channels	Navvy pits	Shore erosion because of impoundment	Rapid incision
	P	Polders	Cutoffs		
	A	Flood-control dykes, dams	A from dredging channels		A behind dams
Agrogenic	E	Waterholes	Excavation pits	Rapid gullying	Deflation forms
	P	Terraces	Pseudoterraces	Sheet wash	Silt spreading
	A	Lynchets	Stone ridges, walls	Alluvial fans	Delta expansion
Warfare	E	Moats	Bomb craters	Avalanches triggered by explosions	Erosion by water-courses modified for defence puposes
	P	Glacis, airfields	Destroying settlements		
	A	Earthworks	'Trümmelberge' (rubble heaps)		
Tourism, sports	E	Recreation lake basins	Field sports (riding, moto-cross, quad) landscapes	Abrasion along recreation lake shores	Accelerated erosion along hiking paths
	P	Sports tracks			
	A	Ski-jumping ramps			

Landform types: E = excavation; P = planation (levelling); A = accumulation.

Even where artificial landforms are created largely for aesthetic or artistic ends, as is often the case in landscape architecture, the processes of their generation are often a primary concern. The contemporary use of landform in landscape architecture owes a significant debt to the land art movement of the 1960s and 1970s. As discussed in chapter one, land artists were not only concerned with the received form of their work, which tended to express ideas stemming from Minimalism, but also with the process of creation. Burnham relates land art specifically with his "system esthetics" and ideas from instructional art. (§1.8.) The process of creation is seen subtly in Richard Long's walking lines, where he would pace back and forth through the landscape to create an emergent "cow-path" but with linear geometry.[16] Much less subtle, but equally dependent on a process of creation, are the works of land artists which rely on moving earth and material in much larger quantities. This is seen in Smithson's works, such as in Spiral Jetty, whose dimensions owe as much to the physical process of its construction as to the concept idea of the spiral.[17]

The strategy of leveraging the processes of artificial landform creation, by for example measuring the sizes, capacities, and turning radii of construction equipment such as backhoes or dump trucks, also finds expression in contemporary landscape practices. These generative rule sets of technological processes in turn are often integrated into the process of computational landform creation, as seen for example in the work of students from Chris Reed's Mat Ecologies studio. Here, students explored how remedial technologies and the processes of their implementation, deploy themselves as a system that is "characterized by a set of component parts or units, governed by operational logics, that can be deployed flexibly across sites or territories in ways that respond to conditions on the ground."[18]

Increasingly as digital technologies begin to make a mark on the designed landscape, a new category of "procedural traces" are being observed in artificial landforms that are initially conceived in computational environments. Andrea Hansen traces many of these artifacts, finding the "faceting" of triangular computational meshes in landscape architectural works, such as in Foreign Office Architect's La Gavia Park, Vogt Landschaftsarchitekten's Laban Dance Center site, or in much of Vicente Guallart's work.[19] She also critiques the frequent appearance of "mimesis" or mimicry in computational landscapes, which she describes as a lazy "fascination with, if not fetishization of, mathematical and tectonic morphologies in nature."[20] Hansen's critique rephrased into terms presented in §2.6, would be that the formal systems in such projects are incompatible with the informational context, lacking performative aspects and an underlying *isomorphism*. Ultimately, for Hansen, the performative potential of digital landform should be foregrounded and not their formal, ontogenetic expression. As such, the type of computational algorithm used to create landform, whether ontogenetic or teleological, (§6.9) may help increase the performative potential of certain landforms.

13.4. Representations of Digital Terrain

Before examining some of the types of algorithms used to create and manipulate digital terrain, it is useful to introduce the major methods by which terrain in computational space is stored, modelled, and represented. In principle, all terrain in computational space is based on a number of "survey points" mapped to an X,Y, and Z value. The more of these survey points exist, the more precisely the terrain can be modeled. Terrains modeled with the "point cloud" method represent terrain only with a very dense cloud of points, and obtaining these data points with various methods from drone-based photogrammetry to laser scanners represents a large field of specialized research. Most representations of terrain of interest to landscape architects, however, use a much more limited number of survey points than what is found in a point cloud, and from the fixed survey points, model the terrain using either a mesh or, as in Rhino, a NURBS surface. While the process of meshing or triangulating terrain points may seem straightforward, even if the survey accuracy of the points is not questioned, the 3D representation will ultimately contain distortions, as the computer has to make decisions on what happens *between* the survey points—that is it must interpolate the data. This process alone is quite involved, especially with large and complex datasets, or where points are collected in a sporadic manner, and the method used will provide different kinds of distortions based on its internal logic.[21] Deriving a NURBS surface in programs such as Rhino also introduces distortions, as the NURBS construction algorithms assume certain curve continuities between points that do not necessarily correspond with reality. This is a major issue, and will be discussed later in a later case study (§15.5).

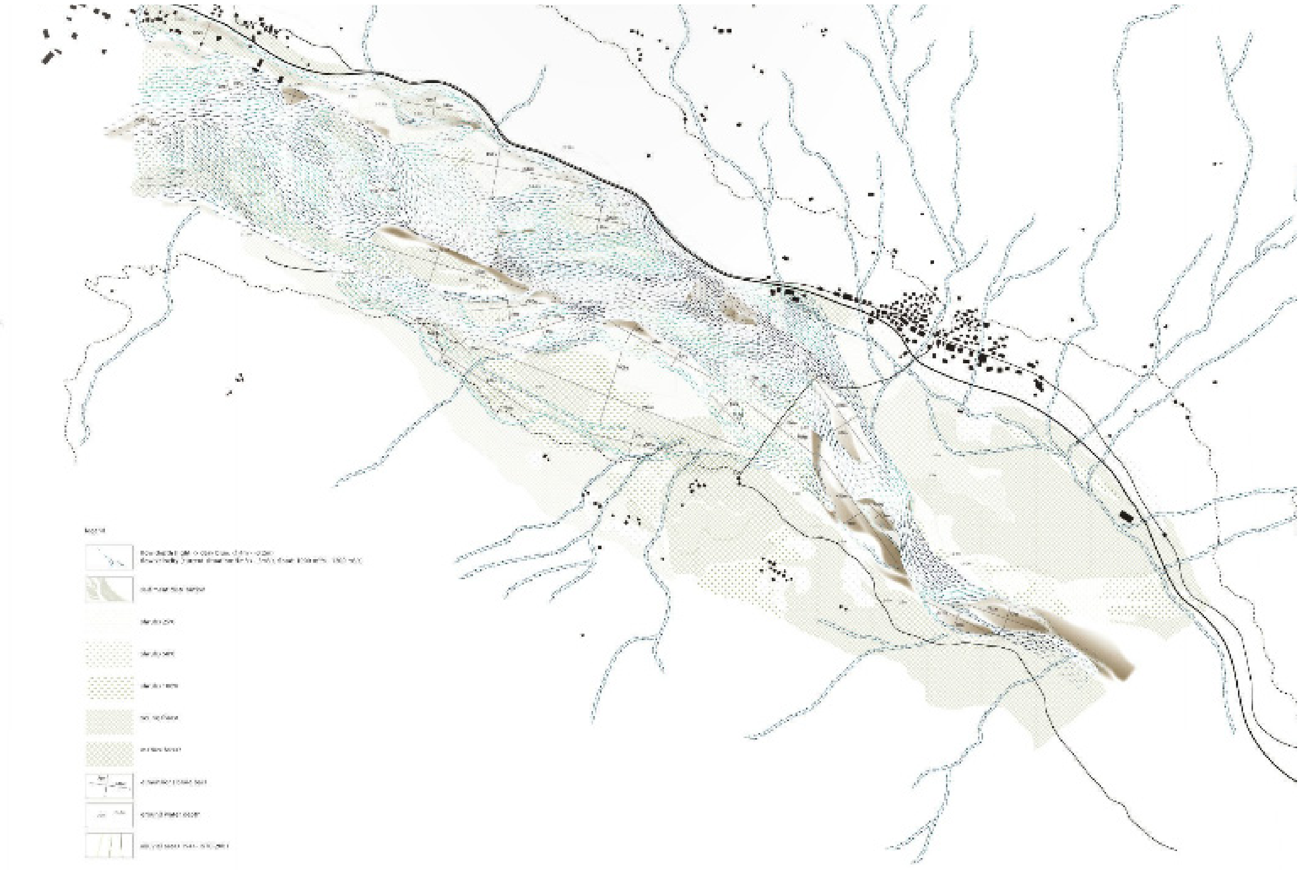
Getting acceptable starting data for any algorithmic manipulation of terrain is an involved and difficult, yet important task. Open source terrain data is plentiful and provides a good starting point for studying landform in the computational environment, although as we shall see is inadequate for design at the scale of the site. The most comprehensive single source for open source terrain data is provided by the Shuttle Radar Topography Mission, which includes radar survey data from an 11-day shuttle mission run in 2000. This data was sampled at the scale of 1 arc-second, which generally corresponds to a survey point on a 30 meter grid over the earth's surface.[22] The estimated accuracy of the survey points is around ±5.94 meters.[23] Because of the way the data is collected, a large number of errors happen around bodies of water, including coastlines, and in mountainous regions. A large number of post-processing algorithms have been developed to correct these areas in the dataset to improve its applicability, for example for hydrological studies.[24] Despite these improvements and the advanced nature of interpolation algorithms, the source data can never improve on the initial 30m grid, and the estimated error, making it unusable at site scales. Methods of collecting more accurate data at the scale of the site are constantly being developed and improved, from airborne LIDAR to drone-based photogrammetry, to laser-scanning, but such methods are expensive and introduce additional difficulties which must be addressed before they can be used on a design project.

13.5. Computational Landforms

Where difficulties with obtaining base data are overcome, or when site survey data supplied by a client is of sufficient quality for the purposes of a project, various algorithms can be used to evaluate and manipulate the terrain. Again these approaches can be categorized as ontogenetic or teleological approaches (§6.9). Many of the first kinds of algorithms were initially developed by computer scientists working on computationally efficient approaches to creating digital art or high-end graphics for movies. In such algorithms, speed, computational resource efficiency, and final aesthetic appeal are priorities, and not necessarily simulating the processes which led to the creation of that terrain. This does not mean that the final product does not provide a good approximation of reality. Scenery generation programs, such as Terragen or Bryce, make use of these algorithms and create scenes hard to distinguish from reality, but with very little computational complexity. An example of one of the algorithms such programs use is the midpoint displacement algorithm, and is described later in this chapter. (§A13.1) Such algorithms, however, can only generate superficial representations of reality and the author is unaware of their use or application by any landscape architects.

Of greater interest to landscape architects would be algorithms for terrain generation which tend towards the teleological approach. Many of these algorithms were originally developed by theoretical geomorphologists seeking to approximate real-world processes as part of an experimental method to confirm and to demonstrate hypothetical processes for land formation. As geological processes happen over such long time scales and the processes of land formation often cannot be observed in the context of a human lifetime, let alone over the course of human history, such computational experiments serve in lieu of laboratory experiments when dealing with processes happening in "deep time." Many excellent examples of theoretical landscape architectural projects that have adapted these computational approaches from geomorphology into regional and site-scale design were developed by students of Alfredo Ramirez and Eduardo Rico at the Architectural Association's Landscape Urbanism Program in 2014/15. The project *Littoral Negotiations* by Mouritz, Chang, and Hu, for example, adapted the Coastal Evolution Model developed at the Scripps Institution of Oceanography[25] for modeling sediment transport and deposition along coastlines to speculate as to how interventions in the Mediterranean Sea near Alexandria could be used to create productive new landforms through time.[26] They did not recreate or rewrite the complex model which was developed over the course of three years with specialized knowledge, but instead

Figure 13.3: (*below*) Hydrodynamic Study using the CAESAR Cellular Automaton. Lambert and Darin, 35.



worked on developing an interface which would bring the complex logics of the model into the spatial modeling environment of Rhino-Grasshopper and to use it in ways not anticipated by the original authors.[27] A similar adaptation of an existing geomorphological model—the CAESAR (Cellular Automaton Evolutionary Slope and River) model developed by Tom Coulthard at the University of Hull—was carried out by Lambert and Darin to study the transformation of a river in the Alps. In their *Riparian Land Shaping Machine,* the model was used to test the effects of small interventions in the river's course to see how the flows would transform over time, and how in turn this could be used to structure landscape space around the small alpine village.[28] (Fig. 13.3) A third study, *Aeolian Sand Odyssey* by Kotenko and Kakali*,* utilizes a process described later in this chapter (§A13.2) to model the movement of dunes in coastal contexts, and to speculate as to how this process can be better managed and controlled from a landscape architectural perspective.[29] These are just three examples of many models which have been developed and which *could* be useful in further evolving landscape architecture's vocabulary of landforms. The archive at Community Surface Dynamics Modeling System, for example contains at the time of this writing over 200 open-source geomorphological models, including 95 models applicable for terrestrial landscape evolution, 65 coastal models, 71 hydrological models, 51 marine models, and 15 geodynamic models. [30]

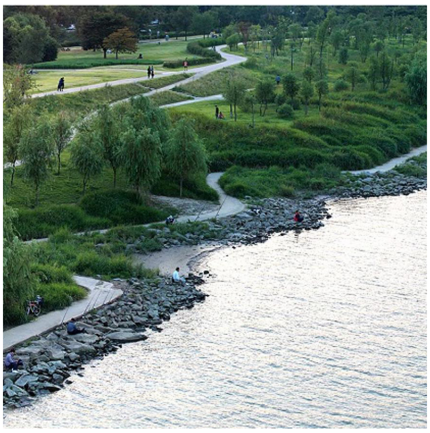


Figure 13.4: (*above*) *Mud Infrastructure*. Seoul Korea, PARKKIM. Photographer: Jong Oh Kim

These speculative student projects represent early experiments in what could be a significant paradigm shift in the computational generation of landscape form. While there are few examples of such methods being implemented on actual projects, the recent *Mud Infrastructure* project along the Han River in Seoul represents a case-study moving in that direction. Initially submitted as a competition entry for a park along the river's levee, the design team at PARKKIM won the competition since they engaged the sediment dynamics in the river and introduced landforms to change these dynamics, in contrast to other teams who did not challenge the form of the levee or engage in processes *in* the river because of a conservative reluctance to become involved with engineered systems.[31] (Fig. 13.4) Although the project did not use CFD methods, the landforms were tested and modeled in Rhino and their potential impacts were discussed with a hydrological engineering consultant, who in the end advocated for landforms even more radical and a more irregular river profile than what had been proposed in the competition entry, since the eddies produced would impede further sedimentation of the main channel.[32]

13.6. Speculative Computational Landforms

Studying the natural and artificial processes that lead to landform creation is a rich source of inspiration for algorithmic approaches to terrain, but algorithms can also be used to generate new kinds of landforms and terrains never seen before, and not necessarily related to identifiable earth or androgenic processes. This is the object of Michael Beaman and Zaneta Hong's Speculative Landformation project documented in "Landscapes after the Bifurcation of Nature" and in an associated exhibition at Harvard GSD entitled "Landformation Catalogue" (2015). Beaman and Hong use a combination of ontogenetic and teleological approaches in their study, categorizing landforms first based on their *morphologies,* which consist in examining the landform's "surface attributes at face-value with no regard for how they have come to be"[33] and later categorizing them based on *process typologies,* examining their "material fields and flows." By crossing *morphological* topologies with various *process typologies,* they create a series of rational, yet otherworldly landforms with names such as "Cryostatic Buttes", "Thermokarstic Ranges," and "Trellised Escarpments."[34] This is just one of many examples of experiments with speculative landformations that have emerged since the advent of digital methodologies in landscape design. (Fig. 13.5)

These types of studies, while aesthetically appealing, return us to Hansen's critique of digital traces in landform. Are such speculative studies, if they are not geared towards performative outcomes on earth, superficial or a waste of time? McHarg might seem to be making this argument when he says that "any project, save a small garden or the raddled heart of a city where nature has long gone, which is undertaken without a full comprehension and employment of natural process as form-giver is suspect at best and capriciously irrelevant at worst."[35] McHarg's critique would seem to allow these types of constructions on smaller sites, but would forbid association with the performative narrative. The argument can be made, however, that such experiments help refine the designers perception and intuitive feel for relation, and even if the precise forms are not seen in nature, with small changes to the generative axioms, they *could* be. Ultimately, however, when such new landforms are built, they must perform in some respects, as even on the smallest sites or sites where landforms are not pronounced, such as on generally "flat" sites, the variations in the ground plane and their impacts on the site's hydrology can have a significant impact on a project's long-term performance, such as on the ability of certain plants to thrive or die. Subtle grade changes can also impact how people move through and use a space. Other algorithms described in part 2 of this thesis can help test these other aspects of landform, and integrate them into the larger project workflow.

13.7. Summary Conclusion

As a primary means of structuring space in sites, a study of landform has always been an essential part of landscape architectural curriculum. Landforms in both natural and cultural landscapes are usually the result of clear formative or generative processes. Many of these processes lend themselves to algorithmic descriptions that can in turn be used in computational models and experiments. Such experimentation with computational landforms has the potential to enrich not only the formal vocabulary of landscape architecture, but also enhance the performance of sites. In general, however, landforms should be conceived as events in a field of forces, being subject to processes of change over time. Landforms which align with forces will endure for much longer, while landforms standing against such forces will be quickly eroded or disintegrated.

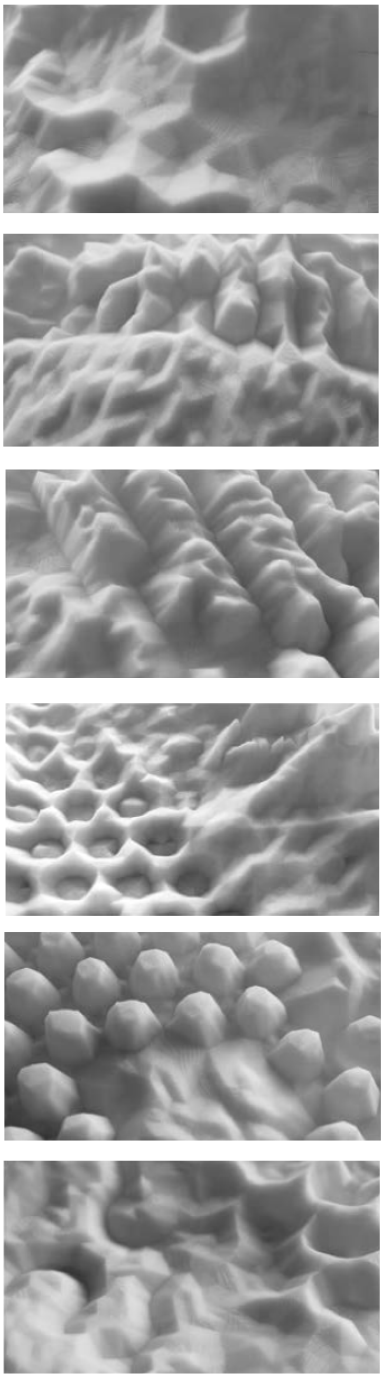
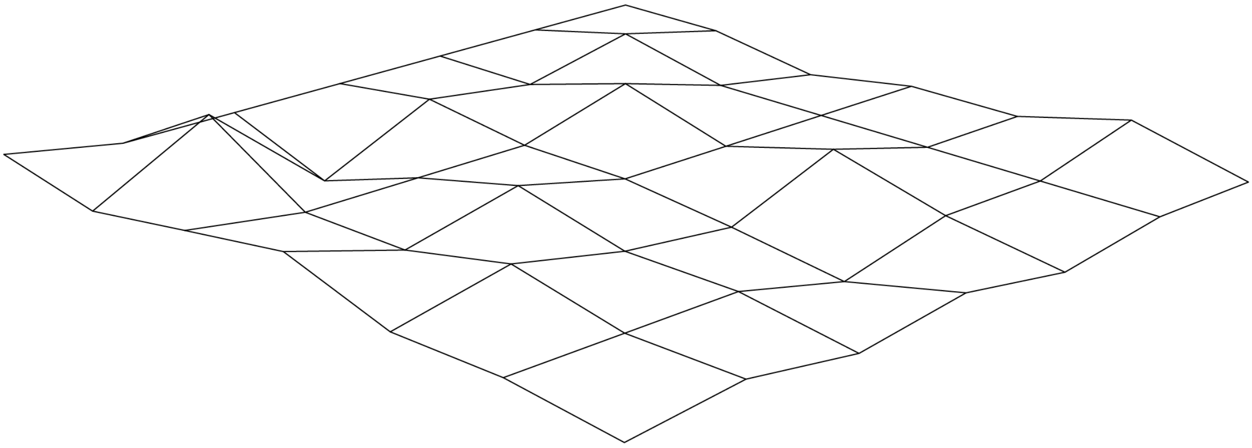
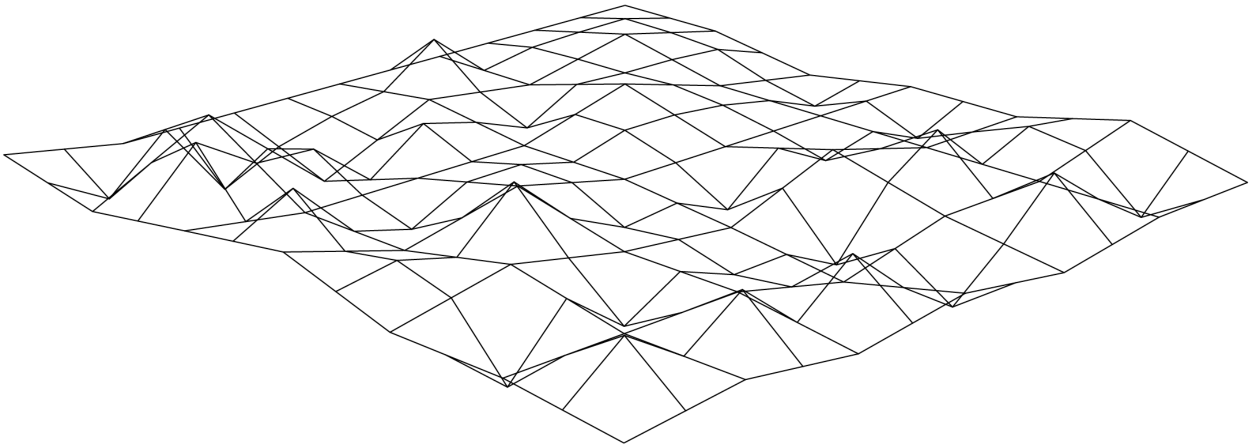
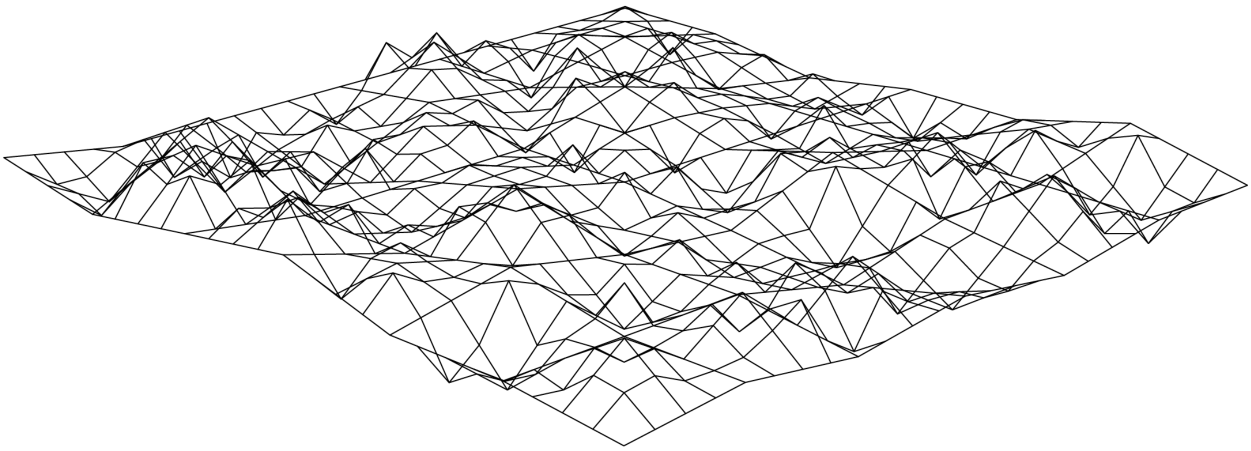


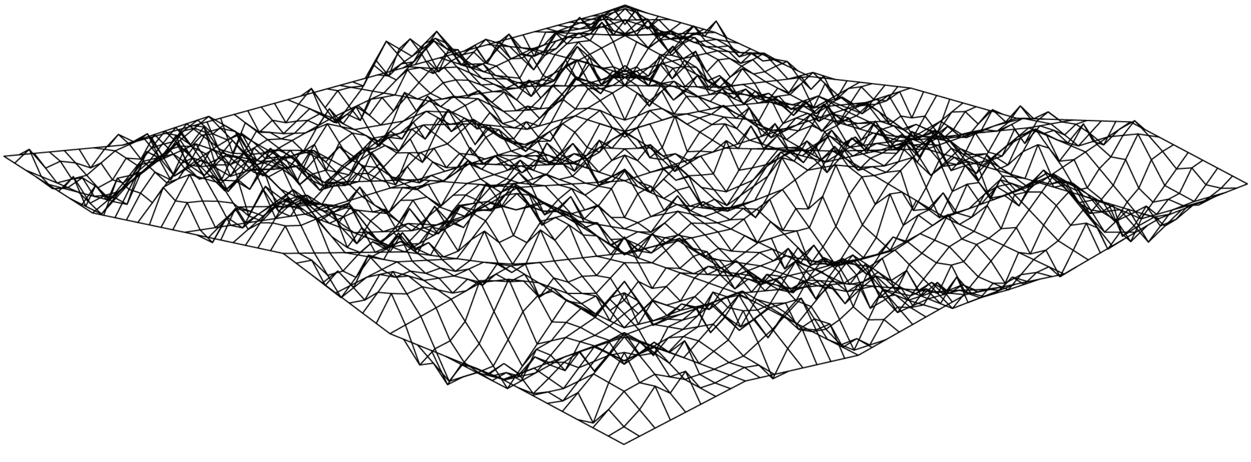
Figure 13.5: (*above*) Speculative Landformations, Beaman, 437.

Image courtesy of Michael Leighton Beaman and Zaneta Hong









Algorithm 13.1. Fractal Terrains - Midpoint Displacement / Diamond Square Algorithm

An early application of fractal methods to computer graphics was through their use in terrain generation programs such as Bryce or Terragen. Such methods are still used at least for the initial generation of terrain in such programs. One of the most well-known of these methods is the midpoint displacement algorithm, with a variation of this known as the diamond square algorithm. Michael Batty enthusiastically embraces the algorithm in *Fractal Cities* citing it as a simple, yet powerful demonstration of the power of recursion, although he notes it alone must be combined with more complex algorithms to begin to approach the realism of actual landscapes.[36] Although early speculation presumed a link between the processes of fractal generation and the processes of nature, this view has been largely discredited and despite superficial similarities to natural forms, Shenker argues that they are fundamentally and ontological distinct from natural forms.[37] For this reason, this algorithm is best characterized as an *ontogenetic* algorithm (§6.9).

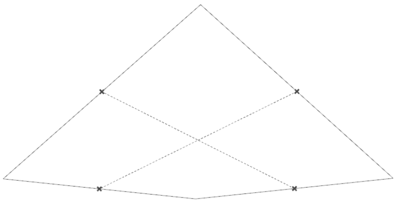
Figure 13.6 (opposite page) Starting conditions and three iterations of the Midpoint Displacement Algorithm

The algorithm starts with a rectangle with corners set at varying heights by the user. The user also sets a maximum scale factor which will ultimately affect the “roughness” of the terrain. In the first recursion, the midpoint of each of the four sides of the rectangle is found and a line is drawn to connect the midpoints on opposing sides of the rectangle. The intersection point in the middle is identified, and will always have a “Z” value that is the average of the “Z” value for the four corners. This point is then moved up or down by a random value which will not exceed the ratio between the overall rectangle size and the maximum scale parameter set by the user. Lines are then redrawn between each of the four midpoints to connect to this new point. At the end of the step, there are now four rectangles instead of the initial one, each sharing two sides with its neighbors. (Fig. 13.7, Steps 1-3)

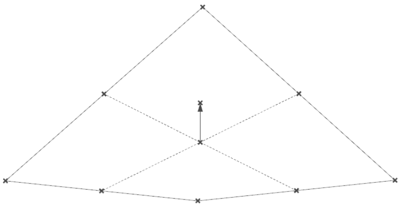
The second recursion proceeds in the exact same fashion, finding the midpoints of each rectangle side, from which the center point is derived, and each center is displaced again either up or down by a random amount independently generated for each point, which can be positive or negative, but which cannot exceed the ratio between each rectangles size and the initial maximum scale factor. In other words, the second displacement, on average, will be half the amount of the first displacement. After the second recursion, 16 rectangles exist. This process continues again and again, with the rectangles and random displacement getting smaller and smaller while the total number of rectangles is getting exponentially larger, 64, 256, 1024, etc. Eventually, if the process is allowed to continue, the computer system’s resources will be taxed to the limit. After 5 or 6 recursions, however, the overall form of the digital landscape is more or less set, so it makes little sense to continue the process beyond this point. The end result is a fractal terrain, which at first glance looks like a natural mountain range. A significant difference, however, is that this digital mountain range contains just as many minima (basins) as maxima (peaks), whereas in the real world, processes of erosion and deposition, and sedimentation tend to erase minima with time.

Figure 13.7 (below) Steps in the Midpoint Displacement Algorithm with contours through final terrain shown at bottom.

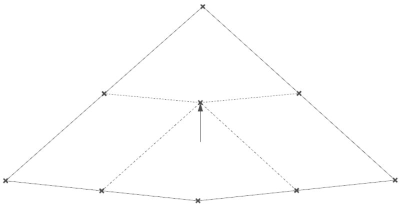
Figure 13.8 (below) Variations of the Midpoint displacement Algorithm with various starting conditions and an adjusted “roughness“ factor.



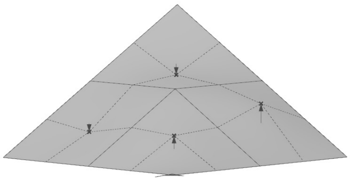
Step 1 -
Draw lines between midpoints of each square



Step 2 -
Move intersection point of lines a random amount up or down



Step 3 -
Draw four new squares from translated intersection point, connecting it to midpoints of overall square



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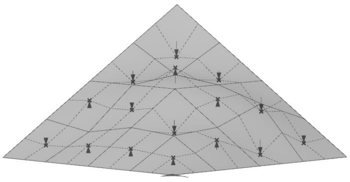

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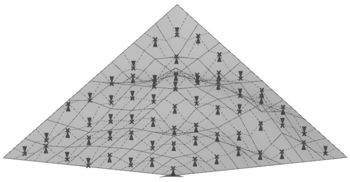

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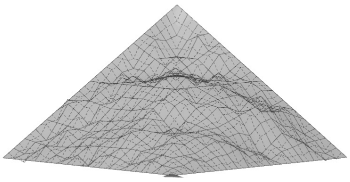

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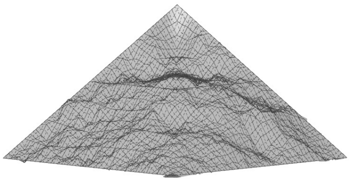

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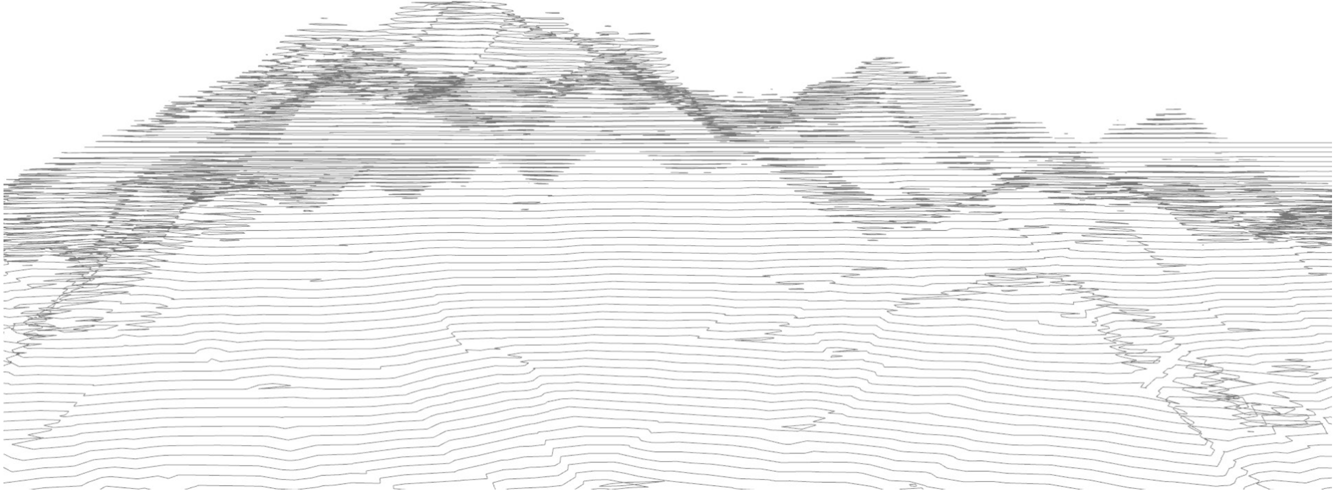
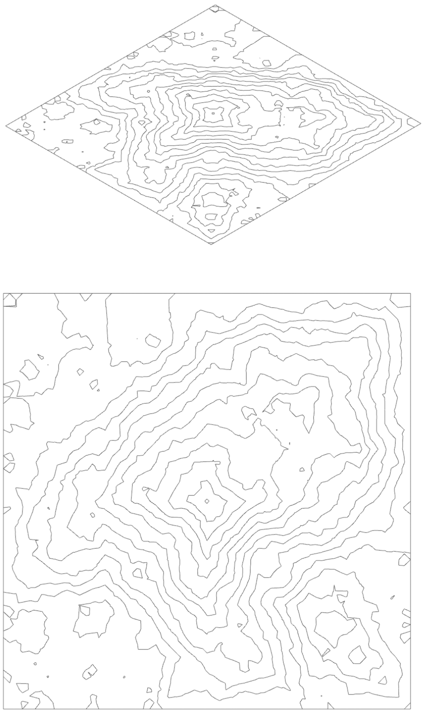
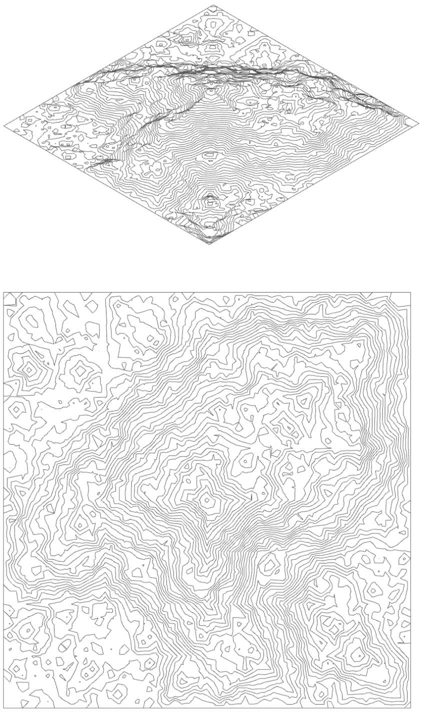
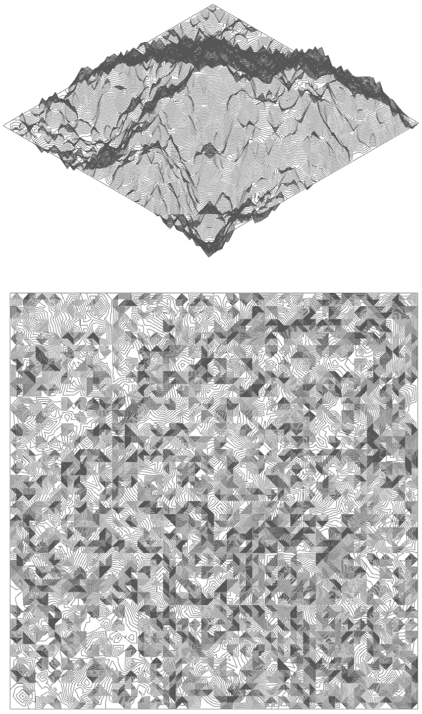




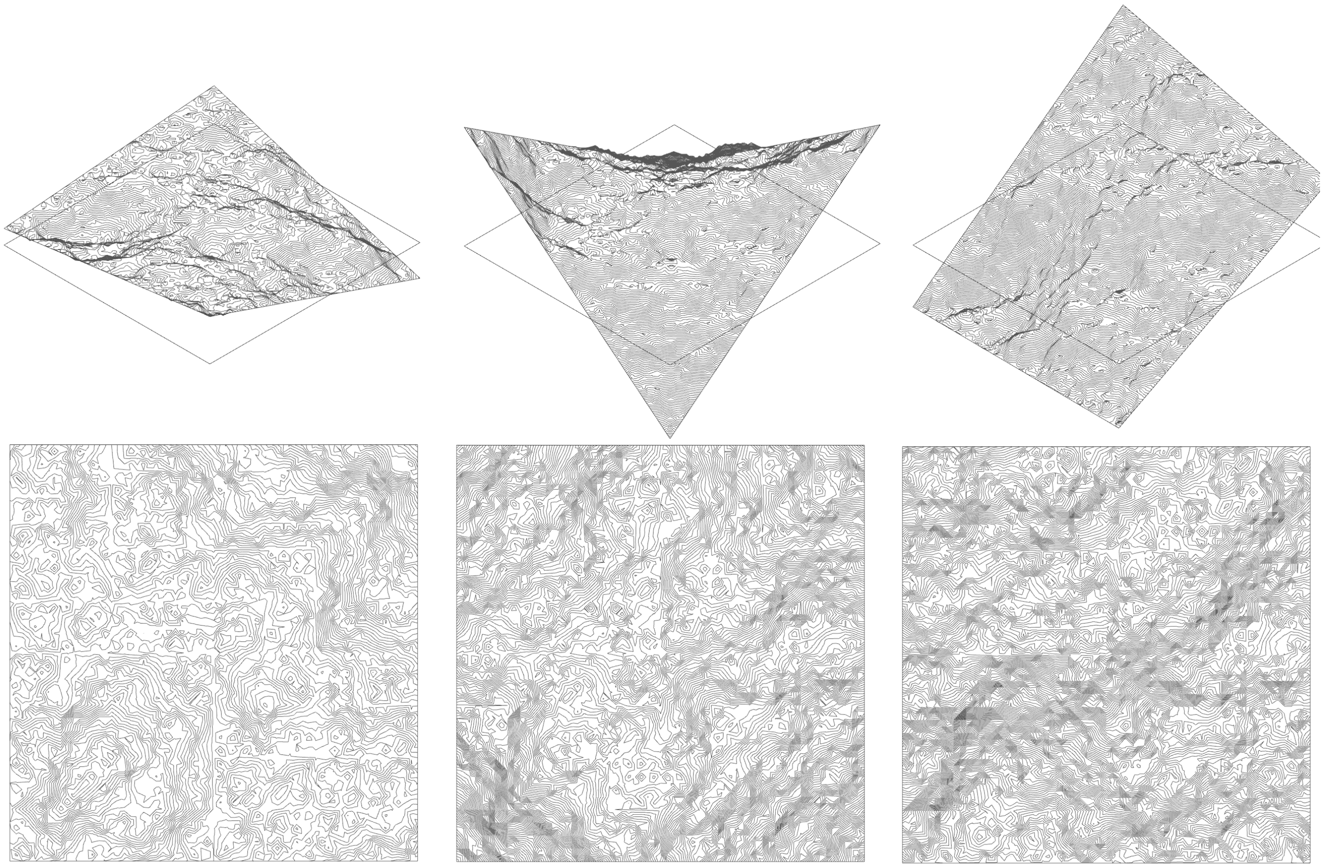
Low roughness (0.10)



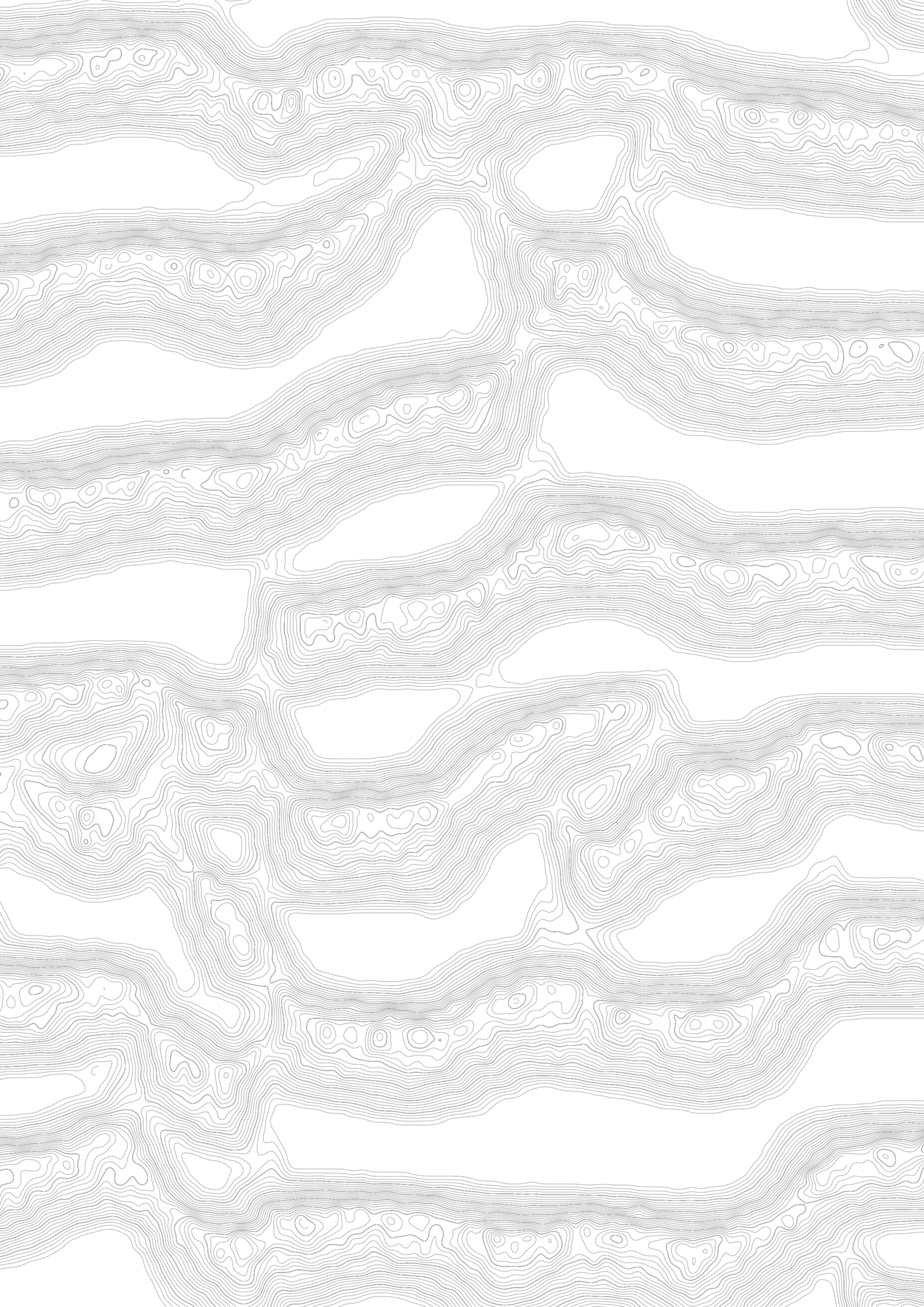
Medium roughness (0.30)



High roughness (0.50)



Results of changing starting boundary



Algorithm 13.2. Dune Fields

Whereas the midpoint displacement terrain method explained in the previous section cannot be said to create realistic terrain following the actual processes of land formation in nature, other well-researched algorithms move in this direction and can be rightly classified as *teleological* models. An oft cited example is Brad Werner's (1995) model of dune formation where he used a type of cellular automaton to speculate on how various morphologies of dunes, from crescent shaped barchan dunes, to dunes with a linear form, emerge based on varying amounts of initial sand availability.[38] An adaptation of Werner's model is presented here. It may be helpful for the reader to familiarize themselves with the basic logic of the cellular automaton as presented in §6.13 and §6.14 before continuing.

The model starts with a grid of cells or stacks of sand where each cell is 5 "units" wide. Instead of having either an "on" or "off" state, the state of each cell is a number reflecting the amount or height of sand in the cell/stack, with the height number corresponding to 1 "unit" of sand. This means if the state of the cell is "5," it represents a 5x5 cube of sand (the cell width times the cell state). The average height of sand is the most important initial parameter which will lead to a range of formal outcomes at the end of the simulation. Sand heights are assigned initially based on a random distribution. The algorithm then begins a recursive loop, going through a number of progressive phases.

Figure 13.9: (opposite page) Contour lines drawn through algorithmically generated sand dunes.

Phase 1 – Avalanches: Before the effect of wind is felt in the sand field, extreme height differentials between high and low points are flattened as would occur in a field of sand in the real world. The parameters for the avalanche procedure here are based on the angle of repose for dry, fine sand, which is 35°. The algorithm routine starts with the cell with the highest overall amount of sand and compares this with its eight immediate neighbors (the Moore neighborhood see Figure 6.12). If the height differential between the highest point and its lowest neighbor is greater than 2, then the sand falls into this lower cell, in effect reducing the state of the highest cell by 1 and increasing the state of the lowest cell also by 1. This continues until no height differential between a stack of sand and one of its neighbors is more than 2. (Fig. 13.11, top)

Phase 2—Wind Saltation: The next major procedure models the movement of the sand itself under a hypothetical wind force. In these examples, the wind always comes from one primary direction, but variations of the algorithm could account for a changing prevailing wind. Before each movement of sand, the algorithm calculations the "wind shadow" for the existing landforms, based on a 15° angle behind each stack of sand. (Fig. 13.11, bottom) All cells are then selected in a random order. If the cell is in a wind shadow, no movement of sand takes place and the algorithm moves on to the next cell. If a stack of sand is exposed to a wind force, the state of that cell is reduced by 1, and the sand is moved to the next stack in the direction of the wind force. There is a probability P that the sand will be deposited in this cell based on the following criteria.

-If the cell is in a wind shadow, the probability is 100% ($P = 1$). The sand is deposited and the cell's state is increased by 1.
-If the cell is not in a wind shadow, there is a chance it will be deposited and a chance it will "bounce" and move on to the next cell. This probability is adjustable, but here the value of P is set to .6 if the cell is already occupied with sand (cell state ≥ 1) and $P = .8$ if cell state is $= 0$. This reflects the empirically observed diminished probability of a "bounce" on a hard substrate.

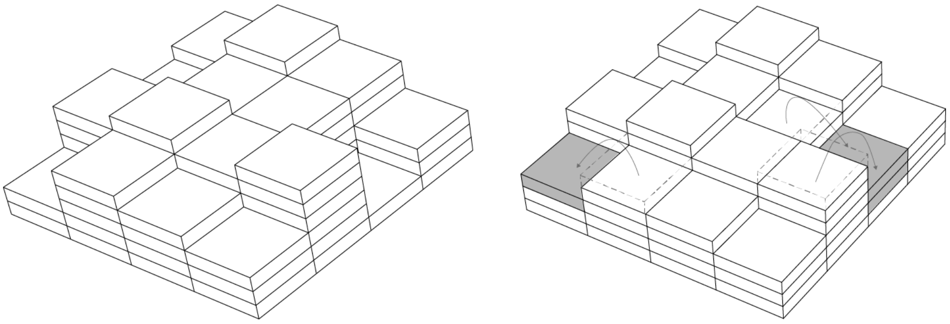
The process now repeats for each cell, modelling the movement of each stack of sand individually. Once Phase 2 is complete, the algorithm returns again to Phase 1, performing avalanches based on the updated states of the cells.

Over many generations, from these basic rules, suprisingly complex and dynamic patterns emerge. If the initial sand supply is low, the dunes, at least in the earlier phases, tend to be cresent shaped barchan dunes (e.g. Fig 13.10, Average Sand = 1.5 or 2.0). As sand supply increases, the linearity of the sand ridges increases, and this pattern also tends to develop at a faster rate. Variations are shown in Figure 13.10 showing the various outcomes of a dunefield 75 cells x 150 cells in dimension after 100 rounds of the simulation.

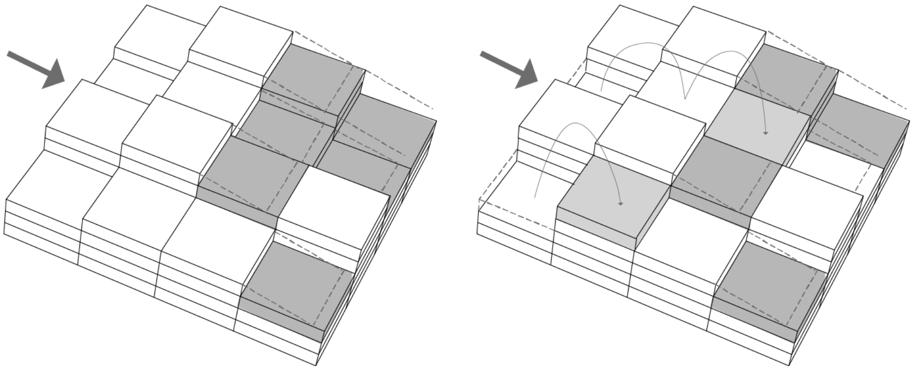
Improvements and extensions to Werner's model have been suggested by a number of authors, with new variations being suggested on a regular basis in the scientific literature. A notable example is Andreas Bass's model, which introduces the effects of stabilizing vegetation into the dune field. He demonstrates how the presence or absence of plants, which can introduce a complex feedback loop of increasing stability in some areas and increasing instability of others, has a fundamental impact on the potential dune forms.[39] An application of this model in a design context was developed by students Anastasia Kotenko and Niki Kakali at the Architectural Association in London in 2014 and will be revisited in Chapter 16.

Figure 13.10: (opposite page) Various dune formations as sand supply increases.

Figure 13.11: (below) The two basic processes active in the cellular automaton.

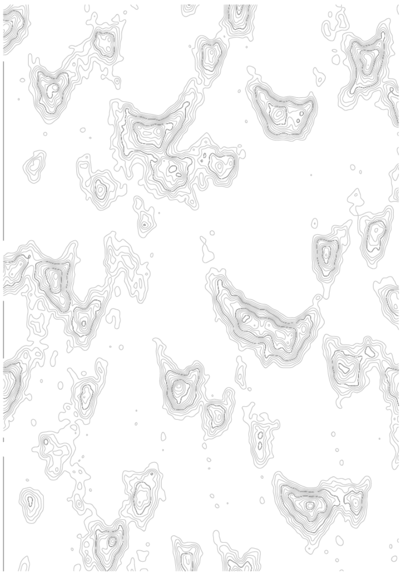


Avalanching Process

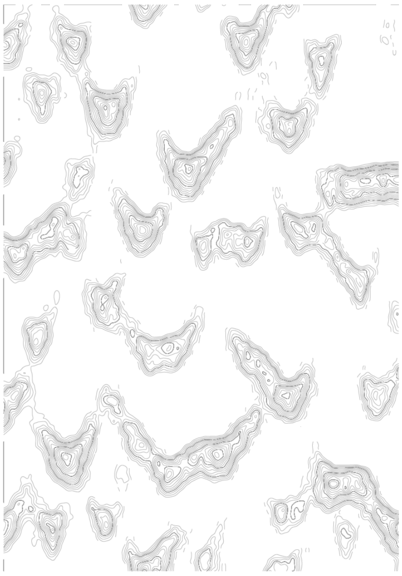


Wind Saltation Process

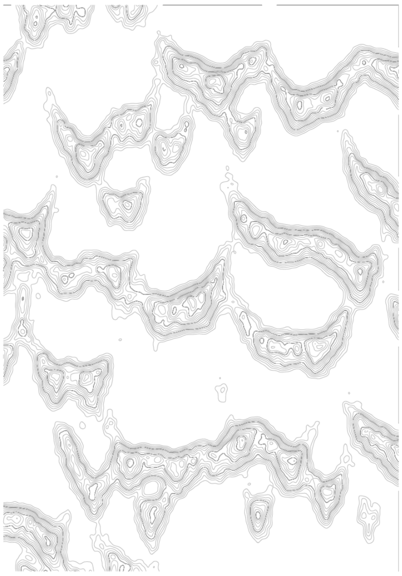
Average Sand - 1



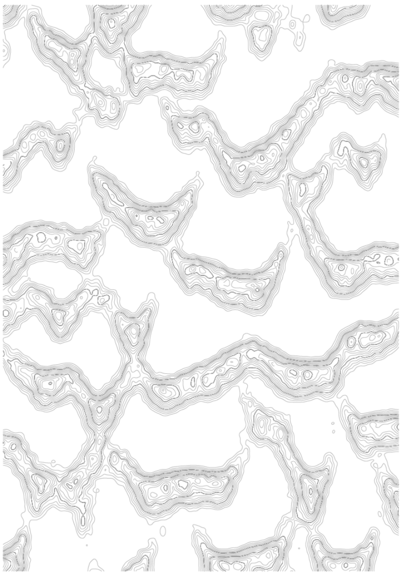
Average Sand - 1.5



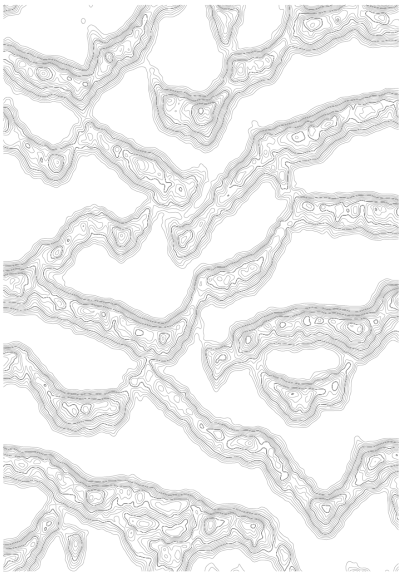
Average Sand - 2



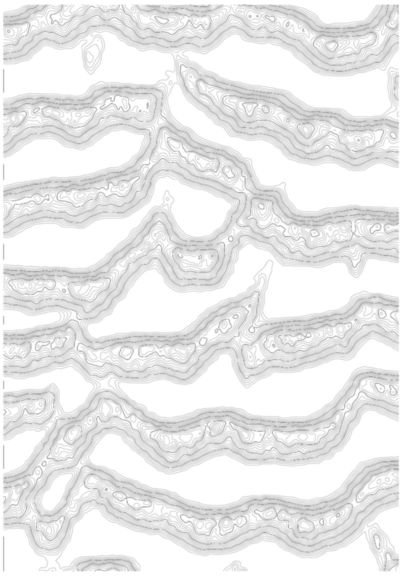
Average Sand - 3



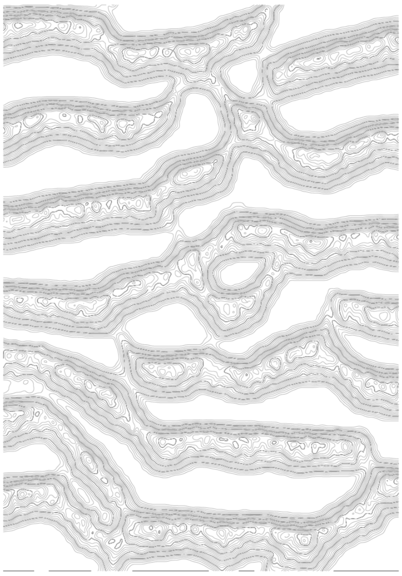
Average Sand - 4



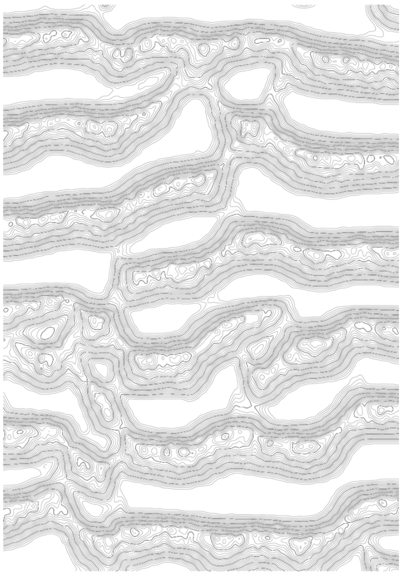
Average Sand - 5



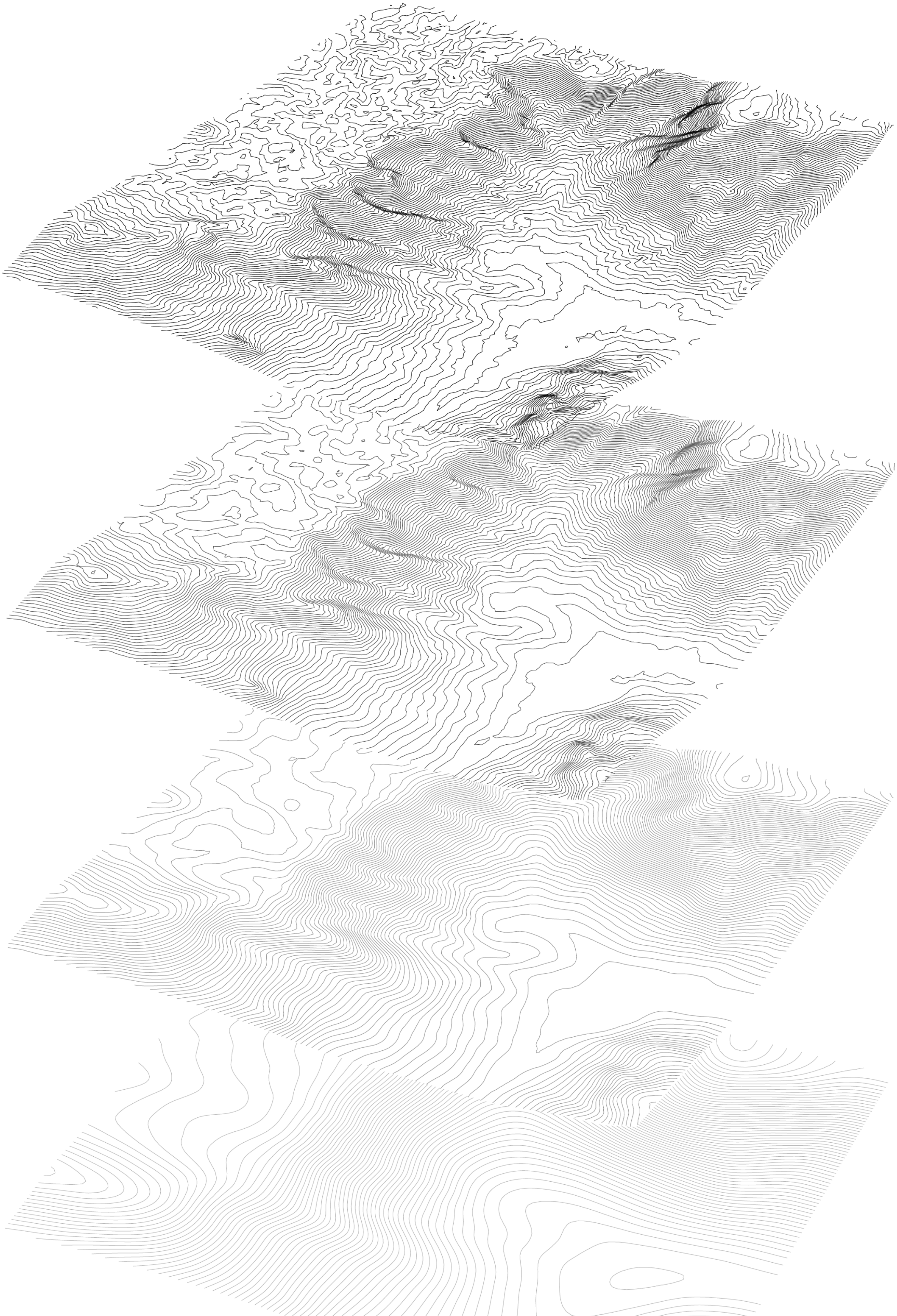
Average Sand - 6



Average Sand - 8



Average Sand - 10



Algorithm 13.3. FIR Erosion Algorithm

During the course of the research, one of the goals was in contrast to the terrain building algorithms described in §A13.1 and §A13.2 to devise an algorithm which could reshape a terrain through the process of erosion. Many good examples of such "hydraulic erosion algorithms exist" and have a clear logic based on the mapping of single "drops" of water across a terrain, which transport sediment with rules closely proximating actual sediment transportation and deposit of water. Such algorithms are commonly used in procedural terrain generation to create convincing landforms. Images of such an algorithm's effects are shown in Fig. 13.18.

Unfortunately in the time for the compiling of the algorithms, it was not possible to get this process working—although the logic is clear and straightforward, obstacles with the coding and data structure prevented this from being completed. A much simpler *ontogenetic* terrain algorithm in contrast to the *teleological* algorithm initially desired is presented here instead. This algorithm is known a FIR (Finite Impulse Response) algorithm. Intended for filtering signals, it is a method for reducing a dataset to "zero," which also can said to be the goal of erosive processes.

Starting with an original grid of points, the algorithm draws section lines through the points in the X direction. Then, moving in the positive X direction, it compares each point to the next point in the sequence. If the point P´x is higher than the next point in the sequence P_{x+1}, the next point in the sequence is raised by a factor equal to the height differential multiplied by an "erosion factor" E. If $E = .50$, for example, and P´1 is 10 units higher than P2, P2 is moved upwards by 5 units. This represents downhill erosion. P2 now becomes P´2 and this moved point will be compared to the next point in the sequence and so on. Note that matter is not conserved in this process, but this will be accounted for in later steps. As points are moved either upward or downward, a new section line is recursively drawn to connect them. Also note that the height differential is calculated for a point after it has already been moved. (Fig. 13.13) An identical process occurs along *all* the section lines simultaneously in the X direction until all points have been moved. (Fig. 13.14) Next the algorithm performs the same process, but this time in the *negative* X direction. In balance, the two runs of the algorithm in both the positive and negative X direction will conserve matter. A third and fourth recursion of the algorithm now perform the process first in the positive Y direction followed by the negative Y. (Fig. 13.15)

The algorithm does not produce the fine results of a hydraulic erosion model, but in some ways, this process does produce a final product which represents years of erosion, as the landscape transistions from youth to old age. (Fig. 13.16)

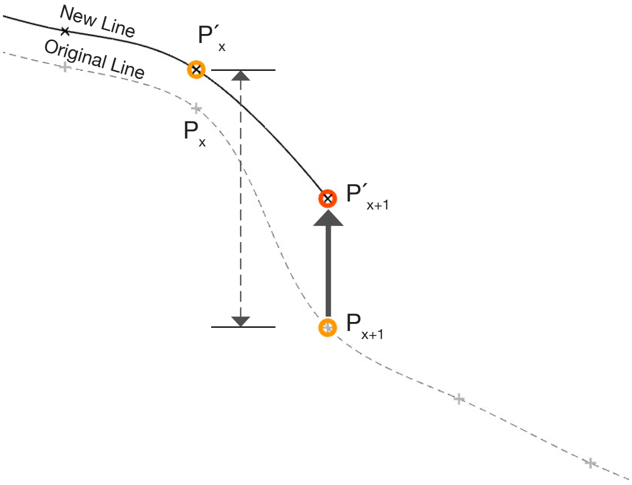
Figure 13.12: (*opposite page*) Effects of the FIR erosion algorithm on a large scale model of the east flank of the Aburrá valley in Medellín, the site of the case study in Chapter 15.

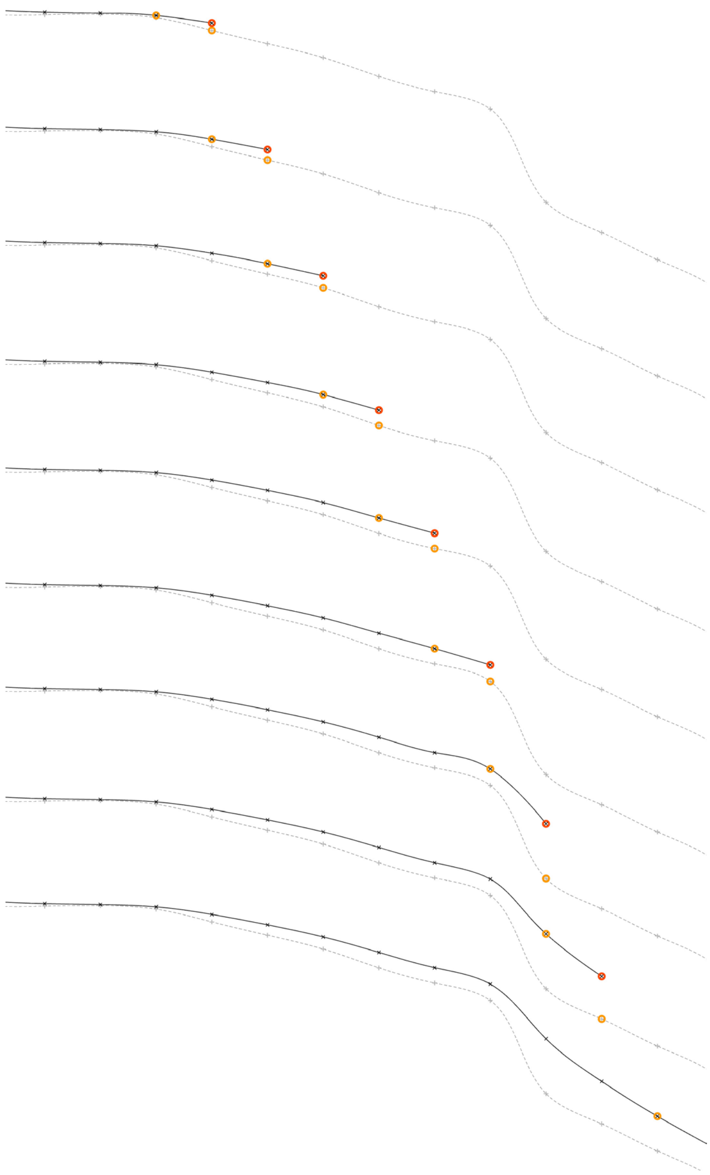
The top terrain represents the starting terrain, the next is eroded with an erosion factor $E = .30$.
In the third $E = .50$ and
in the bottom terrain $E = .30$

Figure 13.13: (*right*) Detail of the algorithmic logic for a single time step, where the height of a point is compared with the height of the previously moved point in the series.

Figure 13.14: (*bottom, left*) Nine steps of the algorithm as points are progressively moved to create a new section.

Figure 13.15: (*bottom, right*) View of the overall progress of the algorithm in the positive X direction





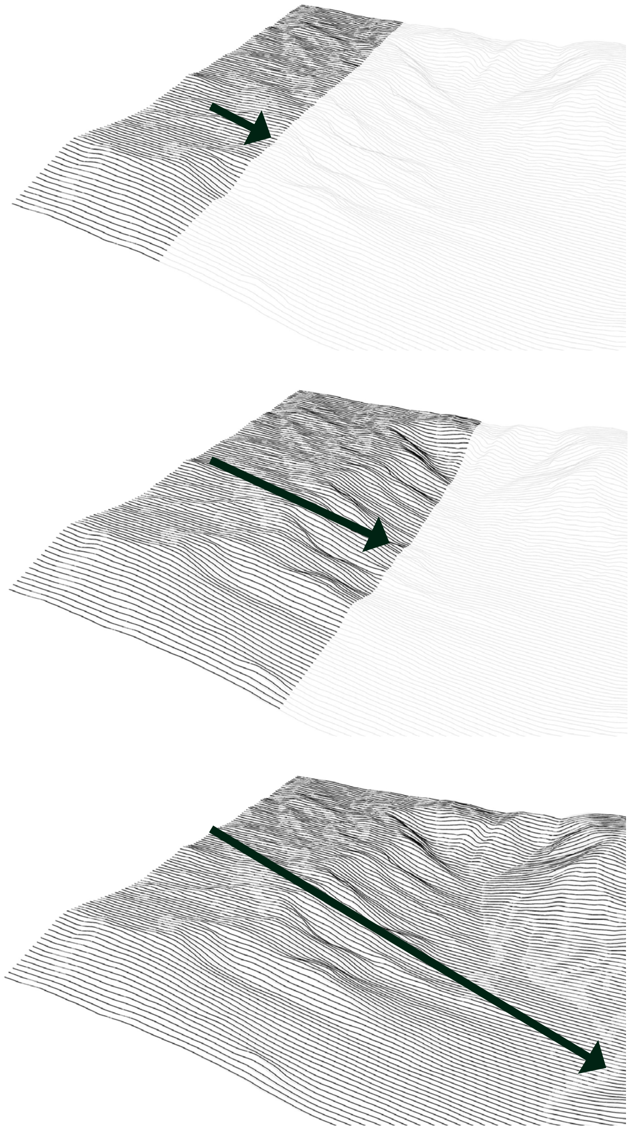


Figure 13.16: (*right*) Landforms of various ages. Hugget, *Fundamentals of Geomorphology,* 7. Used with permission.

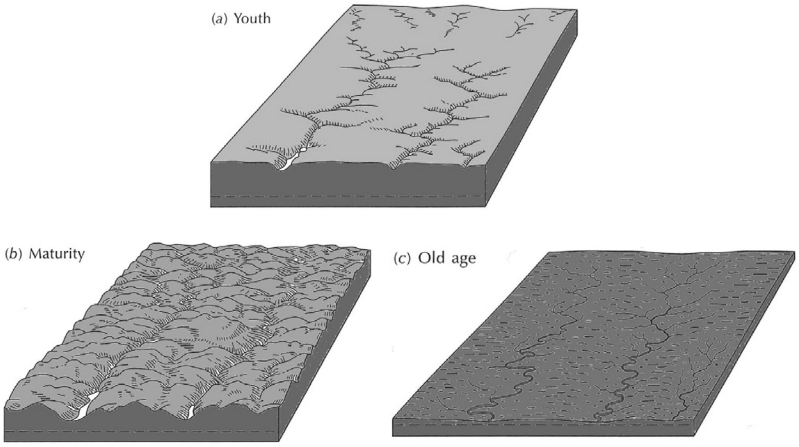


Figure 13.17: (*bottom, lef*) The algorithm repeats in the negative X, positive Y, then negative Y directions

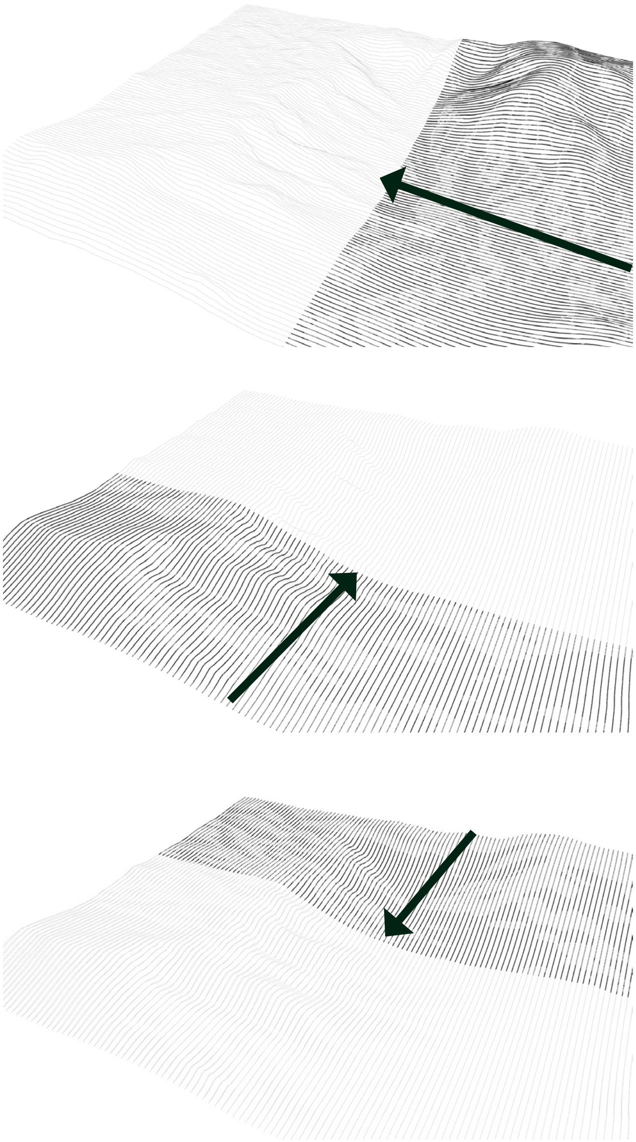
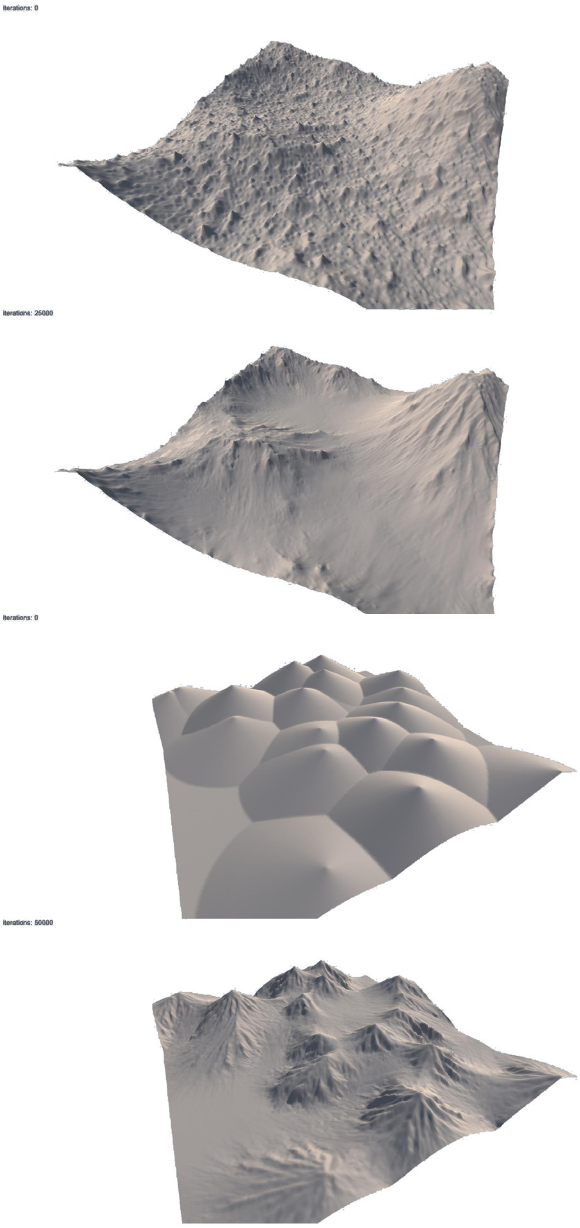


Figure 13.18: (*bottom, right*) Examples of hydraulic erosion scripts, a different approach to erosion which more closely approximates nature processes, for comparison with the results of FIR. Algorithm is not shown here. Image courtesy Hans Beyer (2015)



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Chapter 14 – Ecology & Evolution

"Where the landscape architect commands ecology he is the only bridge between the natural sciences and the planning and design professions…this can be at once his unique attribute, his passport to relevance and productive social utility…ecology offers emancipation to landscape architecture."[1]

14.1. Introduction

In the previous chapter, the creation and transformation of earth's landforms was introduced as the result on long-running processes in nature and more recently in culture. Landform contains elements of both smooth space, with its gradual gradients, and its high degree of potential for alternate futures, as well as striated space, with its sharp boundaries and non-conformities. Landforms also contain a record or a memory of the earth's past forms and states, and although much has been erased, it is still possible to recover much from this past history by understanding what processes led to the positioning of the fragments in their current positions. Yet the history of the earth's landforms, while complex, is only a part of the complex tapestry of processes of interest to those who study the landscape, including landscape architects. Just as important as a form-giver, if not more, are the processes of living systems which have continuously shaped the surface of the earth. These systems and the organisms that comprise them are subject to constant pressures and changes through the process of natural selection, which leads to evolution of organisms, and in turn of systems through time. The relationships between living organisms and their environment are described through the science of ecology. In the last decades, ecology and ecological methods have become of primary interest to landscape architects. The primary role of ecology was most famously promoted by Ian McHarg, who claimed this holistic discipline offered landscape architects, as quoted at the beginning of this chapter, a "passport to relevance." As our understanding of ecology grows and shifts, however, the nature of this "unique attribute" and "passport" also continues to change in the discipline.

Figure 14.0: (*page opposite*) Competition or cooperation? A pine tree being overtaken by birches. The trees seemed locked in either an embrace, or a death struggle.

In their quest to undercover methods for revealing the underlying ecological and evolutionary processes which generate form in nature, landscape architects can be well served by numerous algorithms developed by complexity theorists, as well as by computer scientists to "evolve" solutions to problems which cannot be easily answered with conventional methods. While already hinted at several times, this final chapter on algorithms specifically addresses algorithms designed to understand and model living, evolutionary systems. The physical landforms examined in the last chapter do undergo a certain degree of "evolution", and landforms potential manifestations in the future are somewhat dependent on past states, but earth's landforms cannot be said to undergo processes of natural selection and neither cooperate nor compete with each other. This is a hallmark of living systems, and processes of cooperation and competition through time, combined with irregular disruptive events, lead to interesting and surprising formal outcomes. Landscape architects can use ecological and evolutionary algorithms to better understand and represent potential future states for landscapes, to "speed up" the evolutionary process in other landscapes, as well as to find optimal forms in a controlled setting before the investment of time, money, and resources in actual projects.

14.2. Emergence of Ecology as a Discipline

Landscape architects see their discipline as relatively young, especially in contrast with architecture, but ecology as a discipline is younger still. Earlier chapters explored the idea that certain modes of ecological thinking have been present for millennia, evident in the writings of Lucretius on the one hand, to von Humboldt on the other, but the use of the word "ecology" itself can only be traced back to Ernst Haeckel in 1869. Haeckel, who was a disciple of von Humboldt's world view coined the term Ö*kologie* from the Greek word "oikos" meaning household, with the word literally meaning "study of the household."[2] It would only be after the widespread acceptance of Darwin's theory of evolution by natural selection began changing the study of biology from a descriptive science to a relational one that the discipline of ecology would become structured as a formalized discipline separate from its most important parent, biology. While the two disciplines remain closely related, biology can be said to emphasize study of living organisms from the level of the individual organism downwards to the molecular scale, while ecology studies living systems from the scale of the organism upwards through categories such as populations, communities, landscapes, regions, up to the ecosphere. A golden age of ecology began shortly after the Second World War and extended through the end of the 1970s. A key figure in this period who laid out many of the fundamental principles of the discipline was Eugene Odum, who published his seminal text *Fundamentals of Ecology* in 1953 which has defined many of the key concepts of the discipline. Ecological thinking developed rapidly in the 1960s and 1970s, paralleling the emergence of systems theory (§1.8) in the sciences and in art, as well as structuralism, which emerged first in linguistics and came to define much of postmodern thought in philosophy and in design. Ecology reached an early pinnacle of influence following the Apollo missions to the moon, with the first images of earth as perceived from a distant perspective emphasizing the wholeness of the ecosphere, along with its fragility.[3]

Although some ecologists have been criticized for their focus on studying ecosystems in pristine or idealized states, almost from the beginning ecologists, at least in the sense which Odum conceived, were well aware of the impossibility of separating natural from androgenic systems. By necessity as a scientific discipline, ecology had to be reductionistic to some degree, but its aim was to contribute to a broader, interdisciplinary picture that links and transcends the natural, physical, and social sciences.[45] Odum himself emphasizes the parallels between ecological processes in natural systems and economic processes in society, seeing the two disciplines (both with names derived uncoincidentally from the Greek 'oikos') as compatible rather than competitive paradigms, with economic rules, such as those developed by von Neumann and Morgenstern, applicable to ecosystems and vice versa, with energy rather than money serving as the currency of ecosystems.[6] Other ecologists have focused on the specific relationships between natural and cultural systems. This is especially evident in the work of Richard Forman, a pioneer in the field of landscape and urban ecology who researched how these systems interact, defining key concepts of landscape structure (patches, corridors, matrices, and networks) and landscape dynamics, including natural and cultural forces which induce patterns of stability or instability.[7]

14.3. Broader Definitions of Ecology

Despite its relative youth as a discipline, ecological thinking began to have a profound impact on many disciplines both in and outside of the natural sciences, who in turned adapted ecological thinking to a much broader set of concerns. A notable example includes Bateson's *Steps to an Ecology of Mind*, where based on his experiences researching in the diverse fields of anthropology, psychiatry, biological evolution, and genetics, Bateson elucidates a framework which saw *ideas* interacting and undergoing evolution and processes similar to natural selection, allowing some to live and others to die.[8] Ideas are not amorphous, unstructured entities, but can be studied in terms of form and pattern. Bateson argues that "mental process, ideas, communication, organization, differentiations, pattern, and so on are matters of form…" and that the understanding of "form has been dramatically enriched in the last thirty years [~1940-1970] by the discoveries of cybernetics and systems theory."[9]

Two decades later, at a time when the related frameworks of ecology, systems theory, cybernetics, and postmodern structuralism were again being re-evaluated, Guattari found in ecology something beyond the standard linguistic-structuralist narrative explored in his text "The Three Ecologies," which explored what he termed "social ecology, mental ecology, and environmental ecology"[10] Here Guattari sees ecology as having the potential to go beyond the related paradigms of cybernetics or structuralism as ecology allows for growth change and evolution, what Guattari terms the "infinitely varying rhythms and refrains - which are nothing more or less than the buttresses of existence."[11] This stems from Odum's observation that ecosystems cannot be seen in homeostatic terms, a position advocated by cybernetics, but rather as self-regulating systems with feedback loops creating a rhythmic pulsing behavior-what he terms *homeorhesis*, a neologism derived from the Greek for flow or river.[12] It is precisely the evolutionary nature of ecosystems with their pulsing flows which allow for the introduction of innovation or novelty—designed ecologies and interventions.

14.4. Ecology and Landscape Architecture

With this background of the emergence of ecology as a new integrative scientific discipline and the broader readings of ecology espoused by Bateson, Guattari, and others, the role of ecology in landscape architecture as the design discipline most concerned with interventions into natural systems should be read. As ecology was emerging as a new scientific discipline in the 1960s, landscape architects quickly saw parallels between ecological thought and thinking within their discipline. Despite its origins in the natural and specifically biological sciences, ecology sought to be holistic and cross-disciplinary, seeing humans as part of the innumerable processes shaping the environment. Ecological thinking was especially important for Ian McHarg, who two years before his transformative text *Design with Nature* published a brief article in *Landscape Architecture* magazine calling for landscape architects to adopt an "ecological method." Here McHarg claims that "ecology provides the single indispensable basis for landscape architecture" and that when a landscape architect "commands ecology he is the only bridge between the natural sciences and the planning and design professions, the proprietor of the most perceptive view of the natural world which science or art has provided."[13] McHarg realized, however, that the use of ecology by landscape architects could not be grounded in purely scientific terms. He argues that landscape architects must use ecology "selfishly"—with the concern begin to find "a method which has the power to reveal nature as process, containing intrinsic form."[14]

The borrowing of ecological thinking as a germ of creative energy, rather than as a purely scientific endeavor, was more deliberately articulated by McHarg's successor as chair of the landscape architecture program at the University of Pennsylvania, James Corner. In "Ecology and Landscape as Agents of Creativity," Corner presents an argument where ecology is co-opted not solely for its purely "scientific" manifestations, but in the broader sense advocated for by Bateson and Guattari. Corner sees the "creative practices" of ecology and landscape architecture as allowing for the construction of "alternative forms of relationship and hybridization between people, place, material, and Earth"[15] "Evolutionary principles," introduce "enabling strategies [which] function less as instruments and ameliorants and more as agents, as processes, as active imbroglios and ever-emerging networks of potential."[16] The theoretical discourse surrounding ecological thinking in the discipline continues to expand, with those advocating for a more scientific and concentrated reading of ecology on the one hand, and those advocating for broader interpretations on the other. Notable texts include Bart Johnson and Kristina Hill's *Ecology and Design: Frameworks for Learning* (2002) and Chris Reed and Nina-Marie Lister's *Projective Ecologies* (2012). While both take broad readings of ecology, which is in its nature a broad discipline, Johnson and Hill's text can generally be characterized as leaning towards more specific applications of scientific ecology applied to landscape design problems, adopting the term "landscape realism" for their approach which envisions a "creative synthesis of human culture and ecological processes."[17] Reed and Lister's text, on the other hand takes a broader view embracing Guattari's definition of ecology as "at once environmental, social, and existential."[18]

14.5. Pitfalls with Ecological Thinking

McHarg, Corner, Johnson and Hill, and Reed and Lister all make the argument that ecology needs to be a paradigm for the basis of action. Several pitfalls, however, need to be avoided. The first is a kind of resignation or passivity which can result from ecological thinking, the belief that the systems and processes in place in ecosystems or cultural systems as they already exist are the sum of a deterministic field of relations and that they should not be worked against. This dilemma can be traced back to Leibniz, who on the one hand expressed the positive view that all processes in nature are productive, that there is no chaos or error in what is, and that we should try to understand, rather than change the processes at play. This attitude by Leibniz of believing this was "the best of all possible worlds" was famously critiqued by Voltaire, who espoused a more modern view that mankind should define its own teleological aims outside of nature. Guattari summarizes the dilemma thus:

> "If today, human relationships with the socius, the psyche, and 'nature' are increasingly deteriorating, then this is attributable not only to objective damage and pollution but to the ignorance and fatalistic passivity with which those issues are confronted by individuals and responsible authorities. The implications of any given negative development may or may not be catastrophic; whatever the case, it tends today to be simply accepted without question. Structuralism, and subsequently postmodernism, have accustomed us to a vision of the world in which human interventions … are no longer relevant."[19]

In landscape architecture this attitude can be seen in projects where even minor interventions such as removing a tree are met with fierce resistance from stakeholders on ecological grounds, or where a landscape cannot be redeveloped because some stakeholders have an attachment to what already is there, and a common vision of what the future could be is not shared by all, such as in Berlin's Tempelhofer Feld. On the other hand, it is seen in an acceptance, even a fetishization of certain types of landscapes. Alan Berger's *Drossscape,* for example attempted to suspend judgement on whether the wasting on land in urban America was good or bad, arguing that dross was "natural." Berger adopts the controversial position—based in ecological principles—that sprawl, ecological degradation, and the accumulation of waste can be seen as "a natural process that can be ignored, maligned, or embraced, but never stopped."[20] In other words, rather than trying to reverse the destructive changes to the earth's ecosphere, we need to just understand and adapt.

A second pitfall is one generally avoided by those with a deep understanding of ecology and the principle of *homeorhesis* in contrast to *homeostasis*, but is still frequently encountered in the fields of restoration ecology or environmental protection. This is the notion that nature can be preserved in a steady, pristine state, and that disturbance can be minimized, or that ecosystems in a disturbed transitional state should also be protected as they exist today. Guattari points out that:

> "In the wake of the data-processing and robotics revolutions, the rise of genetic engineering, and the globalization of markets, neither human work nor the natural habitat can return, even to their state of being of a few decades ago. As Paul Virilio has pointed out, the increased speed of transport and communications, and the interdependence of urban centres are, equally, irreversible. The proper way to deal with what we have to acknowledge as a de facto situation is to reorient it.."[21]

With the realization that 'natural habitat' can never return, some fall into the opposite trap of trying to preserve landscapes in a 'degraded' condition. Relatively stable as well as highly disturbed sites both have certain "assemblages of key species," leading to efforts to protect "blasted heaths, bare bogs, acid grasslands."[22] What such efforts fail to realize is that "to protect one combination of species, we prevent other combinations from developing there."[23]

A final pitfall in ecological thinking might the too broad application of the paradigm to the point where it loses its usefulness. The rather tongue-in-cheek reading of shopping as ecology by the Harvard Project on the City demonstrates the broad flexibility, but also the instability of arguments or paradigms based on ecology. Using diagrams from Richard Forman's writings, shopping centers are described in terms of patches and corridors, with structurally diverse edges and paths of "ecosystem dispersal."[24] The connections made in the images are superficial, but once the argument is made and is published, it begins to take on an authority once it is cited again and again. The success, but also perhaps the overreach of the ecological paradigm might be seen in the rollout at Harvard GSD of the faculties overarching research focus into ecological urbanism in 2009. While many of the studies published in the rollout text on this research track in *Ecological Urbanism* can legitimately be said to extend ecological thinking, other projects pay only lip service to this broad, but not infinitely broad paradigm.[25] The overreach was probably best captured by the keynote lecture of the inaugural ecological urbanism conference, where the first keynote address was given not by a deep ecological thinker, but by the star architect Rem Koolhaas, who himself openly wondered why he was asked to give this keynote.[26] The overall impression was that his work and thinking, as impactful as it is, was being shoehorned into a paradigm he himself had not deeply considered or identified with.

14.6. Ecological Algorithms

For ecological thinking to have a deep and substantive impact on landscape architectural design as a series of justifiable *interventions* into natural and cultural systems, near paradigms need to be devised which combine scientific principles with the power of the artistic hypothesis. This thesis proposes that algorithmic coding and computer simulations are one way forward to incorporate ecological thinking and performance into the creative process. This is a view also proposed in some senses by Odum, McHarg, Guattari, Corner, and Reed. Odum explains how in order to scientifically study ecological processes, simplifications, that is models, need to be made. At first models can be informal verbal or graphic descriptions, but eventually they need to be formalized, that is described statistically and mathematically.[27] Since ecosystems generally cannot be studied in controlled laboratory settings, many of the models ecologists use to study ecosystem dynamics or behaviors are computer models. Despite the complexity of most ecological systems, well-constructed models can demonstrate important principles with only a few variable inputs. According to Odum, good models can be produced if the following factors are take into account:

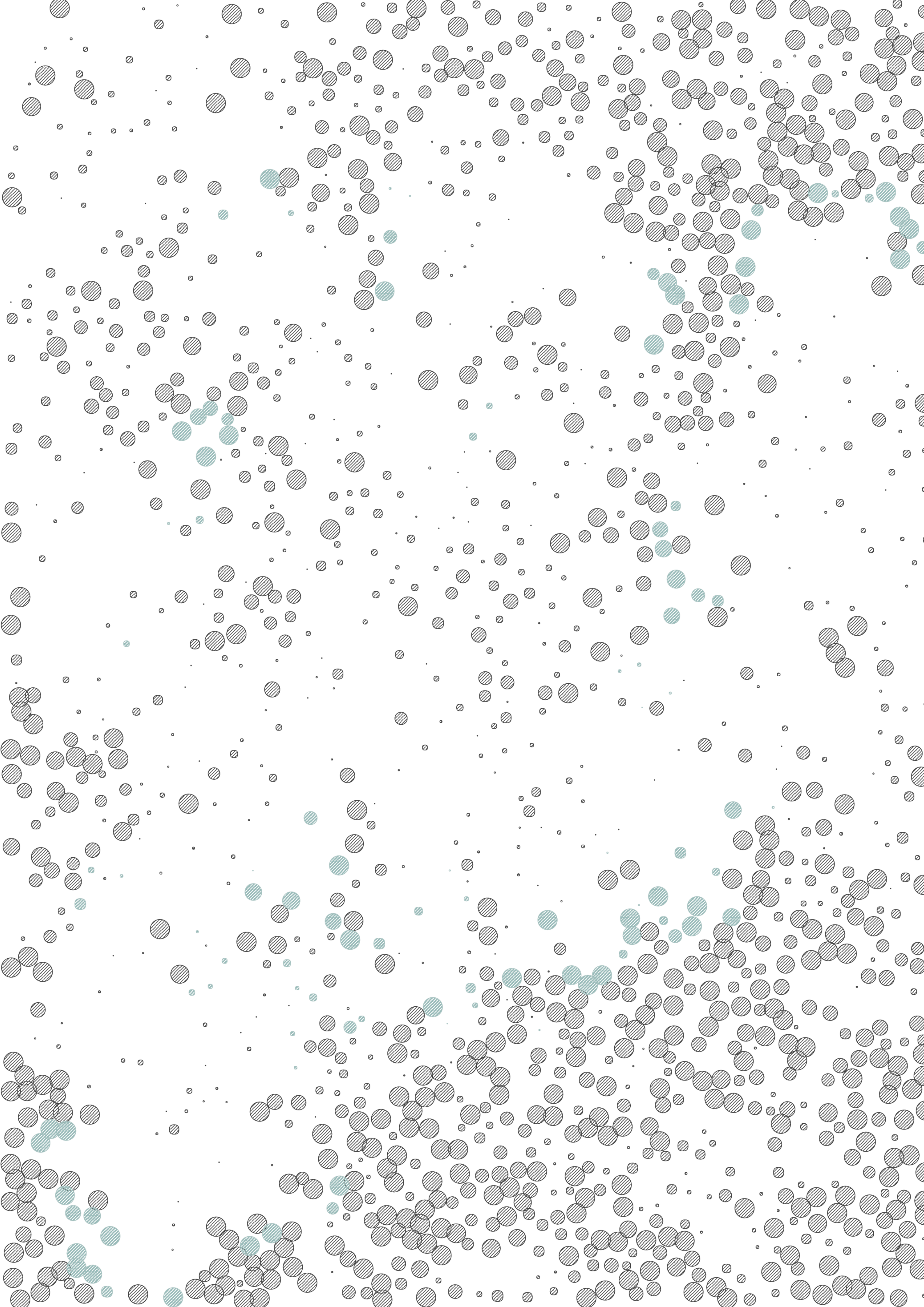
> "1)the space to be considered (how the system is bounded);
> 2) the subsystems (components) judged to be important in overall function; and
> 3) the time interval to be considered."[28]

Guattari's saw models and computation not in objective scientific terms, but as a possible mechanism for aiding what he might describe as creative subjectivity—that is as a possible path of not necessarily understanding, but of intervention.[29] Already in the late 1980s Guattari observed that: "with the acceleration of the technological and data processing revolutions, we will witness the deployment or, if you will, the unfolding of animal, vegetable, cosmic, and machinic becomings which are already prefigured by the prodigious expansion of computer-aided subjectivity."[30] For Guattari, what is important in mechanistic descriptions or computer models is that they become "'living mechanisms, not mechanisms of empty repetition."[31]

Reed and Lister reach a similar conclusion to Odum while at the same time advocating for the "subjectivity" and the prioritization of creative outcomes as hinted at by Guattari. They see in the design disciplines a proliferation of Odum's "informal models" and observe that "few designers have yet ventured beyond the metaphors and mechanics supplied by these two-decades old models to design effectively for adaptation or change, or to work incorporate learned feedback into the designs…"[32] Reed and Lister propose that one of the routes (among others) of moving beyond metaphor is through "new modelling programs…[offering] one path forward for exploration and experimentation. Flow modeling, scripting, and processing software in particular provide time-based platforms for representing and programming change and evolution."[33] These representations and models, however, invoke "creative instabilities" and hint at "multiple states (of being)"[34] and should not be seen as deterministic scientific instruments.

14.7. Summary Conclusion

This chapter has served as a brief introduction to the position of ecological and evolutionary thinking in the discipline of landscape architecture today. Ecosystems are seen not as static, stable, steady-states, but are instead seen as pulsating, dynamic systems with flows of matter and energy, and evolving through time into new conditions which cannot be reversed. The processes of ecology and processes in landscape can be one of the most important givers of form, pattern, and process to landscape architectural projects. Landscape architects, however, should not fall into traps of passive acceptance of the forces acting on sites on the one hand, or a naïve belief that systems can be restored to prior states or maintained under current conditions on the other hand. In the end, ecological thinking needs to be a catalyst for change, not an argument for complacency. Landscape architects must also avoid the trap of ecology becoming a loose metaphor for action, and need to find more rigorous and formal methodologies for applying ecological principles to design problems. One way forward is to introduce algorithmic and computational methods to describe and define, and later evolve the ecological relationships on sites. Following are three examples of algorithms defining and exploiting ecological principles. The first uses a cellular automaton to demonstrate the principle of self-organized criticality in ecosystems, specifically in the case of a slow spreading pathogen. The second algorithm explores the concept of the succession of plants in ecosystem, while the third adopts principles from evolutionary genetics to find a solution to problems through the introduction of simple, random mutations along with the introduction of fitness criteria.



Algorithm 14.1. Disturbance Cellular Automaton

This script is based on a well-known cellular automaton known as the "Forest-Fire Model" described by Hergarten and others to describe and to model patterns of disturbance in ecosystems. These models exhibit a phenomenon known as self-organized criticality, where minor stochastic disturbances have limited destructive potential in an ecosystem with low plant mass, but once a certain threshold is crossed, a fire can rapidly spin out of control.[35] Such models were used to demonstrate the dangers associated with fire suppression strategies by land managers in fire-prone ecosystems by showing that if the interval between fires is too long, once a fire does break out, the fire will be much larger and devastation will be much worse.[36] [37]This particular adaptation attempts to model a much slower destructive process in an ecosystem—the spread of disease—and combines a slow spread on an 'infection' to neighbors together with slow regrowth afterwards. By adjusting parameters such as regrowth-rate and chance of spontaneous outbreak, lessons can be learned about how real ecosystems might function and how patterns might emerge under certain environmental stresses.

Figure 14.1: (*opposite page*) Tree pattern of a digital forest subject to a high degree of stochastic disturbance, in this case, a hypothetical disease bearing parasite. In this version, in contrast to the images of the simplified model shown on the next page, trees also increase in size as they grow.

The setup here in contrast to a normal cellular automaton which uses a regular grid of cells, uses a random population of points based on a parameter "area per tree." This is used to establish the centers of possible tree locations. The topology of these possible centers in relation to all other centers is described in terms of a maximum radius for infection, in this case about 20m, although this can later be adjusted. This means if a neighboring tree within 20m is infected, there is a strong possibility the infection will spread in the next round. By adjusting virulence and the neighborhood for the spread of the infection, different kinds of patterns will emerge. The last thing done in the initial setup is to determine the cell-states for the tree centers. There are three possible states in this simulation:

0 (vacant/dead)
1 (alive) or
2 (infected/dying)

Initially no trees are infected so there are only 0's and 1's

Once this is setup, the data enters a loop. Each cell is checked if it is a 0, 1, or 2. Every time the loop runs, four basic operations will be performed to determine if the cell state changes, and what it changes to. The operations, in this order, are:
1-Cells that are infected die based on a random probability. For purposes of clarity in these diagrams the chance is 100%. That is, if the cell-state is equal to 2, it will now be reset to 0.

2-Living Cells that are in the "neighborhood" of a cell that was infected in the previous round, have a chance of becoming infected, in this case again for clarity the chance of infection is set to 100%. That is, if the cell state is equal to 1 AND at least one of the cells in that cell's neighborhood was equal to 2 at the start of the round, then the cell becomes infected, going from 1 to 2.

3-A new plant has a chance to sprout in each vacant cell. This is determined by comparing a random list of values to a probability test. If this chance is 5%, then in each round, about 5% of the cells will randomly go from 0 to 1.

4-Test for “spontaneous” outbreak. There is a chance that a living cell will spontaneously become infected, despite not being near an infected neighbor. In nature, spontaneous outbreaks of disease can be caused by introduction of a foreign pathogen to a new environment, by mutation of a previously benign version of a disease, and other causes, but these are by nature, very rare. For our first example, we will have an infection probability of 0.02% to see what happens. But in the rare cases of spontaneous infection the cell would go from 1 to 2.

Various types of patterns emerge based on parameters such as virulence, regrowth rate, and chance of spontaneous infection. If no regrowth is modelled and virulence is high, this particular model is nearly identical to the forest-fire model.

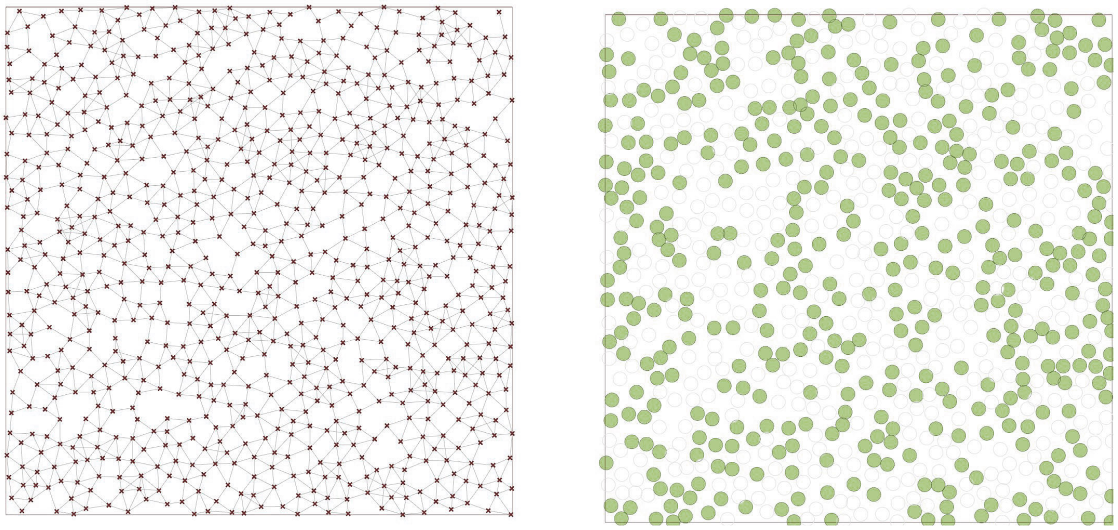


Figure 14.2: (*below*) The cellular automaton here has an irregular structure, with “neighborhoods“ determined by an inital proxity matrix of closest neighrs. At the beginning of the simulation, only a random percentage of the potential tree locations or cells are activated.

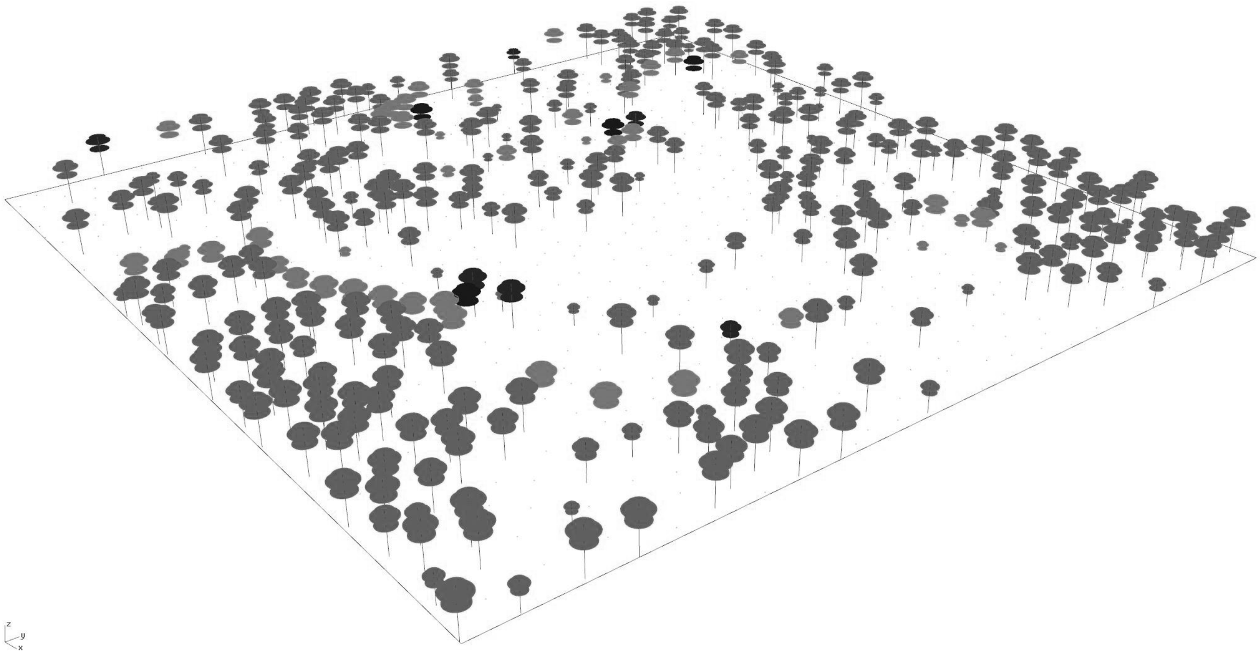
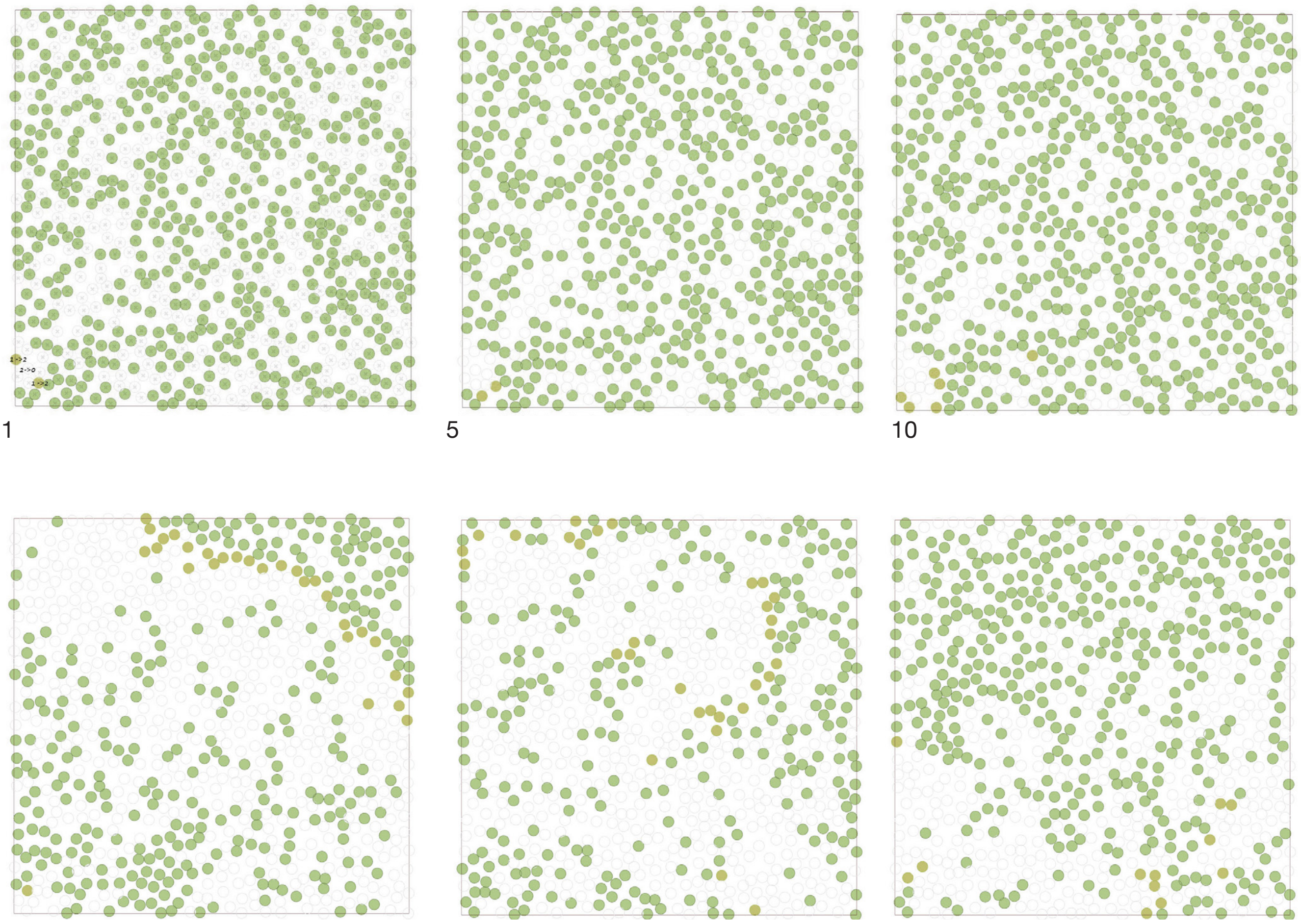


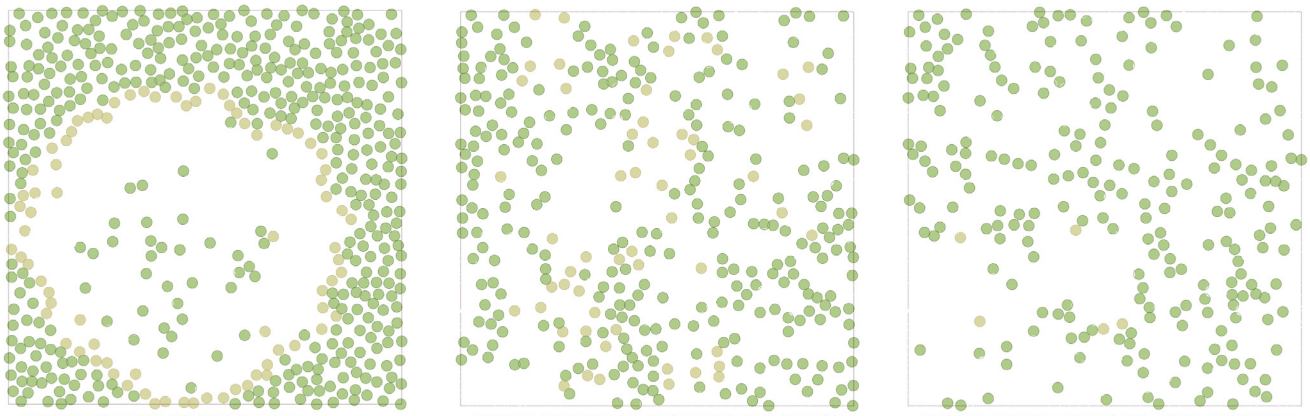
Figure 14.3: (*below*) New trees appear in every time step filling in the cellular matrix. At a certain point, however, disease breaks out and breaks down the homogenous pattern

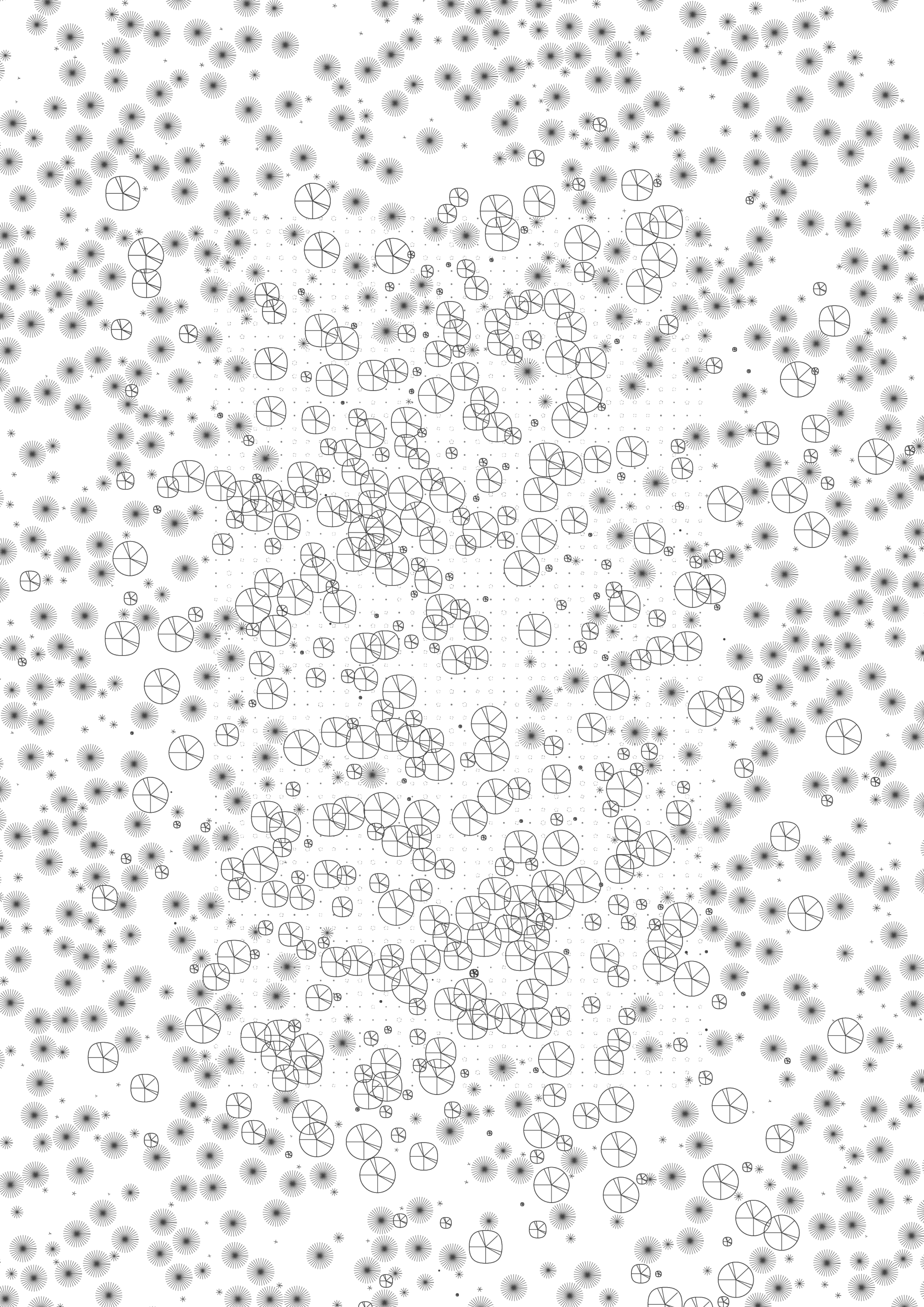


1 5 10

20 30 40

Figure 14.4: (*below*) If the chance of outbreak is set too low, when disease does breaks out, it can devestate the population (left image). In more scattered populations, the effects of disease are less dramatic (right)





Algorithm 14.2. Model of Plant Growth and Succession

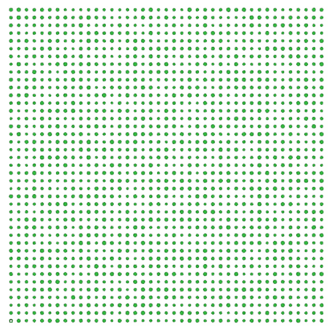
This algorithm also attempts to model ecosystem development, in this case the growth and succession of various plant species. The algorithm is based on a milestone paper by Brendan Lane and Przemyslaw Prusinkiewicz at the University of Calgary's algorithmic botany group (see §10.3)[38] together with an adaptation of this research by a landscape architectural researcher, Philip Belesky at RMIT University in Melbourne.[39] The Lane and Prusinkiewicz paper gives a clear model on how forest ecosystems could develop with various species interacting based on their growth rates, shade tolerance, reproductive strategies, and affinity or antipathy towards certain neighboring species. If the parameters for the plants are well-tuned, a convincing representation of ecosystem development and plant succession can be observed. If this is combined with additional factor such as soil moisture content, elevation, slope, and stochastic disturbance patterns, a "global" model for biome development could theoretically be established.

Two runs of the algorithm are shown here. The first simulates the growth over 100 years from an initial 2 meter grid of a single, fast-growing but shade intolerant species, such as birch or pine. The second run simulates the growth with two distinct species. The first is again fast-growing and shade intolerant, but the second is slow-growing, but relatively tolerant of shading. In both simulations, with each time step of the algorithm, the tree's radius representing its canopy dimensions is incrementally increased based on its unique growth rate attribute. Soon, the circle associated with each tree will come into contact with a neighbor. Once a tree contacts a neighbor, the algorithm runs a calculation to see which tree is "dominant," in this case larger. If a tree is dominated, its growth is halted and has a chance of dying and being removed from the simulation based on its shade tolerance. If the tree is relatively shade tolerant, it bides its time but growth is slowed significantly with respect to its neighbor. In each round, there is a renewed chance that the shaded tree will die.

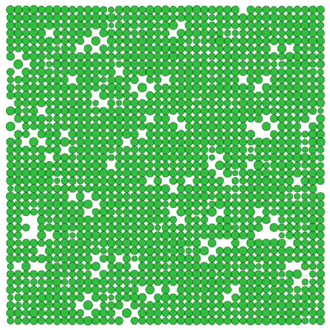
Once the trees reach a certain maturity, they have a chance of producing offspring. This chance and the number of offspring they produce is determined by an additional parameter. Yet another parameter determines how far from the parent a child can be produced, with the location of potential offspring determined by a Gaussian distribution from the parent. Offspring which appear near an existing tree are likely to fail a test to determine if the become established. A final parameter governs a trees maximum age, with the probability of tree death increasing very slowly for most of the trees lifespan, but then increasing rapidly towards the end.

This model, if the parameters are properly tuned, produces a convincing simulation of the process of ecosystem succession. In the second version of the algorithm with two species, the slow-growing, shade tolerant species languishes for the first thirty or so years, but eventually it comes to dominate the core area where the initial grid was planted. The pioneer species continues to do well in the un-colonized edges, and occasionally is able to find a niche in the core zone, but after 300 years have largely been displaced.

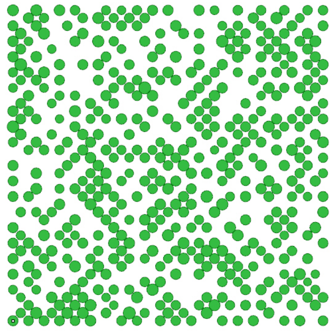
Figure 14.5: (*opposite page*) Tree pattern of a digital forest undergoing the process of succession. From an initial grid in the central part of the image (denoted by grid points), fast growing but shade intolerant species, such as pines, are eventually crowded out of the center as slow-growing, shade tolerant species such as beech, take over. The fast growing, shade tolerant plants still have a chance to find a niche in the old-growth forest, but are more successful in pioneering open sites.



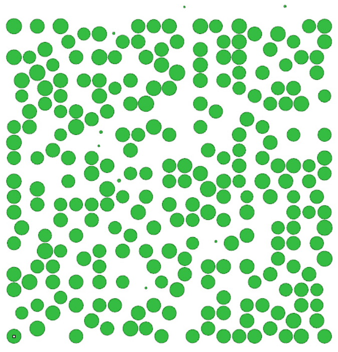
Year 1 - A single shade intolerant species is planted with initial random variation in size on a 2 meter grid



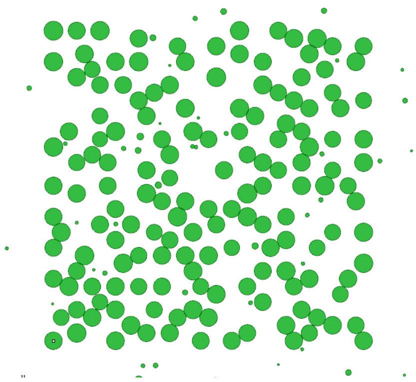
Year 6 - Grid fills in and first gaps start to appear where trees are outcompeted by neighbors



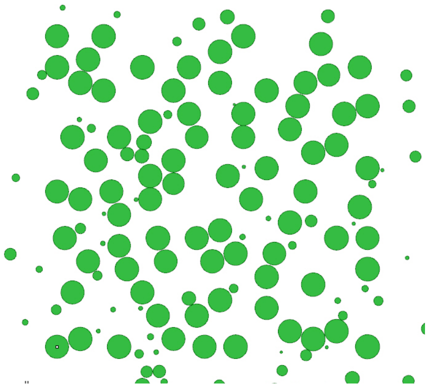
Year 10 - Competition has now thinned out the initial tree population considerably



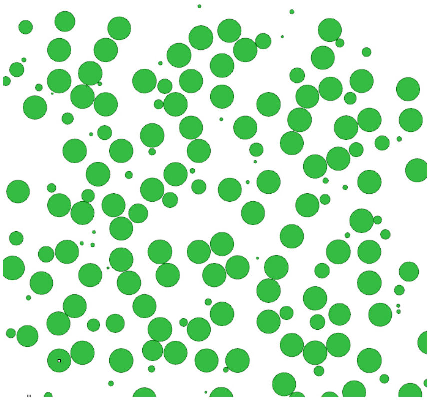
Year 15 - The first offspring from the initial tree populaiton begin to grow



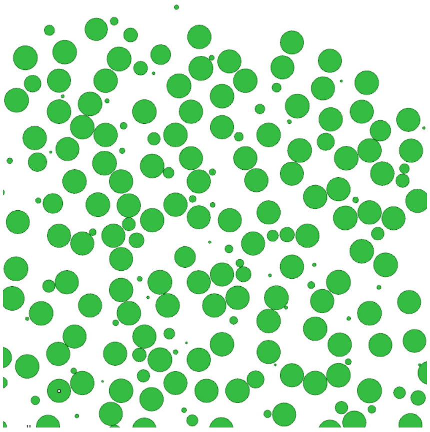
Year 20 more new trees appear as fewer mature trees survive



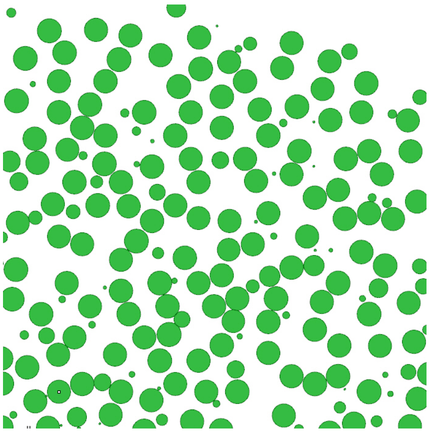
Year 30 - The original grid is mostly gone



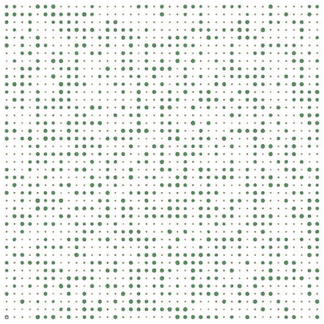
Year 50



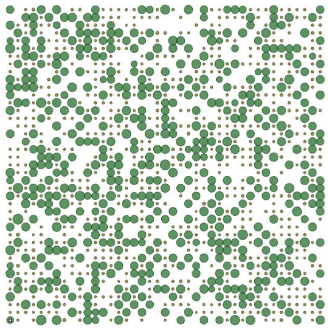
Year 80



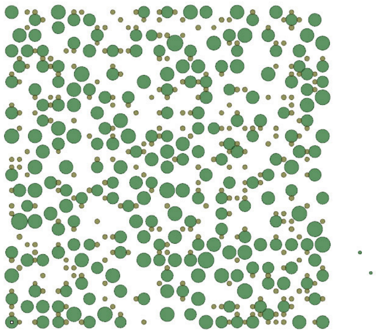
Year 100



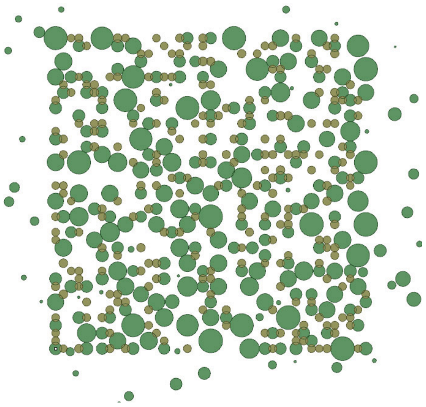
Year 1 - Trees are planted with a 50/50 random distribution in a 2 meter grid



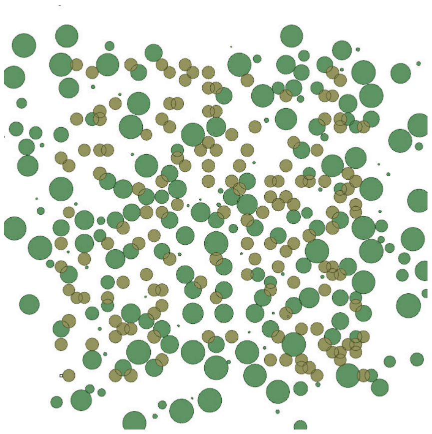
Year 7 - Grid begins to fill in. Dark green species grows faster and dominates in comparison with slower growing tan species



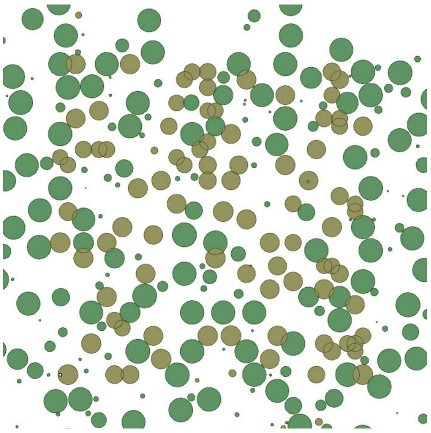
Year 15 - Dark Green species with low shade tolerance starts to crowd out weaker neighbors. Some tan species also are crowded out, but most survive.



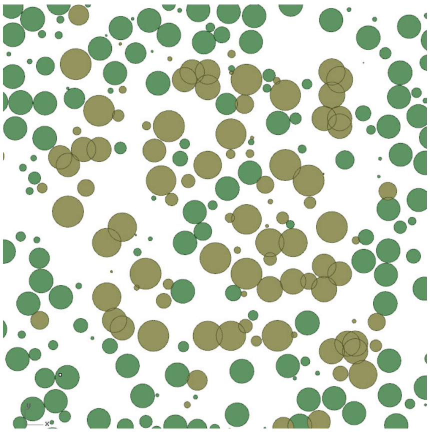
Year 30 - Initial population is mature and sending seed to colonize empty spaces. Dark green still dominates.



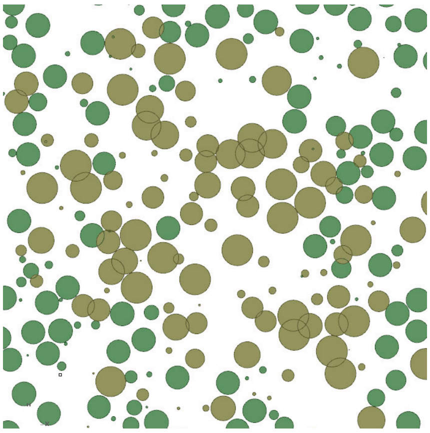
Year 50 - At year 50, the fast growing dark green species is rapdily colonizing outside of the original grid, but is starting to lose its dominant position in the old growth area due to old age and crowding by slow growing tan species.



Year 80 - The tan species is establishing a dominant position in the older growth areas, and dark green is marginalized.



Year 150 - The trend continues, with tan dominating the old center



Year 300 - Tan still dominates the old center. Dark green is still able to find niches in the center when a tan tree dies, leaving a gap.

Figure 14.6: (*opposite page*) Nine time steps in the 100 year growth simulation of a fast growing, shade intolerat tree species

Figure 14.7: (*this page*) Eight time steps in a 300 year simulation with two tree species, a fast growing shade intolerant species in dark green, and a shade tolerant, slow growing species with a tan color

Algorithm 14.3. Genetic Algorithm for finding a Shortest Path

This final example is a rather basic example of a "genetic algorithm," one of a family of algorithms used to solve problems for the optimization of form. De Landa described as early as 2001 the creative potential of these algorithms, with the caveat that: "only if virtual evolution can be used to explore a space rich enough so that all the possibilities cannot be considered in advance by the designer, only if what results shocks or at least surprises, can genetic algorithms be considered useful visualization tools."[40] The example introduced here does not create shocks or surprises, but it still demonstrates how this very simple principle can solve problems without any intelligent agency, and despite its simple, straightforward logic, is fascinating to watch unfold. Much of the logic of the algorithm is based on the description of genetic algorithms by Schiffman in *The Nature of Code.*[41]

Genetic algorithms adopt a metaphor from natural selection, but can be used to solve a range of problems not necessarily biological in nature. Computer scientists, for example, use these to search for data, while engineers have famously used them to design, for example, antennas (see figxxx). All genetic algorithms start with an initial "population" with a certain "genome," and the algorithm then "evolves" the population to perform certain tasks. Two key variables in almost any genetic algorithms are population size and mutation rate. Also important is to define the "fitness" criteria to determine what "genomes" are preferred, and which will be allowed to pass their "genes" to the next generation. In this simple example, a population of random walkers (see §A7.1) are evolved to move from one starting point to an adjustable "goal," while avoiding or moving around a series of obstacles on the way. The "genome" for the walker is simply a list of four movement possibilities, up, down, left, or right. (U,D,L,R). The length of the "genome" is the number of steps the walker might take. A walker taking forty steps might have the randomly generated genome: (UUDLLRULRDDLDRRUDDRRLRLDUDURLULLRDUURLDR). Other walkers have similar, randomly generated genomes following the same principles. In this particular example, 16 walkers are used.

After the random population is generated, the algorithm starts to simulate an evolutionary process. First, the simulation sends the population of walkers loose based on their genome. If a movement instruction would put the walker into a space occupied by an obstacle, that particular movement instruction is ignored and the next instruction is then followed. After all the walkers have moved, they are then evaluated for "fitness." In this case, fitness is determined by linear distance to the "goal." In this particular example, the most successful half (the 8 out of the 16 closest to the goal) are determined to be the fittest and produce two "children" with an identical genome to the parent, but with a single random mutation introduced into the genome. This mutation replaces a U,D,L, or R with another U,D,L, or R. The algorithm then repeats the next generation with the children, who at the end are again evaluated for fitness, with the most successful becoming parents, and so on.

The amazing thing about such algorithms is that even though the mutations are random, and even though the instructions are so basic and fundamental, after a few rounds the walkers slowly seem to develop intelligent strategies. This comes only through the process of mutation, selection, and reproduction, but eventually, barring faulty fitness criteria, the walkers will reach the goal, usually along the shortest or most direct path. Interesting phenomena can be explored by changing the fitness criteria when the population is only partially through the evolutionary process, moving the

Figure 14.8: (*opposite page*) Evolved random walks from the square starting point at the bottom left. Fitness is determined by proximity to the goal, the black square near the top right. Using concepts of fitness, reproduction, and random mutation, the algorithm eventually finds optimal paths, avoiding obstacles along the way.

In this image, lighter paths indicate paths of previous generations, as the lighter circles indicate the end points of previous generations of random walkers. Darker paths and circles indicate more recent, evolved variants.

goalposts so to speak, and strategies which were maladaptive before suddenly becoming optimal.

Depending on the nature of the problem, times to solve a problem generally go down as the mutation rate increases initially, but only up to a point, after which the solution time goes up. If the mutation rate is too high, the problem will never be solved as successful genomes are changed too quickly for successes to be built upon.[42]

Figure 14.9: (*above*) After each generation, the random walkers which are closest to the final goal are judged as "fit." Their genetic code is reproduced almost exactly, but with random variations introduced based on a mutation rate parameter.

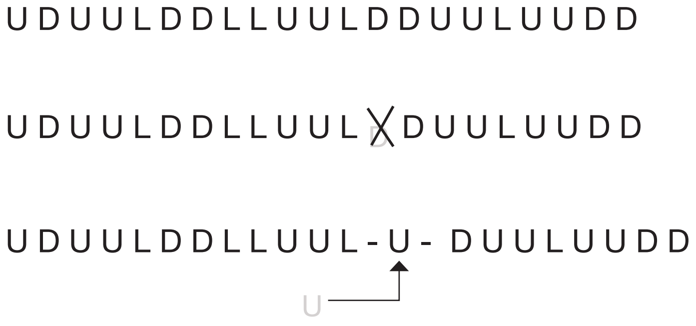
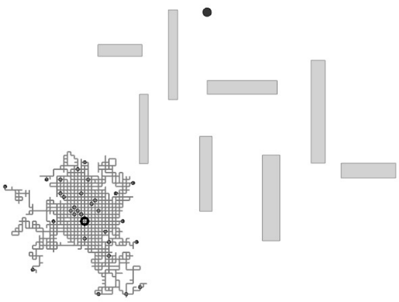


Figure 14.10 (*right*) A snippet of a walker's "genetic code." At each generation, there is a chance one or more "genes" will be replaced

Figure 14.11: (*opposite page*) The genetic algorithm run through many generations towards the goal. In generation 90, just as the goal is reached, the goal is changed. While the walkers can adapt to this new circumstance, a genetic memory of prior conditions remains long afterwards.



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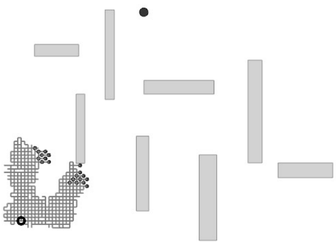

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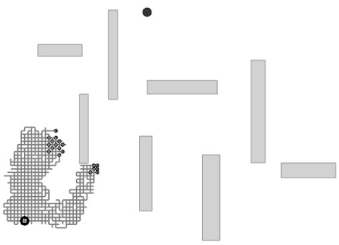

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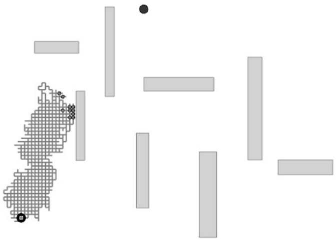

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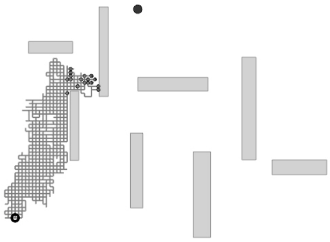

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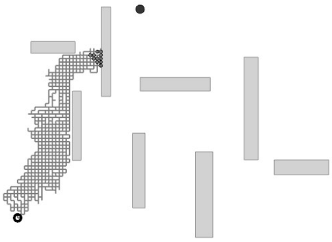

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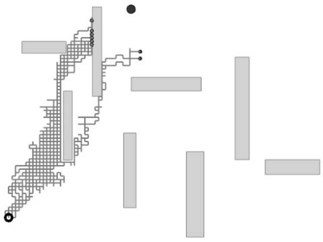

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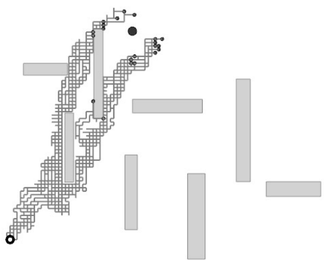

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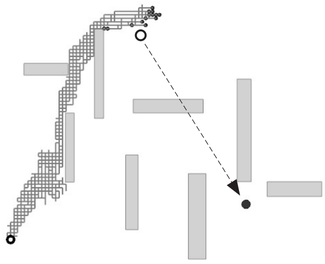

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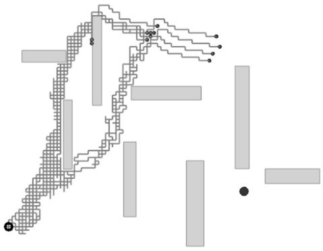

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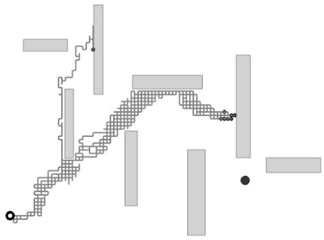

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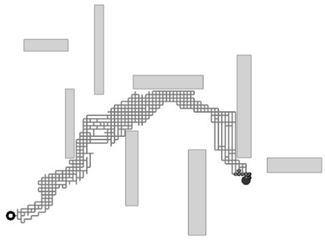

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Summary Part II

The goal of Part II was to provide a catalogue of algorithmic patterns grouped by critical themes in contemporary landscape architectural discourse. The nature of the research in Part II is characterized primarily as "research *for* design," with the goal of developing methods which can modified, assembled, and combined to contribute contemporary design expressions. These experiments are contextualized into a larger theoretical context, research which, like Part I of this thesis, is "research *about* design." Many of the methods and patterns developed in Part II are in turn applied to case studies characterized as "research *by* design" in Part III of this thesis. (§0.4) Like Part I, Part II is loosely structured around one of the three research questions, here seeking to answer the inquiry: "What are untapped potentials for integrating algorithmic tools and models from sister disciplines into the design and production of contemporary landscapes." As such, the chapters introduced a range of algorithmic patterns and approaches from many outside perspectives, seeking to relate them in each case to core issues in landscape architectural discourse, theory, and practice. While each chapter draws from a number of sources, major perspectives in each chapter come from the disciplines of computer science (Chapter 6), quantum mechanics and probability theory (Chapter 7), mathematical topology (Chapter 8), postmodern philosophy (Chapter 9), botany (Chapter 10), nonlinear dynamics (Chapter 11), agent theory (Chapter 12), geomorphology (Chapter 13), and finally evolutionary ecology (Chapter 14). Some of the key findings of each Chapter are summarized in the following paragraphs.

Chapter 6 focused on concepts from computer science, providing a general introduction to algorithms as the fundamental driver of computation along with several paradigms that are used in computer programming in general and in design computing specifically. It introduced concepts germane to computation, such as recursion and iteration, as well as the specialized concept of ontogenetic vs. teleological algorithms, which is of interest to landscape architects concerned with the limits of form and performative systems especially in the context of simulation. The chapter also provided examples of how algorithms can be designed using native graphical algorithm editors in programs such as Rhino and Grasshopper and also using a relatively accessible programming language (Python); this was done in the context of introducing two frequently encountered algorithmic paradigms, fractal systems and the cellular automaton.

Chapter 7 introduced the idea that randomness is an essential component to contemporary formal expressions and plays a role in nearly all of the algorithmic patterns shown in this section. It introduced a caution, however, noting that randomness, chance, and indeterminacy need to be considered in new ways as they are introduced into algorithmic models in landscape architecture, especially if the algorithmic models are to move beyond mere formal experiments and become performative objects.

Chapter 8 expanded on the relational mathematics of topology introduced in Part I (§2.11), and reiterated the importance of relational thinking for the understanding and modeling of systems. Systems behavior is integrally tied with concepts surrounding networks, which have often counterintuitive logics that need to be understood when working in network space. Two general types of networks, *trees* and *meshworks* were introduced, with designers often striving to achieve a *tree*-like logic in their proposals (optimized, non-redundant systems), but this is done at the cost of the resiliency and long-term performance.

Chapter 9 continues some of the ideas introduced in the previous two chapters and makes an essential observation about the emergence of hierarchies and the ordering of space from a state of entropy using an unexpected cross-disciplinary perspective. Numerous correspondences were found between the philosopher Gilles Deleuze with his concept of *smooth space* and *striated space* (§9.2) and the ecosystem scientist Robert Ulanowicz's concept of *maximally articulated* versus *maximally connected* spaces. This has profound consequences for the development of potentials in complex systems where *smooth, maximally connected, meshwork* spaces prohibiting high level development on the one hand, but allowing for new modes and paradigms on the other. The potentials of smooth and striated spaces are tested in a design context using Stan Allen's concept of the "Field," who also stresses the priority of relations in contemporary design expression over the classic focus on objects. Observations from the modeling of Allen's fields in terms of smooth and striated space is a concept which informed the structure of the rest of the chapters in Part II with the author discovering it was generally a straightforward task to algorithmically model and describe *striated spaces,* but that *smooth spaces* which are structured by vectors, fields, and ambiguous topological relationships present special challenges.

Chapter 10 focused on striated, hierarchical systems, especially derived from botany, and found a relationship between the growth of urban infrastructural networks on the one hand and the growth of plants and simple life forms, such as bacterial colonies, on the other. Because of this, such algorithms have a longer history of being integrated into design practice, especially as a representational tool, but to date, there are few examples of these algorithms being used to change large-scale designs (such as urban plans) in a significant way. This may be because of a lack of correspondence between these formal structures and their informational context—a lack of *isomorphism* as introduced in §2.5.

Chapter 11 and **Chapter 12** focused on *meshwork* approaches where hierarchies are not strongly evident, and sought to explore the design potentials latent in the complex emergent properties of the physical forces of nature as explored in Chapter 11 together with that of biological agents as introduced in Chapter 12. These Chapters introduced new, but difficult to master computationally paradigms to create *meshworks* which can serve to enrich the sterile hierarchies that dominate the planned and ordered landscapes of traditional urban, regional, and landscape planning.

Chapter 13 and **Chapter 14** proposed that in two areas of special interest to landscape designers, the design of landform as well as of ecosystems, algorithmic models combining logics from both *smooth* and *striated* spaces can be integrated. These models from ecology and the engineering disciplines, from geomorphologists and scientists of artificial life, offer potentially productive, but challenging opportunities for landscape design.

The twenty-six algorithmic patterns presented in this section are formal experiments which should only be considered as a small part of an overall design expression. Each one alone *could* have the potential to form the basis of a project, particularly at a smaller scale, but here they are conceived primarily as design *objects* which need to be integrated into a broader relational *field*—informed by a situational and informational context—before they can begin to approach their performative potential. This will be explored in the next section. The categorization presented in this section, however, should serve as a useful starting point for those wishing to approach algorithmic design in the context of landscape architecture. Efforts to expand the richness of the eight categories would provide a productive avenue of future research, and could in turn introduce new categories. This process can only be aided by looking at the critical practice and successes stemming from other disciplines. It would also be imminently helpful, even, for landscape architects to engage experts from these various disciplines from an early stage, especially experts who have an interest in computational methods. Such interdisciplinary collaborations might help the designer quickly and effectively move beyond frequently encountered pitfalls, and should serve to enrich the internal relational logics of algorithms in the context of the landscape project.

Part III

Algorithmic Applications to Landscape Architectural Projects

Introduction to Part III

Part I of this thesis introduced the topic of algorithms and algorithmic design, and sought to contextualize this historically and specifically in terms of the evolution and the design of landscapes as it concerns landscape architects. Part II presented a series of algorithmic patterns of increasing complexity, drawn from various disciplines from the natural sciences to game programming, which can be used as generators of design expressions in their own right, but which are largely intended to serve as "objects" or components which can be integrated into a larger algorithmic design process.

One of this thesis' hypotheses is that project scale plays a significant role in determining to what degree the use of such a formal pattern in its own right as a design expression is justified, or whether it must "do more." Almost any one of these patterns could form the basis of a design expression for the right small project, such as a plaza, a playground, or an office courtyard, but as scale increases, as argued in §2.6, the patterns need to begin to *perform* by means of a correspondence, analogue, or *isomorphism* with their informational context. They also cannot act alone, but must become part of a greater project with multiple connections to groups of human and non-human actors, as well as to the set of forces which shape the field in which it operates. It is at this "intermediate scale" where design, indeterminacy, and emergence meet that the thesis hypothesizes algorithmic design offers the most potential and promise.

As such, this section presents three projects or proposals on sites judged by the author to fall into this intermediate scale. Each project borrows a series of algorithmic patterns or tools from Part II to develop new hybrids. These hybrid approaches can inform approaches—per Table II in the summary of Part I—that are tactical, functional, and evolutionary, involving an assemblage of actors, and enacting design transformation—or in short, that move beyond form into the field of performance.

For each of the projects presented here, an introduction to the design context is first presented. Next, a short description of the algorithms used, referring back to Part II as applicable, is presented. Finally a short reflection on the successes and difficulties encountered in the projects is presented. The images strive for a pleasing graphic quality, but the focus here is not on representation, but on clearly showing what is algorithmically modeled and what is not. As such, any postproduction of the images with Photoshop or other programs is avoided. In addition, the geometry is generally modeled only with the mediation of algorithms, and as such, individually modeled pieces of geometry are not shown. This does not mean such efforts in a design workflow should be avoided, but it is part of an effort to show clearly and honestly what kinds of results may be expected. The algorithms also avoid the slick graphic style of much of computational design so as not to distract from the core content. The one exception is some of the final axonometric drawings for the Medellin case study (Chapter 15) were post production was necessary to prepare the drawings for a major exhibition. The drawings are still by and large the product of an algorithmic process alone.

Chapter 15 – MEDELLÍN

La montaña nos acogió cuando la Ciudad nos dió la espalda” –
Resident of La Honda[1]

15.1. Introduction – Case Study Medellín

This section represents the first of three in-depth case studies to test strategies for applying algorithmic methods to specific landscape sites and problems. In a broader sense, this chapter is intended to serve as a dual to some of the ideas introduced in Chapter 3 Euclid | Lucretius which explores the slippery categories of formal and informal while looking at the emergence of complex form, especially in vernacular context, through repetitive, easy to reproduce, yet highly evolved procedures. In a narrower sense, this chapter's focus is on developing algorithms and methods to test the spatial implications of strategic, landscape-based interventions, in this case associated with several pilot projects in an informal settlement in Medellín, Colombia. The strategies are based on research carried out by a multi-disciplinary team in two phases directed by Prof. Christian Werthmann and Alejandro Echeverri of Urbam-EAFIT, Medellín. The first phase of the research, of which the author was not a part, was carried out by Werthmann at Harvard University and Echeverri in Medellín between 2010 and 2012. In the second phase of the research, also directed by Werthmann now at Leibniz University, Hannover Germany, and Echeverri between 2012 and 2013, the author was actively involved in all stages of the process. The research started with an analysis of larger regional dynamics of informal urban growth coupled with catastrophic landslide risk. Later the research hypothesized that various bottom-up, soft, and self-directed strategies could be used to control rapid growth in dangerous, landslide prone sites, primarily by assigning productive land-uses to sites before they were occupied. A second set of strategies aimed to reduce landslide risk by mitigating dynamic, destructive landscape processes through similar sets of self-directed strategies.[2] An early hypothesis of this research was that informal and bottom-up processes, as well as strategic interventions, are particularly well suited to analysis and design with generative, algorithmic tools. This section seeks to try those assumptions by modeling and testing the spatial implications of existing landscape and urban dynamics and proposed, strategic landscape processes.

15.2. Summary of Research in *Shifting Ground* and *Rehabitar la montaña*

As cities rapidly urbanize throughout the developing world, formal methods of planning and allocating housing cannot keep up with the burgeoning demand. Informal urban growth in many developing contexts often happens in areas deemed least suitable for housing (thus depressing land-values), which includes sites with high natural risk factors, high ecological sensitivity, or a combination of both. In many mountainous metropoles, this development often happens on steep, mountainous terrain, especially prone to landslides after heavy rains. While a single event may go unnoticed

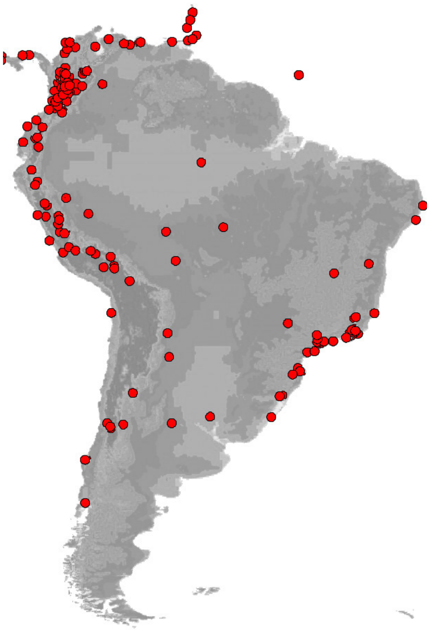


Figure 15.1: Fatal Landslides in South America - 2004 - 2013.
Data provided by David Petley

Figure 15.2: Aftermath of a Landslide in La Cruz, 2007. (Municipality of Medellin)

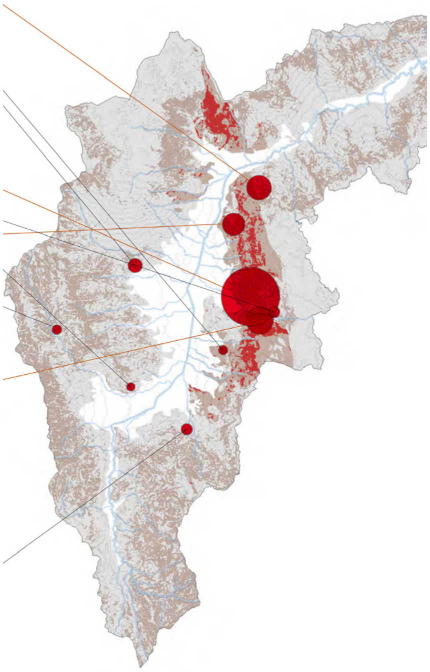


Figure 15.3: Landslide Occurences with Soil Risk Factors. (Echeverri, Werthmann et al. *Shifting Ground,* 33).

in media reports, according to a database maintained by Dr. David Petley, then at the University of Durham, in a seven-year period between 2004-2010, at least 32,322 lives were lost world-wide in catastrophic, non-seismic landslides.[3] The problem is particularly acute in the relatively youthful Himalaya and Andes mountain ranges, where active geological and erosive processes, intense tropical rains, along with rapid informal urbanization combine in an especially destructive mix. (Fig. 15.1)

One metropolitan area where the convergence of these factors can be clearly seen is the fast growing Colombian region of Medellín. (Fig. 15.2) Following a 2010 disaster in the peripheral community of Bello where at least 85 lives were lost in a catastrophic landslide, Werthmann and Echeverri formed a research team to examine the phenomenon of informal growth in the region along with the incidence of landslides. Their findings, summarized in the report *Shifting Ground,* found a clear link between the incidence of landslide deaths in the metropolitan region and a belt of unstable, volcanic soils comprised of weak, serpentinic rock, where at least 750 of the 854 landslide related deaths known to have occurred in the region over the course of the last 80 years were located, including a single incident in 1987 where at least 500 lives were lost.[4] [5] (Fig. 15.3) The research in *Shifting Ground* also examined the patterns of informal growth in the metropolitan region, evaluating various factors contributing to growth combined with four attractors to predict the likely spatial dimensions of this future growth (see 3.1.2). The research found that 45,000 homes are currently located in zones of high risk in the Medellín metropolitan region and that this number was likely to increase to at least 67,000 by 2030.[6]

In a follow-up study published in 2013, two informal neighborhoods located in this belt of instability were identified to explore specific strategies to address these findings. These two neighborhoods, which have spontaneously emerged within the last 50 years on the periphery of Medellín, Colombia, are the relatively long-established neighborhood of La Cruz, and the new and fast growing community of La Honda. Both settlements include large areas of steep terrain designated by engineers as high-risk areas where residents must be resettled to ensure long-term safety, as well as significant areas of medium risk terrain where residents could conceivably stay in the long term if issues of risk are adequately addressed and mitigated. Resettlement plans had already been prepared from the city,[7] but continual growth has made these plans outdated almost as soon as they were prepared and continued growth exceeds the pace of removal and resettlement. The resettlement plan also entailed a relatively high cost amounting to around USD $45,000 per house, and if similar measures were undertaken throughout the Medellín metropolitan region, for the 45,000 homes currently in conditions of precarious risk, this figure would surpass USD $2 billion.[8] Addressing the reality of these high costs combined with the continued phenomenon of informal growth pointed to the necessity for developing alternative strategies, which was the focus of the study *Rehabitar la montaña* published in 2013.[9]

The research undertaken by the joint Leibniz University/Urbam-EAFIT team sought to find new, low-cost, low-tech, and community-based strategies to address the challenges of continued growth in the most dangerous sites with high landslide risk, and to mitigate risk factors in sites categorized as “medium risk.” The research did not address the challenges of resettlement, or the necessity of more conventional, engineered solutions, which inevitably would have to continue playing a role in any comprehensive strategy. The approach developed by the team focused instead on anticipating growth into high-risk sites, and giving these sites alternative, productive land-uses to deter potential settlement. The team hypothesized that when these sites have an inherent value to current members of the community, these residents would protect and "police" the land and hence deter future settlement. The second set of strategies sought to mitigate risk through easy to implement, low-cost measures that would minimize catastrophic landslide triggers by improving surface drainage and stabilizing eroding slopes.[10]

With these goals in mind, the team proposed five sets of compatible, replicable strategies that could be tested in small, pilot projects. The lessons learned from the pilot projects could in turn inform comparable projects on other, similar sites in the metropolitan region. The area of the two neighborhoods was analyzed based on a number of factors, explained in the next section, to develop a map of potential approaches corresponding to the five sets of strategies. Two of the pilot projects would focus on giving anticipatory, productive land-uses to sites, specifically micro-farming and agricultural strategies in the first instance, (Fig. 15.4) and strategies of afforestation and ecological restoration in the second group. A third pilot project sought to anticipate potential disaster in high-risk portions of the settlement through a comprehensive slope monitoring system which would give residents a warning to evacuate before disaster happened, along with a physical infrastructure for evacuation including safe, easy to travel routes along with designated evacuation shelters. The fourth pilot project in areas of the settlement where risk factors could be mitigated in order to ensure long-term safety of the settlement, proposed strategies for improving drainage and improving slope stability with various bio-engineering measures. (Fig. 15.5) The final pilot project would be implemented on vacant sites with low-risk factors, and develop sites for future neighborhoods with important infrastructure already in place, along with a combination of purpose built-housing as well as parcels where self-built construction could safely take place. This so-called "sites and services" has met with varying levels of success since the 1970s and has received renewed interest due to the intractability of the "problem" of informal urbanization. In the case of the neighborhoods of La Cruz and La Honda, adequate sites for this fifth pilot project are admittedly few and far between, but some sites do exist and could serve as successful models in other parts of the region where such strategies could be implemented on a larger scale.[11]

Figure 15.4: Atmospheric collage demostrating Micro-farming Strategies. *Rehabitar la ladera,* 282.

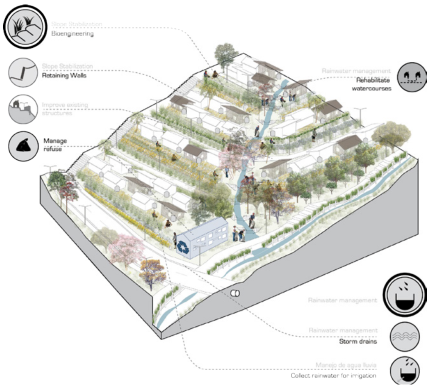


Figure 15.5: Axonometric from report showing a typical condition for mitigation strategies. *Rehabitar la ladera,* 253.

The research concluded with a publication designating potential sites and sets of strategies, but the spatial implications of these strategies at specific sites in the neighborhoods were not tested, and the pilot projects themselves have not yet been implemented. A gap between this strategic framework and first implementation could conceivably be filled by developing algorithmic methods for many of the strategies, and then testing the spatial deployment of the methods in a digital model of the settlement. These tests could then in turn inform plans for the first pilot projects. It is the aim of this section to discuss the development of several of these algorithmic strategies.

15.3. Algorithmic Methods used during the research process and potentials for improvement

During the research of *Shifting Ground,* carried out between 2010 and 2012 by Werthmann at Harvard and Echeverri in Medellín a few specific algorithmic methods were employed, but only at the larger, planning scale. The research in *Shifting Ground* relied in particular on the specific method developed by Carl Steinitz at Harvard University which used GIS based overlays, assigned with specific parameter weights to make judgments relating to specific landscape change. The method, devised and refined by Steinitz over the course of more than 30 years, makes use of various types of models, revisited in a nonlinear, iterative manner, to represent a planning area, understand its operations, evaluate its strengths and deficiencies, and evaluate the impacts of changes, ultimately in order to make decisions.[12] The models themselves often make use of mapping overlays, a method pioneered by Ian McHarg in his 1969 *Design with Nature*,[13] [14] but while McHarg's methodology was largely analogue, overlaying transparent maps with the deficiency that each map or parameter is necessarily imbued with the same weight, an important part of Steinitz' method used GIS-based algorithms, assigning specific weights to the specific overlays or parameters, where the range of parameters selected along with the judgment and intuition used to assign their weights could have significant impacts in the final evaluation.[15]

The research in *Shifting Ground* developed two specific models, one to assess risk and one to foresee growth. The risk model accounted for the presence of serpentinic soils (dunites), heavy rainfall and flooding, as well as high slopes.[16] The growth model accounted for four specific overlays to form an anticipatory model of growth, including proximity to existing informal settlements (informal urbanization tends to initiate a self-reinforcing feedback loop), proximity to public services, proximity to major roads, and proximity to protected areas or the urban boundary, an area designated as officially "off-limits" to growth, but where the likelihood of informal growth is paradoxically increased.[17] Weights and ranges of influences were assigned to the four parameters based on empirical observation of historical maps.[18] The presence of all four "attractors" combined, or even 3 of the four attractors, pointed to areas at high-risk of informal growth in the coming years, and could be overlaid with the risk map to identify "hotspots" where informal growth and destructive landslides would likely occur together.[19]

This method was used again at the finer scale of a settlement in *Rehabitar la montaña.* Three of the four parameters from the previous study were used again in this growth model, but since the official planning office considered the whole settlement off-limits to growth, the fourth parameter used in the previous study was not considered. An evaluation of the relationship between density of settlement and slope percentage, however, pointed to the presence of another parameter likely to influence future settlement, steepness of terrain. This was then put into the model of likely growth and a new, more site specific model was developed.[20] Already, however, the team realized this model stood on a shaky footing. Soon after developing and publishing the model, in a follow-up site visit, in one area identified as having a "low-risk" of future occupation, a dense cluster of 30-40 small wooden houses had sprung up while the team was miles away refining their model. Obviously, the model was not working—either the parameters were not properly calibrated, or a larger issue was at play—while a model may be useful at a larger scale, or to extrapolate general trends, the feasibility of the model to predict specific actions at a smaller scale can seemingly defy rational quantification. There are many reasons for this, but even the most powerful quantitative model must take into account things that are not easily countable, or as Einstein said, "not everything that can be counted counts, and not everything that counts can be counted."[21] The behavior of actors in complex, changing milieux may become predictable in an aggregate sense, but not their discreet actions. Also strong political factors are usually in play, even in societies with problematic governance, and these factors can change unexpectedly and are beyond the capacity of predictive models to foresee. It is also a weakness of the current geo-design methodology, recognized by Steinitz, that the interactions or relations between the various parameters or processes, rather than merely their overlay, are not adequately accounted for by current methods.[22] Whether taking these factors into account would improve the reliability of the model, in the end, only a comprehensive evaluation of the model after the worst (or best) has occurred would point to its validity. Such studies of failures, or successes, however, are crucial to validating and improving the methods of algorithmic approaches to landscape planning.[23]

A few other minor algorithmic methods were used during the research process, but in the end, the research team relied mostly on more traditional methodology. While the analysis of the settlement to identify sites for the five pilot projects, for example, used a simple methodology of GIS overlays, the overlay layers used to identify the territorial situations associated with the pilot projects were assigned no weights and as such hearkened back to the methodology of McHarg, ignoring the advances proposed by Steinitz.[24] (Fig. 15.6) Since landslide risk was an overriding factor, other secondary factors that would have given the categories a finer grain also played a minor role. A secondary gap in the initial research was that the spatial dimensions of the strategies were not adequately tested; in trying to represent the interworkings and spatial impacts of the various strategies proposed, atmospheric collages drawn in Photoshop and schematic axonometric drawings of typical situations were used rather than deploying the strategies in the specific context of La Cruz and La Honda. To resolve this gap, when the chance came to revisit the research work in the context of a major joint exhibition, the decision was made to try and use algorithmic methods to model the spatial extents of each of the five pilot projects as well as the spatial deployment of the strategies that would be employed.

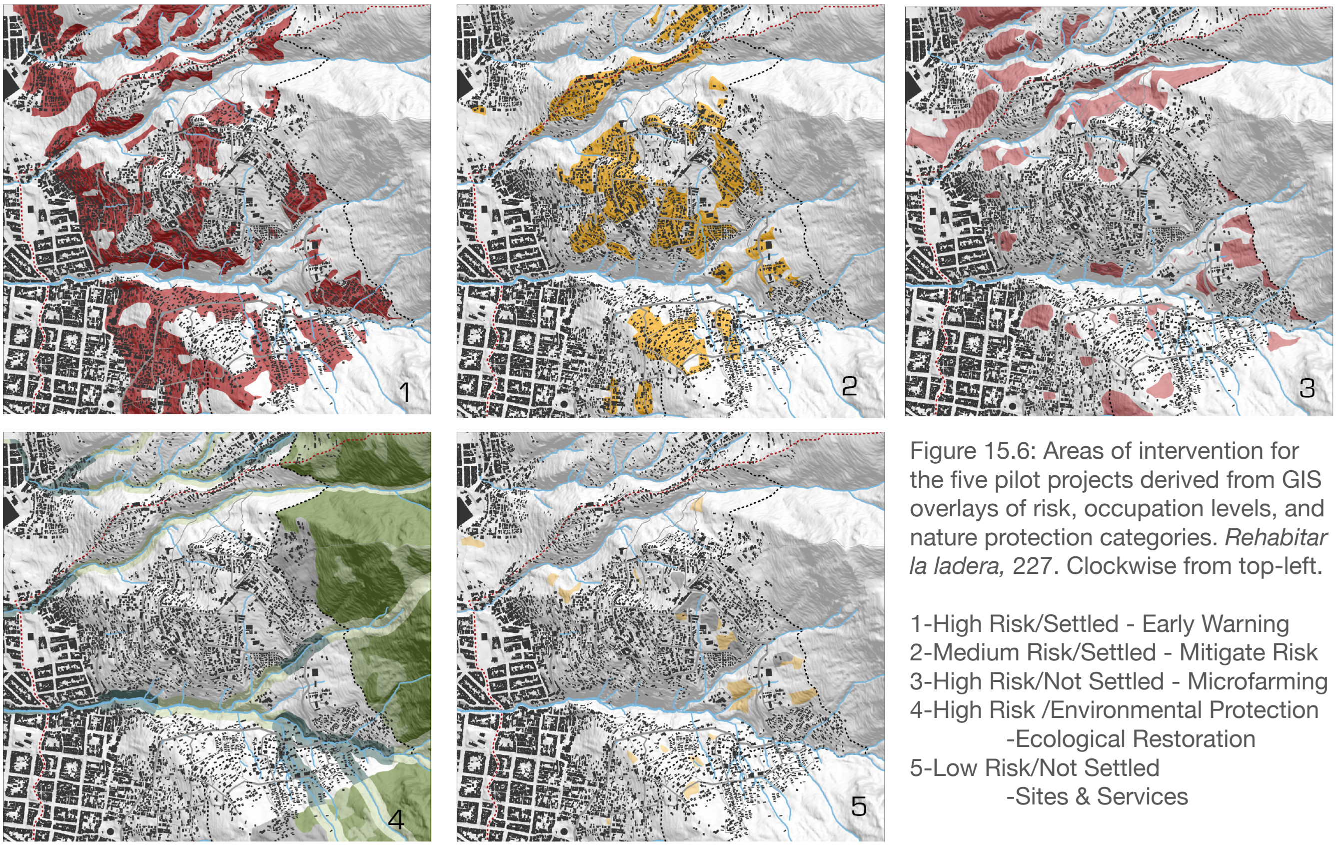


Figure 15.6: Areas of intervention for the five pilot projects derived from GIS overlays of risk, occupation levels, and nature protection categories. *Rehabitar la ladera,* 227. Clockwise from top-left.

1-High Risk/Settled - Early Warning
2-Medium Risk/Settled - Mitigate Risk
3-High Risk/Not Settled - Microfarming
4-High Risk /Environmental Protection
-Ecological Restoration
5-Low Risk/Not Settled
-Sites & Services

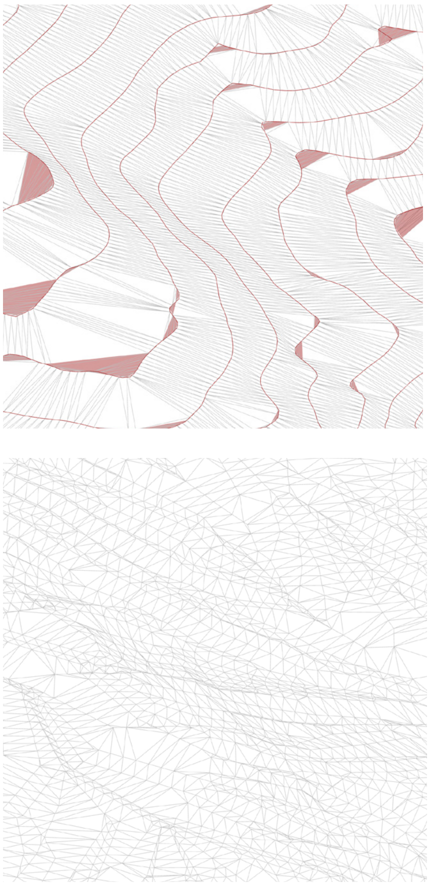


Figure 15.7: Detail of terrain mesh using only contour lines (above) vs. using steepest slope lines (below). Flat areas are indicated with red shading.

15.4. Algorithms Used in this follow-up study

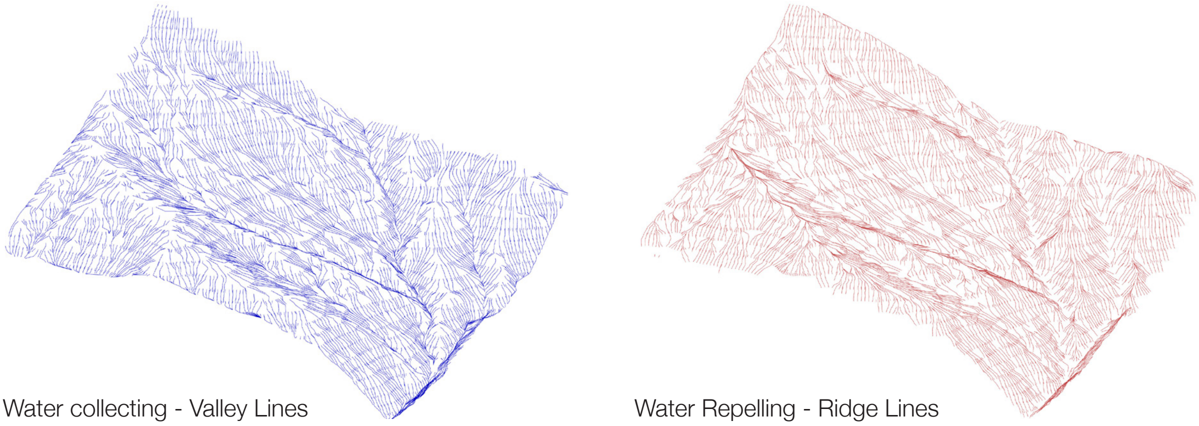
To create representations for the five pilot projects and to test the spatial implications of some of the proposed landscape strategies, a number of digital models were created, including several regional scale models, an overall model of the study area for the joint research project (a site area approximately 2km x 3km in extent with more than 800m of elevation change), as well more detailed models in a potential site for each of the five pilot projects. Algorithms falling into almost all of the categories described in the previous section were tested. Ultimately, however, the goal of this section is to show practical applications of algorithms in three categories: 1) terrain, terrain analysis, and terrain dynamics, 2) the formal allocation of space in a context which does not easily lend itself to formal structures, and 3) the deployment of strategic landscape systems using production rules.

15.5. Terrain Generation

Nearly all of the algorithms tested in this study react to the topographic complexity of the site and as such warrant access to a high degree of accurate topographical data in order to achieve reliable results. For this research, reasonably good topographical data in the form of contour lines was provided by the city of Medellín; although it was not in the scope of this research to field verify the accuracy of the data. Assuming a high degree of reliability for this topographic data, however, the contour lines could in turn be used to generate a 3-dimensional topographic mesh that in turn could then serve as a data input for other algorithms used in the study.

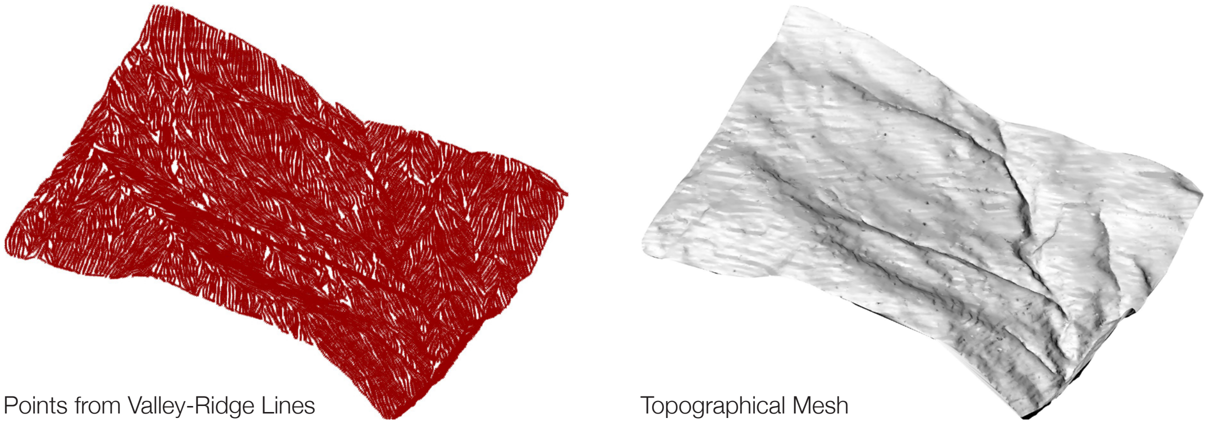
Early attempts to create the topographical mesh sought to generate this data directly from the contour lines by creating a regular spacing of control points every meter along the contour lines, and in turn using these control points to create a triangular topographical mesh using a Delaunay triangulation algorithm. This is a simple and direct workflow and at first this method seemed promising, but upon closer inspection of the mesh, a high number of flat areas became evident, especially near the ridges and valleys of the site. (Fig. 15.7, *top*) These flat areas, in turn, created problems with many of the terrain analysis algorithms, which executed commands based on overall slope at a certain point. This is a long-recognized problem with the creation of meshes and various methods have been devised to minimize these imperfections. One such method focuses on obtaining the “skeleton lines” also known as the “steepest slope lines” of a terrain, that is, the prominent valley and ridgelines, in turn using these lines in conjunction with the contour lines to create the topographical mesh.[25] (Fig. 15.7, *bottom*) (Fig. 15.8)

For this particular case of terrain generation, the skeleton lines are derived using one algorithm, but run twice in two directions. The first iteration of the algorithm follows a simple process that simulates the downhill flow of a hypothetical drop of water. A starting point is identified randomly along a specific contour line—the place where the first raindrop falls. The closest point to this point is then identified on the next lowest contour line, the place to which the hypothetical raindrop as surface runoff would travel. The process is repeated and from this second point, a third closest point is identified along the next lowest contour line, and so on until the series of points reaches a low-point or basin, or leaves the area of the simulation. This series of points are then connected forming the line representing the path that the hypothetical drop of water would have travelled. This process is then repeated many, many times, evenly across the area of the contour lines, until the overall downhill flow of the entire region is modeled. The lines tend to gather in the valleys in all cases. A



Water collecting - Valley Lines

Water Repelling - Ridge Lines



Points from Valley-Ridge Lines

Topographical Mesh

Figure 15.8: Process of Terrain Generation using steepest slope lines.

second iteration of the algorithm, this time run in reverse, or uphill, is then executed. Although these “anti-raindrops” do not neatly correspond to a natural process, a similar structure is generated with the lines congregating along the ridges, the areas that repel water. The basic logic of this algorithm is easy to understand and model, but structuring the contour lines in a dataset, as well as ensuring an even distribution of flow lines without generating too many unnecessary lines presents particular challenges, so the algorithm used for this terrain generation in the end was heavily modeled on one created by Trevor Patt which elegantly addressed these two problems.[26] These two sets of steepest slope lines were then used in lieu of the initial contour lines to create the Delaunay triangulation. The results represented a great improvement and flat areas of the mesh were essentially eliminated. This improved mesh could in turn be used for further operations.

15.6. Architectural Production Rules

After the terrain was generated, the next step before testing the landscape strategies involved was to transfer the two-dimensional urban and architectural plan data to the 3-dimensional mesh, primarily to represent the urban context. The study area consisted of over 12,000 individual buildings, and modeling each individual building in such context would clearly be prohibitively time-consuming. Instead, the buildings are modeled by taking the individual footprints of the buildings and using a simple set of production rules, the character of the urbanization (but not its exact form) is modeled based on a few observed parameters.

The use of production rules to generate architectural form has been extensively researched. Typical approaches involve studying an architectural corpus with a common “genetic code”, such as Soddu’s study of the buildings in an Italian Hill town (§3.12) or the work of Frank Lloyd Wright[27] among other examples, and then attempting to reverse engineer the logic of its production using shape grammars or shape syntax along with parameters representing the range of variability within. It is important to note here that the building form is only modeled for the purposes of representing the context's overall fabric and atmosphere and does not correspond to the settlement's actual real life morphology. This falls in line to a large extent with the most common implementation of such algorithms, the representation of complex situations in computer graphic situations for entertainment purposes, such as in games or in films.[28] It is not here, however, used to propose desired future forms.

For the modeling of the buildings in this context, numerous photographs of the settlement were analyzed and three general parameters were deemed sufficient to represent the quality of the urban fabric: the type of foundation, the number of stories, and the type of roof. (Fig. 15.9) (Fig. 15.10) The type of foundation selected for each building, whether a solid foundation or a foundation placed on stilts, was determined by measuring the overall grade change in the area of each 2D footprint. Where the grade change exceeded a certain value, assumed to be greater than the height of one story (4m), a stilt-post type foundation is used, otherwise the foundation is assumed to be solid or a partially underground story, both of which are represented with the same geometry in the model. The second variable, the type of roof, is chosen based on a random distribution where one-third of the roofs are assumed to be mono-slope constructions, while one-third are assumed to be pitched. This judgment is based on an overall assessment of numerous photographs, while in actuality, the type of roof-slope used seems to share some correlation with the overall footprint size and geometry. A more robust version of the algorithm could take this into account. The third variable, the number of stories, was also made based on a random distribution, but here again, the algorithm made some simplifications when taking into account the age of settlement. In newer settlements, almost (but not all) structures are one-story, while older parts of the settlement tend to have a higher proportion of two-and even three story buildings. In the 3D model, a rough assessment was used based on photographs and knowledge of the settlement's history gained in the prior phases of the research to set the parameters for the random distribution, but only in the two categories of old vs. young. For newer parts of the settlement a distribution of 90% was used for the one-story buildings, while for the older parts, only 25% of the buildings were deemed to be one-story (for the purposes of the representation.) After this overall form for the building was selected, additional details were added to some buildings, such as windows and roof ribs, but not all, so as not to overwhelm the simulation visually and in terms of computer memory usage. Again, since the goal was to reflect character and not to prescribe design, the parameters were rather loosely adjusted.

Figure 15.9: Photographs of housing in the relatively young neighborhood of La Honda. Construction continues in 2012 even after resettlement plans were issued for the area the previous year.

15.7. Field and Parcel Divisions

A major strategy envisioned by the research for disincentivizing growth was to give a productive land use such as agriculture to land on the high-risk peri-urban slopes. A major concern early on in the research was that most models of agricultural production, especially in a western context, take place in generally flat sites with high initial soil fertility. In La Honda and La Cruz, the soil fertility is quite low as the rocky dunitic substrate has a high presence of the mineral serpentine, which inhibits most plant growth, and the topographically complex terrain precludes most conventional agricultural allotment strategies. The concern for the feasibility of high-slope agriculture was soon put to rest after finding numerous examples of this implemented

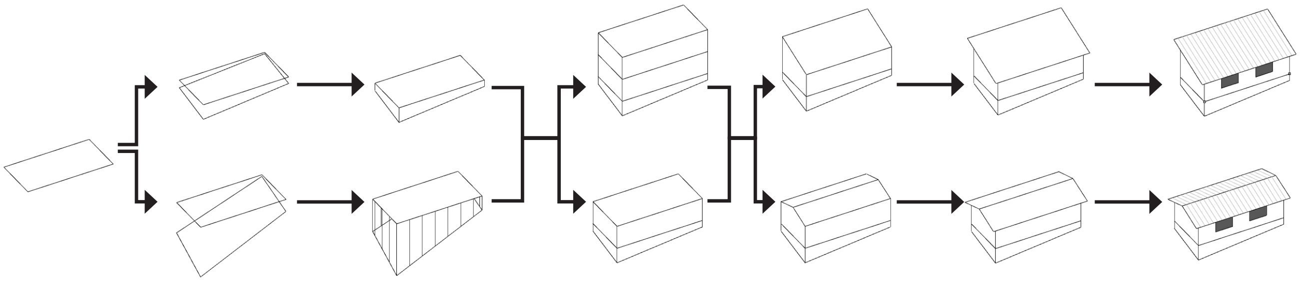


Fig. 15.10: Algorithmic decision tree for generating buildings. See figure 15.17,15.20, 15.22 for examples of buildings used as context layer.

successfully in both the Colombian context and elsewhere in the Andes. The team documented one such site in the nearby neighborhood of Pinareas de oriente, where 39 families actively tended to a 2,000m^2 (.2 ha) parcel, growing vegetables largely for self-consumption.[29] (Fig 15.11) Here the residents used simple wooden structures to create small terraces in the hillside to allow for the growth of a variety of crops, and overall soil fertility did not seem to be a significant issue. The research further hypothesized that soil fertility might be able to be improved if the agricultural program were closely tied to a larger program of waste recycling and composting of organic waste in nearby neighborhoods.[30] Various crops could also be tested during the pilot project process to see which ones did the best in this particular context. A more thorough evaluation of the existing plant material in the settlement, which includes several agricultural plants such as coffee and banana, might give further clues as to what might grow well in the settlement.

In developing an algorithm for field subdivisions, this research consulted a detailed evaluation of ancient Andean terracing systems led by Javier Pinedo, who in turn used this archaeological knowledge gained to develop new terracing systems in mountainous contexts.[31] (Fig. 15.12) Other parameters were derived from an evaluation of aerial imagery of several Andean terracing systems, including one on the island of Amantani in Lake Titicaca, since this system is remarkably well preserved up to the present owing to its isolation from the destabilizing forces of post-conquest Peru. (Fig. 15.13) Further research seems to point to the fact that the basic logic of this algorithm could be applicable to much flatter sites as well, as the divisions of land going back as far as ancient Sumeria used a system of alternating elements (in this case irrigation canals) following a contour with elements drawn perpendicular to this contour.[32] A second basis for developing the algorithm was the recursive topographical paneling subdivision process introduced in §A9.2.

Figure 15.11: Community agriculture in Pinareas de oriente.

The basic logic of the algorithm is this: the designer makes an initial subdivision of the land on a 2-dimensional plan based on existing conditions, taking into account locations of man-make or natural objects to remain, such as buildings, paths, groves of trees, large rocks or cliffs, as well as potential new features such as access paths, service buildings, etc. From here, the algorithm takes over to systematically adapt a potential field system to the topographic conditions. The algorithm then follows a recursive process that alternates divisions along a contour line with perpendicular

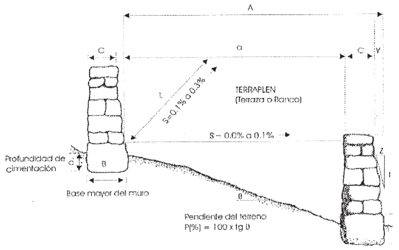


Figure 15.12: Diagram of parameters for an Andean terracing system from Pinedo, 201.

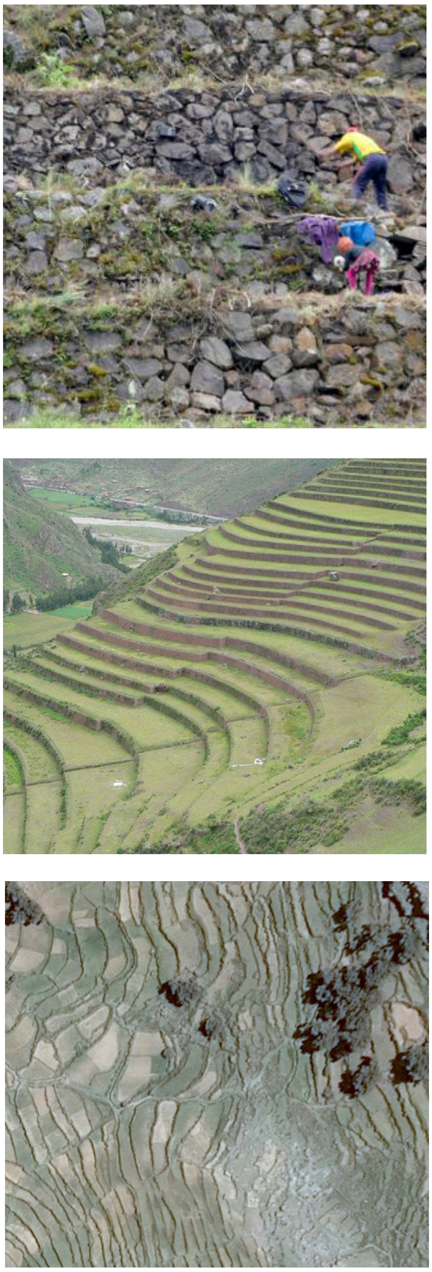


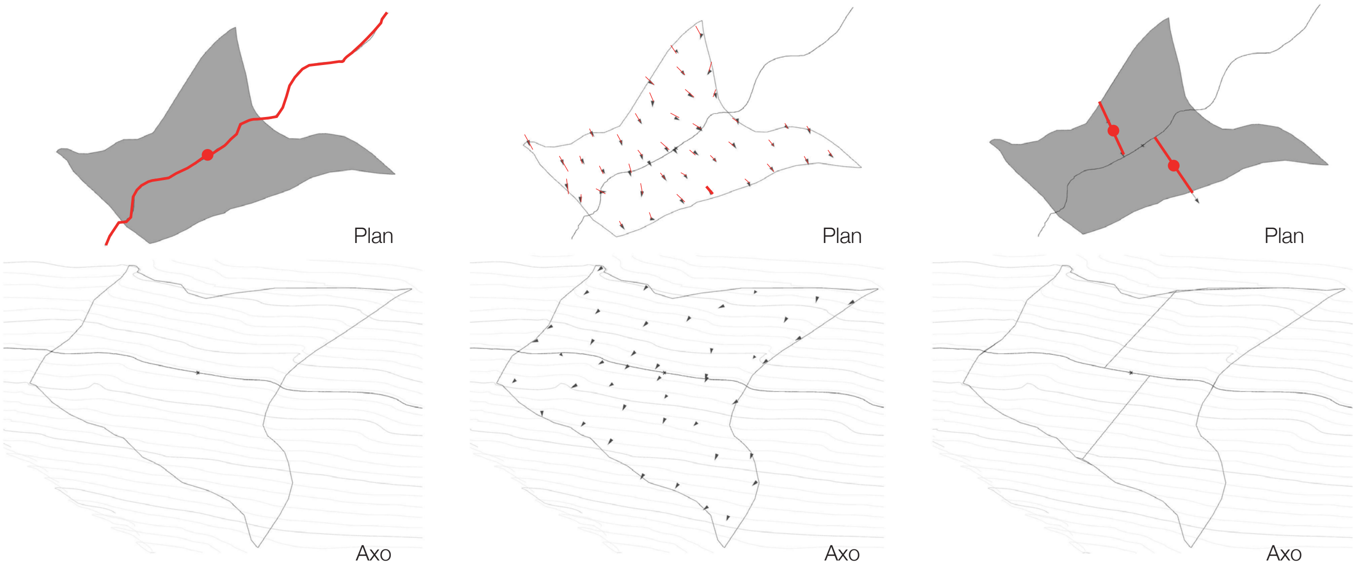
Figure 15.13: Traditional terracing in the Andes.

downslope divisions. For the first division, the algorithm finds the center point of the overall parcel to be divided, and then traces the slope contour passing through this point. This divides the parcel into two sub-parcels. Each of these sub-parcels is then populated with a number of points (based on its overall size), and at each point the downhill slope vector is identified. All of these vectors are then averaged to find an average overall downhill vector for each sub-parcel.[33] This vector is then traced through the center point of the sub-parcels, dividing them into two halves. The initial partial is now divided into four parts. (Fig. 15.14)

The process continues along these lines until one of several conditions are met to remove the parcel from the sub-division algorithm. An exception occurs with the division behavior when the overall length of the parcel is less than a variable parameter, in this case set to 15m based on the minimum field length of the Amantani terraces, although a different value could be used as well. When the parcel length is less than this variable, further subdivisions happen only along the central contour line, and no perpendicular subdivisions are created. Regardless, the parcel is removed from the subdivision algorithm altogether when it either achieves a certain maximum slope or it becomes smaller than a certain minimum size. If the parcel leaves the algorithm because it has achieved the minimum size, a final decision is made to determine if the average slope of the parcel is still too excessive, in which case slope stabilization measures will be needed, or if the parcel can stand on its own without additional slope stabilization. (Fig. 15.15) What this slope is depends on what crops will be planted, their ability to grow on steeper sites, and their ability to slow soil erosion.

This fairly simple process of recursive slope divisions yielded results that took on a character surprisingly close to that of terracing systems around the world. (Fig. 15.16)(Fig. 15.17) The algorithm can and should be refined based on the specific requirements of the system being used, but overall it shows significant promise. It can also be deployed rapidly and effectively over large areas, if not to design the system itself, at least to show the visual character, the potential spatial dimensions, and the visual impact of the deployment of such a system. Additionally, community members and workers can use a process similar to the algorithmic process used in the computer when deploying the system in the field, dividing space by alternating between divisions along a contour and against a contour in a manner similar to the algorithm. As discussed in Chapter 1, this was and continues to be strength of the Euclidean system, the compatibility between the design method and the method for implementation, which should be considered when devising new, algorithmic methods for landscape change. Obviously the deployment in the specific context will produce results that vary to some degree as from the computer representation, but this is to be expected and even encouraged.

While the overall method of the field subdivision algorithm shows promise, the exact dimensions of the subdivisions, the parameters used, and other features of the algorithm need to be adjusted, particularly in light of the system that is ultimately used. This research assumed deployment of a generally low-cost, very soft system with low material inputs, with maybe only simple wood retention elements on the steepest parts of the site similar to what the team observed in the Pinares de oriente project. While the promotion of low-cost terracing methods would undoubtedly yield some benefits, the longtime durability of this mostly soft and bottom-up system may be questionable. A more “formalized” system, such as developing higher quality terraces similar to what is seen further south in the Andes in the heartland of the ancient Inca empire, could prove more beneficial in the long run, in terms of overall durability, in its capabilities for maintaining



1 - Parcel is Cut along Contour through Center Point

2 - Average cownslope vector of each resulting subparcel is found

3 - Subparcels are cut through their center points along average downslope vector

Figure 15.13: Steps of Terracing division on an initial irregularly shaped parcel. 1) Cut along central contour line. 2) find and sum a number of vectors in the resulting subdivisions from step one. 3) cut the resulting parcels along the average downhill vector.

larger quantities of improved soils (maintained through composting), in terms of water management, and in terms of overall public visibility. Such a system would also be fairly inexpensive. In the pilot project described by Pinedo, one hectare of terracing required, depending on slope difficulty, from 336 to 1181 days of labor, averaging 742 days.[34] If laborers were paid at twice the current Colombian minimum wage to construct these terraces, the labor cost for creating terracing would amount to $USD 14,000/hectare or $USD 42,000 on the 3 hectare site envisioned for this pilot project.[35] A few thousand more dollars would be needed for material costs. This is a rather modest sum when considering that the labor cost of this entire three hectare project would be about the same as the cost of removing and resettling a single house in the same context according to the city's published resettlement plan![36] The 3-hectare site itself, if settled informally at currently observed densities in La Honda of around 60 houses per hectare, would contain around 180 houses. If these houses were in a high-risk context, the cost of removing and resettling these people would total $USD 8 million. In this light, a case can easily be made for a modest investment in a durable and visible (and hence policeable) anticipatory farming infrastructure that would yield long-term and tangible benefits to the community. If implemented on a large scale, such actions would have the potential to change the image of the slopes of Medellín and its cultural landscape.

Two major variables, however, are not accounted for in the prior calculation. The first variable is the market value of the land, or the cost of acquiring the land by the city or a community group. These land economics cannot be accounted for here, but it should be noted in much of the current study area, especially in the neighborhood of La Cruz, much of the land is currently owned directly by the municipality. A second big variable not

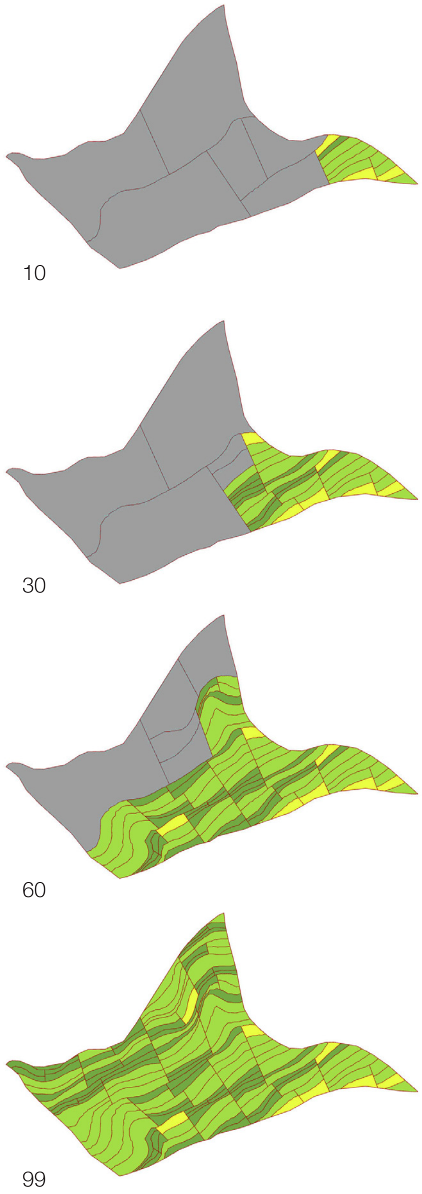


Figure 15.15: Inital parcel after 10, 30, 60 and 99 recursions of the algorithm, at which point all parcels had met one of the exit conditions for the division process to stop.

accounted for in these calculations, however, is the cost of expert knowledge. While some academics or NGOs might be willing to offer some expertise for free on a small-scale project, for long-term project sustainability, or for large-scale implementation, these costs need to be accounted for. While an algorithmic process may not be able to remove the need for expert knowledge altogether, it could be extremely useful in reducing this cost by codifying repetitive knowledge and by aiding in the deployment of a simple system on a large scale in a contemporary context. In this instance, the algorithm has the potential to serve as a vital step in testing, representing, and implementing large-scale landscape change. The algorithm as described could also inform the process of building itself without the mediation of the computer. Much as Euclid's algorithms executed on compass and paper could also be executed with ropes and poles in the field, a system of progressive land divisions following the steps explored in the computer on the site itself should yield similar results. While the second step of finding the average downhill vector for a sub-parcel may be difficult, especially with larger parcels, or finding the exact center point of a parcel in steps one and two, these quantities can be estimated in the field through visual observation without drastically altering the algorithm's ultimate outcome. What is more important that the general logic is followed rather than prioritizing a specific formal outcome.

15.8. Deploying a Landscape System – Drainage Fascines

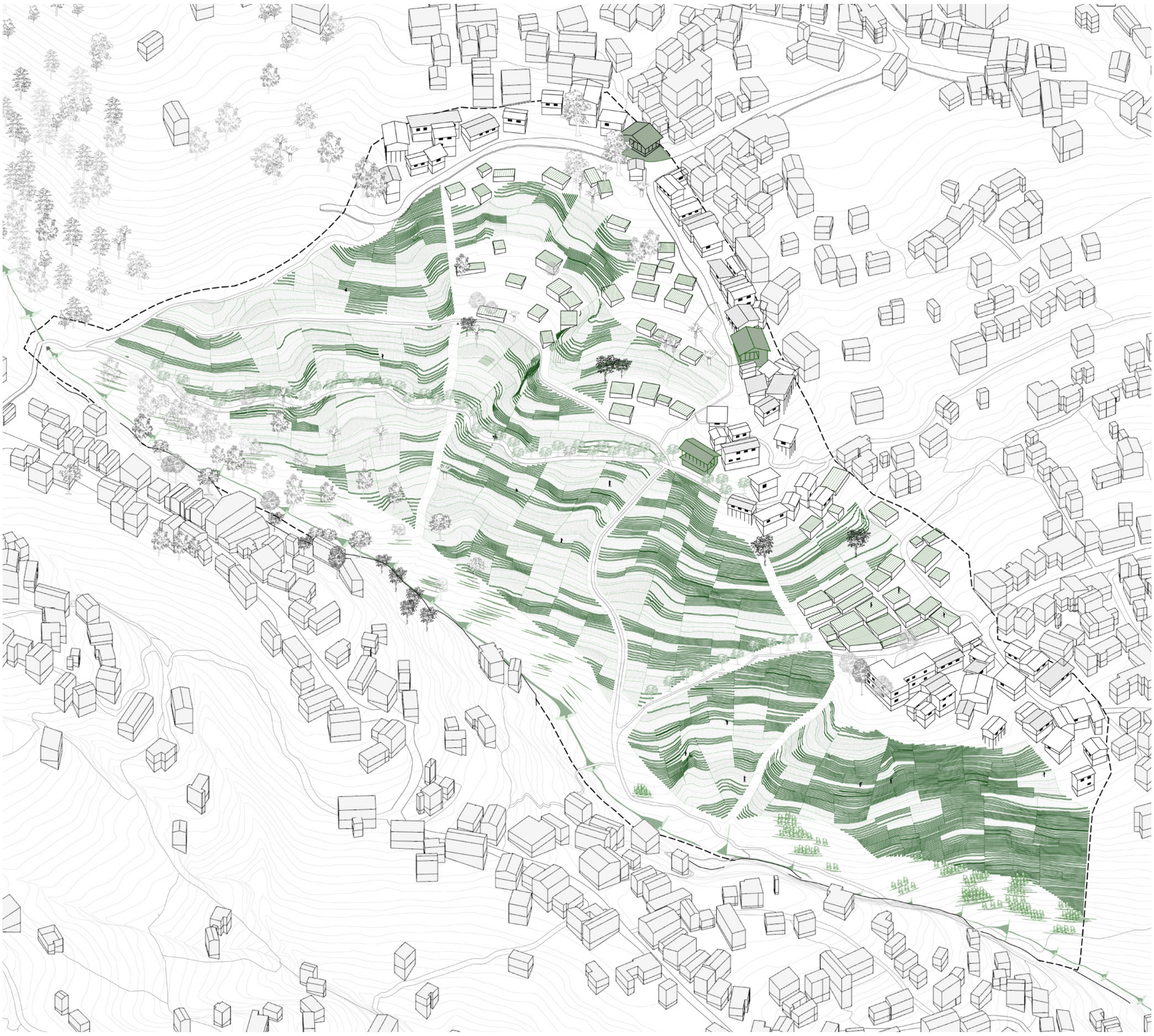
In the research, the team proposed deploying several bio-engineered slope retention and drainage improvement systems to both mitigate landslide risk in and around existing settlement and to facilitate speedy ecological restoration in areas deemed at risk of potential future settlement.

A potential bioengineered system that could be used on site to improve slope stability and to promote good drainage while encouraging rapid plant colonization is the living slope fascine. The technique, as described in Studer and Zeh's *Soil Bioengineering : Construction type manual,* promotes slope stability in three ways. First, living plant material is arranged as a series of bundles in a continuous arrangement of trenches forming an artificial drainage network through which water will rapidly flow first to a receiving stream, and then to natural drainage channels and creeks, thus significantly slowing rapid soil saturation, the primary landslide trigger. Second, the living plant material quickly sprouts into dense plant cover, whose roots mechanically stabilize the soil, also reducing erosion and landslide risk. Finally, as the growing plant material becomes established, lessening the effectiveness of the underground drainage network, the mature plant material compensates for this by "drinking" large quantities of water and removing it harmlessly into the atmosphere through evapotranspiration.[37] In establishing the system, however, slope steepness must be carefully accounted for, as the system requires specific configurations and spacing of elements and overall orientation with respect to the fall of the slope. In the manual, three specific configurations are given described with a vignette and typical plan.[38] (Fig. 15.18) It is then up to a design professional to translate these templates into an arrangement which works on a specific site.

The straightforwardness of the method in light of the topological variability and complexity of the slope and in the context of existing features of the settlement suggested that this was another system that could lend itself to study and spatialization through an algorithmic method. (Fig. 15.19) The logic of the algorithm developed merges a local reading of slope steepness with the three distinct spatial configurations suggested for the three categories of slope steepness in the manual. To begin, slopes are read in the computer model with an initial 2 meter grid, as this is the spacing

Figure 15.16: *(top)* The 3 hectare site for this study is algorithmically divided through a total of 684 recursions of the algorithm.

Figure 15.17: *(below)* Resulting field divisions showing slope stabilization measures in dark green and plant material at various cropping heights. Context of the project is also shown.



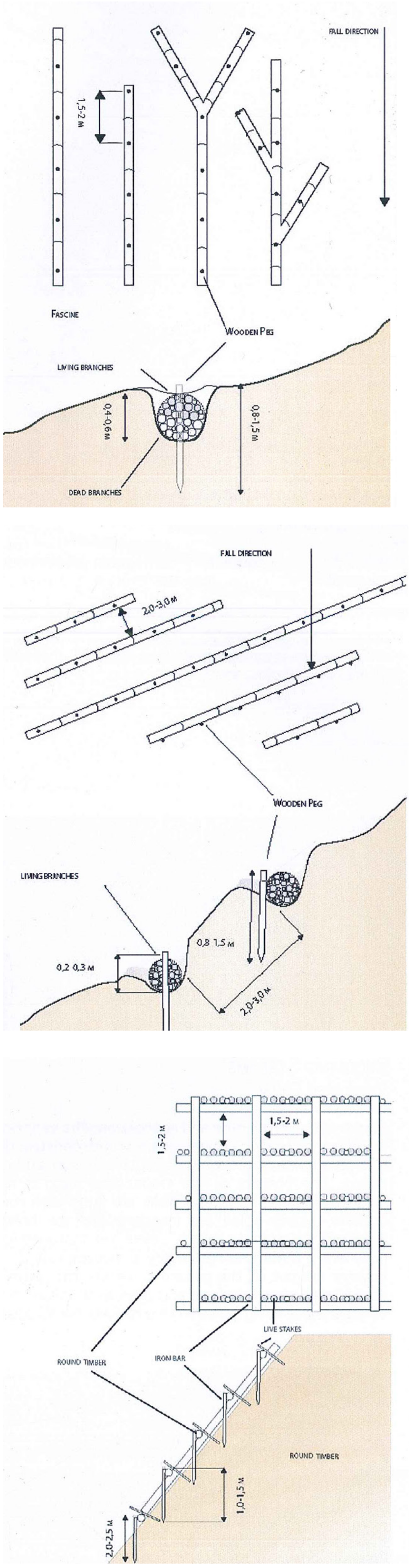


Figure 15.18: Schematic drawings of fascine systems on slopes of 20-50% (top), 50-70% (middle), and above 70% (bottom). Roman Früh and Marten Urban, from Studer and Zeh.

between elements recommended by the second of the three configurations, and which is the most sensitive to overall spacing. To account for sudden local variations, which may reflect errors in the computer model and not necessarily actual conditions, the downhill slope vectors are also normalized based on their neighbors. Then, the slope vectors are sorted into three categories associated with the three configurations described in the manual, being respectively, slopes from 20-50%, slopes between 50-70%, as well as slopes steeper than 70%. The algorithm also sorts out slopes less than 20%, where it is assumed the living slope fascine method would not be needed, but in the particular site chosen for this test, no slopes less than 20% exist.

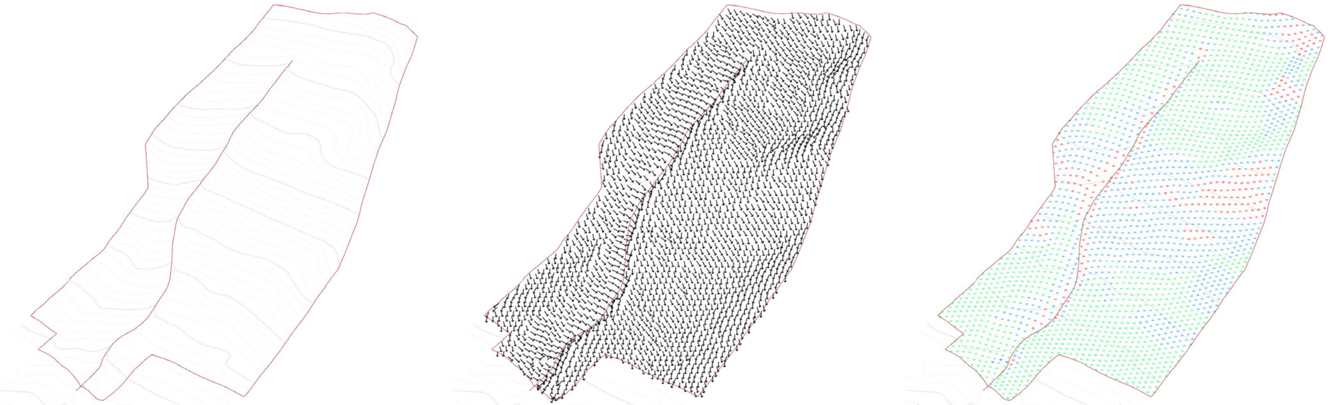
The next step is to rotate the slope vectors based on the configuration recommended at each point as per Studer and Zeh's technique. First it is necessary to identify the primary receiving stream, the place to which the water in the fascines must be directed. Next, the vectors can be rotated, where needed, towards this receiving stream. On slopes between 20-50%, no rotation is necessary, as ideally at this slope, the water should follow the direct downhill vector. On slopes between 50-70% where the water would hypothetically travel much faster, the water must run diagonally with respect to the fall direction. This amount of rotation should be around 30°. Slopes higher than 70% cannot be populated with fascines, and must instead be stabilized with a vegetated wood grating, and water must be collected and taken to the receiving stream only at the bottom. The consequence of this is that the slope is given a pattern of downhill vectors and diagonal vectors, which form the basis of the network.

The final stage is to connect the various localized vectors into a coherent, complete network. The first version of the algorithm did this by simply connecting the endpoints of each line to its nearest neighbor, and then applying a smoothing algorithm to the resulting network. This worked well for at least laying out an initial condition, but the method would require a degree of post-processing to connect sections of the network with no outlet. A second version attempted to remedy this problem by adding segments, in a recursive fashion, to an overall established network of branching forms. For this, the logic of a growing plant, similar to the logic described in §A8.1/*branching* was used. (Fig. 15.20)

In the initial setup, two groups of geometry are established, either (1) part of the established network, or (2) yet to be added to the network. The first group consists of the receiving streams, the second group of the short segments of the fascines oriented to their ideal configuration based on slope steepness. Then in each round, the segments are tested by measuring the distance between their outlet point (the low point of each segment) and their distance to the established network (group 1). The segment with the shortest distance to the established network is then connected to the established network by drawing the shortest line between its outlet point and the network. This segment is then removed from group 2 and added to group 1, the established network. In this manner, the network grows recursively until all segments have been added. If a segment cannot be added in a logical way with a downhill flow, it is moved to a third group of geometry, or "problem cases." These problem cases need to be addressed manually by the designer after the algorithm completes. If the initial input topography is accurate, the generated network should provide a plan for a viable, workable network that can be built in the field. A second test may need to be added which takes into account the water carrying capacity of each segment so these can be properly sized, or so that a part of the network that is overburdened with inputs and not enough outlets can be closed down to further additions to its part of the network.

This initial test showed that the algorithm could be very useful, at least for establishing an initial configuration. The illogical conditions require some degree of post-processing to work around, these usually occurring in the vicinity of the high slope areas which need special slope retention measures. The designer must be aware of the limitations, and some care must be made in setting up the initial conditions, in terms of potential receiving streams and the area where the fascines are to be deployed, based on local micro-drainage basins. This brings to light an important point that needs to be kept in mind for any algorithmic-based workflow in the context of design as opposed to software engineering. In software engineering, much more time can be spent in debugging a program than in the initial coding process. Every conceivable user and user error must be accounted for to deliver a reliable product. This is not necessarily the goal when approaching a design project. When writing an algorithm to answer questions specific to only one project, or if the algorithm is primarily intended for personal use, that is just to help the designer understand the phenomena at play, a comprehensive optimization and debugging process yields increasingly diminishing returns. On the other hand, if the algorithm is intended to be reused by many different users in many different contexts, or for instance, by many members of a design team, special attention to clarity and functionality more akin to software engineering must be taken into account.

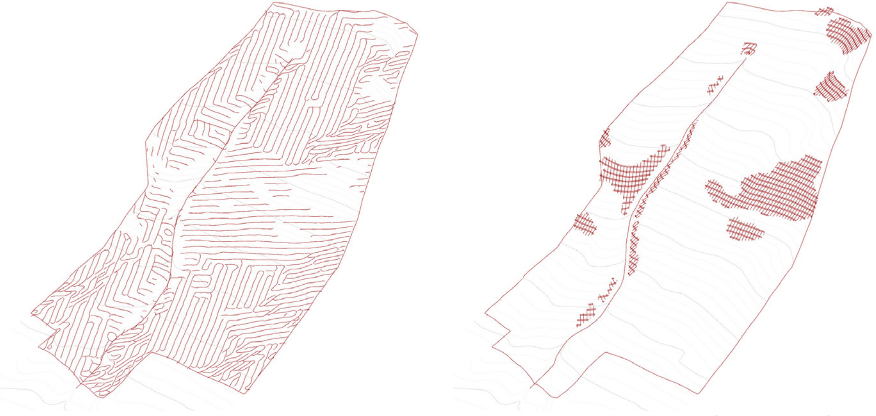
Figure 15.19: Steps of the Fascine drawing algorithm. (1) Identify boundaries and catchment stream (2) Find downslope vector on 3m grid (3) classify vectors based on slope (4) draw network on slopes 20 - 70% (5) draw grid on slopes over 70%



Micro-watershed boundary with receiving stream

Downhill Vectors on 2m grid

Slope steepness - Green: 20-50% Blue: 50-70%, Red: over 70%



Preliminary fascine sections oriented according to criteria from Studer and Zeh

Areas for grid system (high slope) according to Studer and Zeh

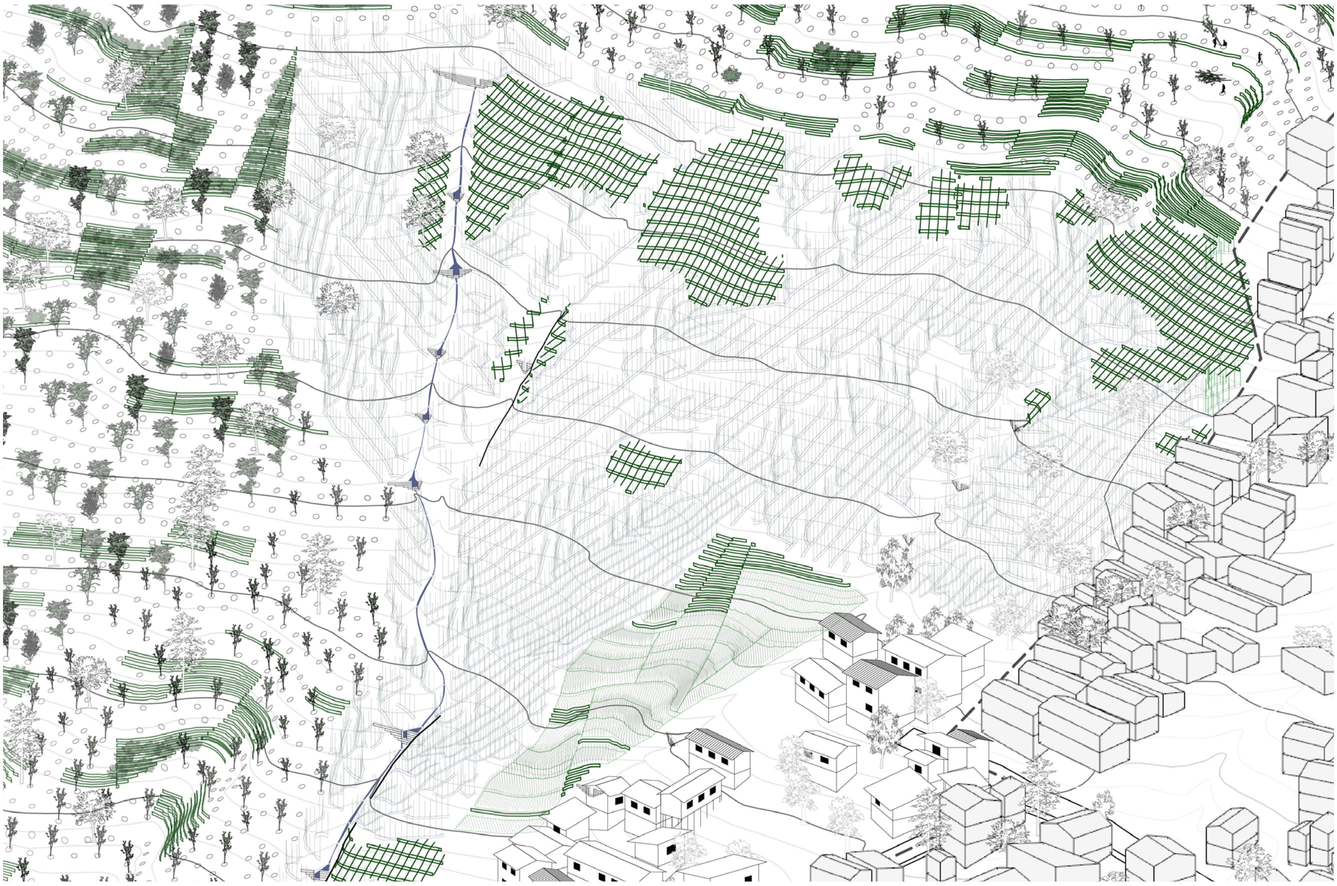


Figure 15.20: Network of drainage fascines shown in context per the logic of §15.8.

15.9. Additional Tests

Several other algorithms were used to model both the implementation of strategic systems in the settlements and the distribution of space. Additional elements following a series of simple production rules include the stairways, drainage canals, lighting elements, and various bio-engineered slope retention and stream stabilization mechanisms. The algorithms did not exhibit a high degree of complexity, but could be enriched as more about the rules of the system are known.

One example would be for the size and configuration of the check dams for the stream corridors. The algorithm designed in these representations placed the check dams relative to the total fall of a stream over its course. For example, every 4 m of stream fall a check dam might be attempted. If the terrain at that position is too flat, or if the channel is too broad or shallow, the check dam is not drawn. This was based on a general "head-to-toe" rule in check dam placement where the height of a check dam is in direct relationship to the toe of the next upstream dam.[39] In reality, other methods for determining placement exist ranging from equations to find an equilibrium point for sediment motion on the one hand, to empirical observations of on site of sediment deposit in restored channels on the other.[40] Each approach—the rule-of-thumb approach, the highly engineered approach, or the trial-and-error approach— has its limits. In reality, as the system is quite dynamic, the construction should also be seen in a dynamic light, and the exact placement and size of the dams should change as the stream bed morphology evolves, and as the growth of plants or of the settlement changes the initial conditions.

Some systems were modeled only partially algorithmically, with "algorithmic thinking" informing decisions that were made in an analog manner, based on experience or intuition. One example of this was the proposal for the fifth "sites and services" pilot project. Initially, the plan was to model the streets with a modified L-System as described in §10.4 that would account for the growth of streets or ways, and then parcels would be allocated in the areas between the streets. This still might be a promising approach for much larger areas which are to be allocated for anticipatory housing strategies, but in the settlement of La Cruz and La Honda in particular, there was very little land for new housing plots and on the one test plot, it made more sense to draw the overall structure in a fairly systematic way by hand without spending much time developing an algorithm which would accomplish the same results. The cut and fill of the housing plots is then determined by a simple algorithmic process but overall the design uses an analog logic.

15.10. Reflection and Conclusions

Overall, of the algorithms developed for the three case studies, those developed for use in Medellín were the most involved with the largest time investment. While the two systems described for field subdivisions and for slope fascines explored the possibility of using algorithms to develop strategic systems, the other algorithms focused largely on issues of representation. This is largely owing to the nature of these studies as part of a larger research project and with the goal of producing drawings and models for a major exhibition and not specifically built projects. Should the research continue to actual implementation of the pilot projects, the initial logic of the algorithm for the field subdivision system as well as the construction of a fascine drainage network, however, should provide a solid foundation for further refinements which would make the algorithms useful as a tool for both refining a strategic methodology for on-site implementation. Refined versions of these algorithms, along with the development of a system for allocating parcels for informal construction with infrastructural services already installed (Pilot 5, Sites and Services) show the most promise in this particular context for deploying algorithmic strategies in a design context. It is also possible that an algorithmic approach could address new models for architectural interventions in this context along the lines of the method described by Julian of Ascalon and Besim Hakim in §3.12., but this would be a multi-disciplinary effort involving architects, landscape architects, and urban designers.

Using such production rules for the architectural fabric, the urban design, and the strategic landscape interventions opens up the possibility for new manifestations of built-form with emergent qualities, compressing the effects of 100s of years of growth, as Thom Mayne proposes, into a quickly executed computer program.[41] These ideas have been around for several decades now, however, and up to this point there are no good examples of a successful implementation of such a system for creating built form on a massive scale. Critics of such approaches might argue that even if such a system were to be implemented, which will undoubtedly happen given enough time, such "fake complexity" is just as shallow as other approaches to planned development, as true complex form is an expression of the social dynamics and social networks of a city, which are constantly in a state of flux or becoming, and as such, such approaches are doomed to fail. If a methodology were devised, however, which as Carpo suggests in §7.6 introduces true, end-user driven complexity and non-linear indeterminacy and not computationally generated pseudo-randomness, perhaps some of these shortcomings could begin to be addressed.

An algorithmic approach did, however, yield productive results when dealing with the massive, complex datasets associated with this site. The

Figure 15.21: Algorithmically generated model of terrain and settlement structure in and around La Cruz and La Honda from 2-dimensional plan data.

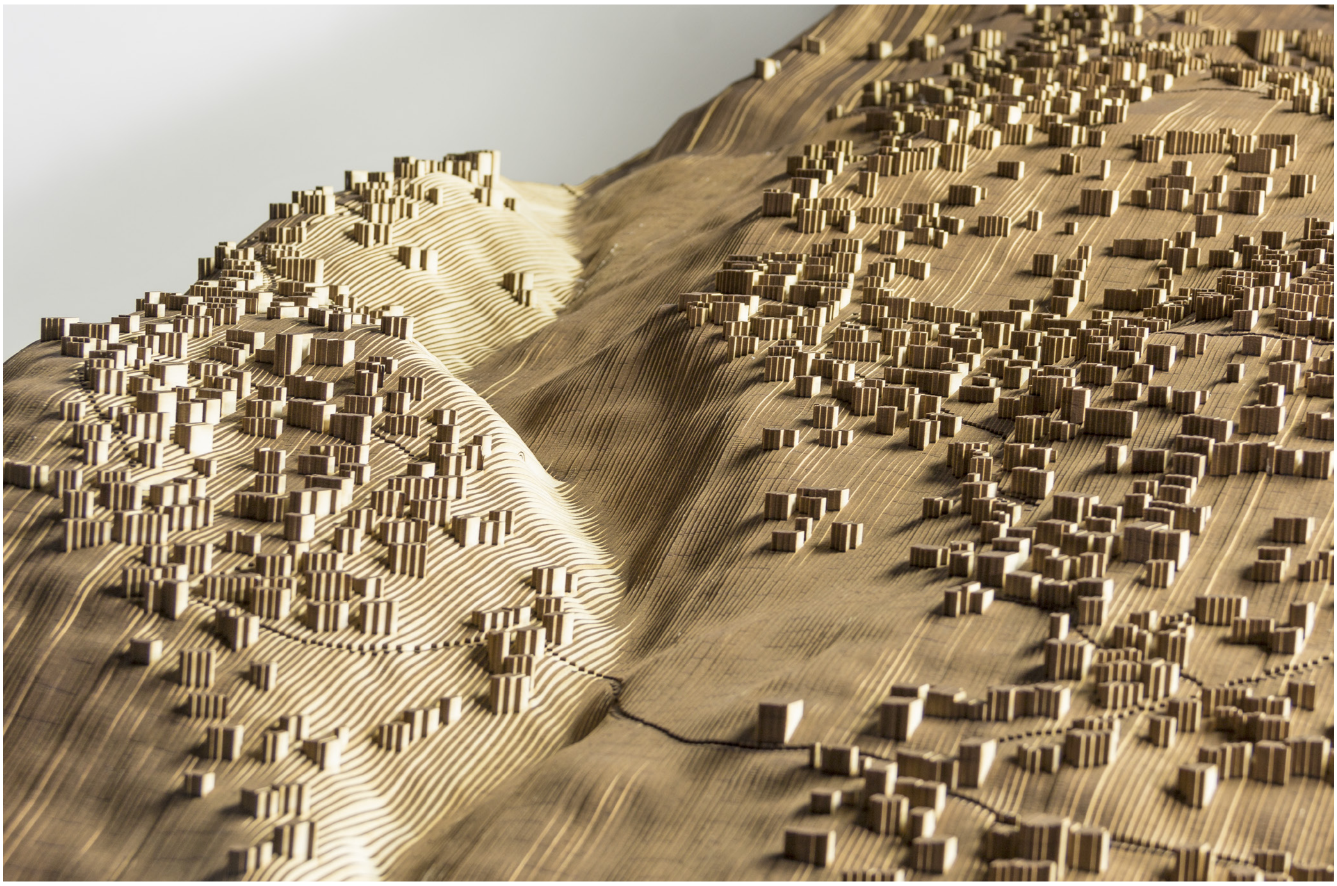


Figure 15.22: Laser-cut model of settlement built from an algorithmically generated model of the settlement. Photo: Marcus Hanke

overall axonometric drawing of the project study area and its surrounding context (Fig. 15.21) could not have been realistically produced without the help of an algorithmic workflow. The axonometric drawing itself contains around 20,000 buildings, all of which needed to be modeled and then moved to the proper topographic elevation. Doing this manually would tax even the capacities of even the most diligent intern and would waste hundreds if not thousands of hours of time. This complex 2D drawing was also used to produce a 3D, laser cut model (Fig. 15.22) which also could not have been modeled in 3D and subsequently cut and arranged into 300 individual sections without the assistance of various scripts and codes. The ability of computers to handle such large datasets is well-known, but the scale of problems facing the planet, such as rapid urbanization and environmental degradations, also require the development of approaches that are easily replicable and transferable to much larger scales than that at which our profession is currently operating. An algorithm, at its core, is a model of such an easily transferable and replicable process. Despite the shortcomings and sometimes tediousness of this approach, the potential to model and test the emergent properties of self-organizing systems still shows great promise.

Endnotes

1 "When the city turned its back, the mountain took us in." Resident of La Cruz.
Alejandro Echeverri, Christian Werthmann, and Francesco Orsini, eds. *Rehabitar la montaña: Estrategias y procesos para un habitat sotenible en las laderas de Medellín.* (Medellín: Urbam EAFIT, 2013), 10.

2 Joseph Claghorn and Christian Werthmann. "Shifting ground: Landslide risk mitigation through community-based landscape interventions." *Journal of Landscape Architecture* (1:2015), 6-15.

3 David Petley. "Global Patterns of Loss of Life from Landslides." *Geology 40/10,* (2012), 927-930.

4 Alejandro Echeverri, Christian Werthmann, and Ana Elvira Vélez Villa, eds. *Shifting Ground: Precarious Settlements and Geological Hazard in Medellín* (Medellin: Urbam EAFIT, 2012), 32-33.

5 J. Klimes & V. Rios Escobar. "A Landslide Susceptibility Assessment in Urban Areas Based on Existing Data: An Example from the Iguaná Valley, Medellín City, Colombia," *Natural Hazards and Earth System Sciences 10,* (2010), 2067-2079.

6 Echeverri, Werthmann et al, *Shifting Ground.* 52.

7 Municipio de Medellín – EDU. *Proyecto de regularización y legalización urbanística del barrio la Cruz y el sector la Honda.* (2011).

8 *Ibid.* The figure published in the 2011 report was 106 billion Colombian pesos (COP), with 1300 houses designated for removal and resettlement in the report. At the average 2011 exchange rate of 1800 COP per USD, this would amount to USD$45,000 per house. The exchange rate has of course widely fluctuated since then.

9 Echeverri, Werthmann, et al. *Rehabitar la montaña*

10 *Ibid,* 137-155.

11 *Ibid,* 223-297.

12 Carl Steinitz. *A Framework for Geodesign* (Redlands: Esri Press, 2012), 25.

13 *Ibid,* 10.

14 Ian McHarg, Design with Nature. 25th anniversary edition (New York: John Wiley and Sons, 1992).

15 Steinitz, 60-63.

16 Echeverri et al., *Shifting Ground, 30.*

17 *Ibid,* 56-57.

18 *Ibid*, 58-67.

19 *Ibid*, 72-89.

20 Echeverri, Werthmann, et al., *Rehabitar la montaña*, 84-85.

21 attributed to Einstein, as quoted in Steinitz, 183.

22 Steinitz, 182-183.

23 *Ibid*, 192.

24 Echeverri, Werthmann, et al., *Rehabitar la ladera,* 144-151.

25 T. Gökgöz and F. Gülgen, "Comparison of two methods for deriving skeleton lines of terrain," *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* 34, 30 (2004), 1-5.

26 Trevor Patt, *Assemblage Form: An ontology of the urban generic with regard to architecture, computation, and design.* (EPFL Laussane, 2016), 33-41.Algorithm accessed from www.codequotidien.com (1.Dec 2016)

27 H Konig and J Eizenberg. "The language of the prairie: Frank Lloyd Wright's prairie houses," *Environment and Planning B, 8* (1981), 295-323.

28 Yoav Parish and Pascal Müller. "Procedural Modelling of Cities." *SIGGRAPH '01 Proceedings of the 28th annual conference on Computer graphics and interactive techniques* (2001), 303-304.

29 Echeverri, Werthmann et al., *Rehabitar la montaña,* 170-171.

30 *Ibid*, 206-207.

31 Javier Blossiers Pinedo, Carmen Deza Pineda, León Huaco, Ricardo Samané Mera, "Agricultura de laderas a través de andenes, Perú." *Manual de Captación y Aprovechamiento del Agua de Lluvia.* (Santiago, Chile: Oficina Regional de la FAO para América Latina y el Caribe, 2001.

32 Christophe Girot, *The Course of Landscape Architecture* (London: Thames & Hudson, 2016), 18.

33 The first iteration of the algorithm used only the vector at the center point itself, but a small topographical quirk only at this spot could yield unsatisfactory results. An averaging of vectors sampled from points across a larger area yields better and more predictable results.

34 Pinedo et al., 213.

35 *Ibid*, Colombian minimum wage as of Jan. 2017.

36 See §15.2, note 7.

37 Rolf Studer and Helgard Zeh. *Soil Bioengineering: Construction type manual.* (Zürich: vdf Hochschulverlag AG, 2014), 234-235.

38 *Ibid.*

39 C. Castillo, R. Pérez, and J.A. Gómez, "A conceptual model of check dam hydraulics for gully control: efficiency, optimal spacing and relation with step-pools," *Hydrology and Earth System Sciences.* 18 (2014), 1705-1706.

40 *Ibid*, 1706.

41 Thom Mayne, *Combinatory Urbanism: The Complex Behavior of Collective Form* (Culver City, CA: Stray Dog Café, 2011.

Chapter 16 – Wilhelmshaven

“Keen nich will dieken, de mutt wieken” – Low German Proverb[1]

16.1. Introduction – Case Study Wilhelmshaven

This section represents the second of three in-depth case studies to test strategies for applying algorithmic methods to specific landscape sites and problems. In this study, the focus is on developing algorithms and methods to test a combination of engineered, dynamic, and emergent landform strategies associated with an important piece of flood-protection infrastructure in Wilhelmshaven, Germany. The case study is intended as a dual to the ideas introduced in Chapter 4 on Leibniz and von Humboldt, where the increasing scientific and engineering knowledge of the Enlightenment and the eventual reaction against these mechanistic attitudes towards nature led to a break between civil engineering and landscape design as part of a larger attitude seeing culture and nature as separate and distinct. Recent landscape architectural discourse has sought ways to reverse this trend, reinterpreting mono-functional, engineered infrastructures as multivalent constructions that function better from both an ecological and a social perspective. The sea dike in the German port city of Wilhelmshaven offers a unique opportunity to synthesize various activities and spaces into the most important park and open space in the city, increasingly the desirability of the city’s southern neighborhoods in accordance with the city’s overall future development vision. As the largest urban condition in Germany bordering directly on a national park, this important infrastructural object, which mediates between a dynamic natural and human shaped landscape, has the potential to be reinterpreted in a contemporary way. In spirit, however, the proposal hearkens back to a much earlier attitude as expressed by Leibniz, where engineered infrastructure should be conceived to serve a multiplicity of perspectives, from the practical to the aesthetic, from the cultural to the natural. (§4.12) The strategies were developed by the author in parallel with a master’s level design studio that looked at the same site in summer of 2016. While the students approached the project with non-algorithmic methods, a few of the student’s drawings and ideas are cited as inspiration for the proposals presented here.

Figure 16.0: The sea dike in Wilhelmshaven is a landscape characterized by the minimalist, engineered geometries of the dike on the one hand, and the dynamic processes of the Jade Bay‘s tidal flat on the other.

16.2. Wilhelmshaven Case-Study Background

Landscapes experience constant change due to a combination of natural and human induced processes. Few locations in Germany have experienced as much change in the last centuries as the landscape around Wilhelmshaven on the Jade Bay (*Jadebusen)* in northwestern Niedersachsen. A thousand years ago, the land to the south of the future city was fertile farmland with small villages, until a series of storms in the late Middle Ages catastrophically flooded the landscape as much as 30km inland. An ongoing battle between the local farmers and the sea ultimately reached a truce in 1850 when the Jade Bay achieved its current dimensions.[2] (Fig. 16.1) This reclamation of the land ceased when engineers recognized that the catastrophic creation of the sea inlet had created a deep-sea channel, kept free of sediment through tidal

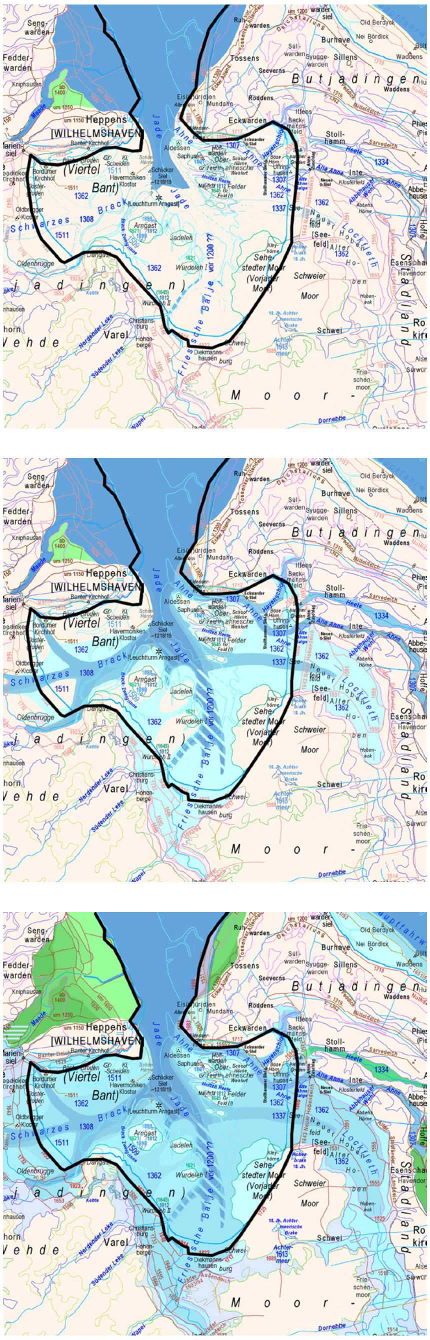


Figure 16.1: The landscape of the Jade Bay is young and dynamic and has changed dynamically in the last centuries. The upper image represents the coastal extent in the middle ages, while the second represents the sea intrusion following the Marcellusflut in 1362. The maximum extent of flooding was reached by the 1500s, when the area was slowly reclaimed until reaching its present extent (marked in black) in the mid 19th century.

action, and which offered the potential to create Germany's only deep water shipping port. (Fig. 16.2) After a laborious process, a new port was hewn out of the ground in this inhospitable corner of Germany, along with a new town named after Wilhelm, the recently unified Germany's first Kaiser.[3]

Wilhelmshaven itself was not designed or conceived with a multiplicity of actors, social groups, or economic goals in mind. Like the engineered infrastructure designed to keep the encroaching sea at bay, it had one intended purpose—to support the military dominance of Prussia and later unified Germany's naval ambitions. In the first decades of its life it grew at an exponential rate, stabilizing at a population of around 70,000 after the first World War, and quickly growing to over 130,00 under the militaristic buildup of the National Socialist regime.[4] After the thorough defeat of the German war machine in the second World War, this reliance on a single industry paralyzed the young city's ambitions and like many towns boomtowns, it experienced the inevitable bust, and since 1970 the town has experienced one of the sharpest declines in population in western Germany.[5] In recent years, the port city has been trying to reinvent itself as a smaller, more compact, but also economically more diverse regional center, and as a touristic gateway to the popular Ostfriesland region. As such, and despite the population decline, the city has focused on an ambitious redevelopment of the city's southern neighborhoods between the historic center and the Jade Bay, not only with new housing and spaces for businesses, but by rethinking the potential to develop the open spaces between the former port and the sea.[6] [7]

One of the most significant of these open spaces occurs on the sea dike between the Jade Bay and several of Wilhelmshaven's harbors. The harbors between the Jade Bay and the city center, closed to the public during the city's heyday owing to their military functions have since become public water bodies and the land around them is in a process of redevelopment. The dike itself, named the "Fliegerdeich" due to its former use as a military air landing strip, has also since been demilitarized and is now a popular destination both for local residents and tourists. The northeastern parts of the dike closest to the city center contain lively spaces, cafes, restaurants, hotels, and museums, but as one moves to the southwest, the landscape gradually gives way to splendid isolation. Along its entire length it is bounded by the Wattenmeer National Park, an ever-changing landscape of great scenic, cultural, and ecological value.

16.3. Coastal Classification of the Jade Bay

Before adopting an approach to the Fliegerdeich site, it is important to understand the dynamics at play in the Jade Bay near Wilhelmshaven. Coastal environments are part of complex, dynamic systems with a multitude of processes at play shaping and reshaping the interface between land and sea. Geomorphologists however, have devised several different classification schemes to simplify a reading of a coastline. Common classification schemes look at the sediment budget at a coastline, tectonic trends, as well as the effects of wave action and tides. Two common schemes include:[8]

> Erosional vs. Depositional Coasts: Erosional coasts lose more sediment than they gain, while a depositional coast gains more than it loses. Erosional coasts often have features like sea cliffs, while depositional ones have mudflats, salt marshes, and barrier islands.
>
> Submergent vs. Emergent Coasts: Relative sea-level is rising on a submergent coastline, while in an emergent coastline, relative sea-

level is falling. Climate change and tectonic activity affect these variables.

Much of Germany's North Sea coastline can be classified as a submergent, depositional coastline. Despite the fact that the landscape was flooded after the last ice age, and that relative sea level is increasing, the continental shelf here is relatively flat, leading to an ambiguous boundary between land and sea. Tidal action, with a small input of sediment provided by rivers such as the Ems, Weser, and Elbe, creates landforms in the form of dunes, barrier islands, and tidal flats, which are generally being created faster than erosive processes can remove them.[9] Occasionally, however, the relative gains of land that nature makes against the sea are lost through powerful storm floods, such as with the creation of the Jade Bay. The landscape here is also strongly influenced by tides, creating an ambiguous topological relationship between land that is part of a barrier island system at high tide, but connected to the mainland at low tide.

The landscape around Wilhelmshaven is also part of the larger Wadden Sea/Wattenmeer biosphere, described as "the largest unbroken system of tidal sand and mud flats worldwide with natural dynamic processes proceeding in a widely unimpaired natural state"[10] extending from the the mouth of the IJsselmeer in the Netherlands to about halfway up Denmark's Jutland Peninsula. (Fig. 16.3) It is considered one of the most important habitats for migratory birds in the world as well as a rich resource for aquatic life, with ecological connections in a web extending much further afield, linking the European arctic to Canada and Africa.[11] It is interesting to note that despite its importance as habitat for numerous animal species, its importance for humans has been marginal and historically few large towns developed along this coastline due to its unstable character on the one hand and the shallow continental shelf on the other, making natural harbors almost non existent.

The creation of the sea dike in Wilhelmshaven, which is part of a much longer system of dikes along much of the Lower Saxon coast that has been progressively constructed since the Middle Ages, along with the construction of the massive, artificially excavated deep-water harbor of Wilhelmshaven itself in the late 19th and early 20th centuries, can be seen as a project of human defiance in the face of these natural forces. (Fig 16.4) The

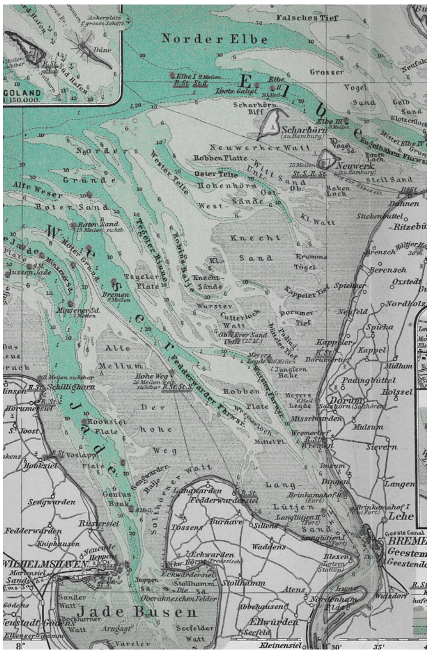


Figure 16.2: *(above)* Bathymetry of the North Sea near the Jade Bay, with deep water channels demarcated in blue. The underwater survey revealed a unique natural condition with deep water close to land, leading to the city's founding in the late 19th century.

Figure 16.3: *(below)* The Wadden Sea landscape with areas of mud flats shown in drak grey, and slat marshes in yellow. Drawing by Marianne Cabanis, Aranzazu Ceron Herrera, Lenka Podolakova, Mengyao Xing, based on data from Wadden Sea world heritage site.

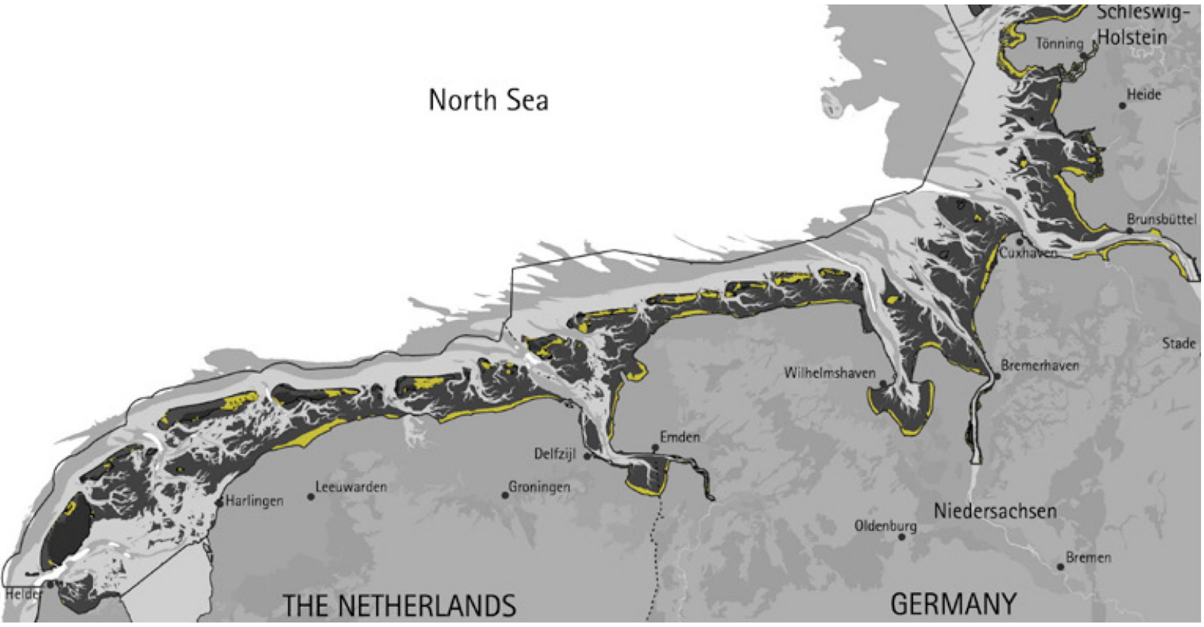


Figure 16.4: *(above)* Sea and river dikes characterize almost all of Lower Saxony's coast, and the lower reaches of most of its rivers. The dikes protect humans from disaster's, but change the fundamental nature of the water-land interface and its corresponding ecologies.

dike changes the topologically ambiguous coastal ecotone of a depositional, submergent coastline into its opposite, the hard edge of an erosive, emergent coast, typical of mountainous parts of the world undergoing tectonic uplift. The deep-water harbor is also an artificial feature more typical of geomorphological situations along steep mountainous coasts, or where steep valleys were flooded after the last Ice Age.

16.4. Design Approach

The area around Wilhelmshaven's harbors, formerly dedicated to military use but now in need of urban renewal strategies, should become the focus of concentrated development according to the city's long-term development plans. The dike landscape between the city, its harbors, and the Wattenmeer National Park / Wadden Sea Heritage Site should become the new focus of the city's overall public open-space strategy. The area should be redeveloped with the following goals in mind:

1) Increase the structural integrity of the dike near the city and mitigate erosive forces directly adjacent to the dike in the light of potential sea level rise.
2) Increase the species diversity and habitat quality adjacent to the dike by introducing ecological niches and an enhanced intertidal zone.
3) Create safe and protected offshore habitat and nesting grounds for migratory birds.
4) Enhance the usability of the dike as Wilhelmshaven's premiere open-space, creating a diversity of programmatic niches for residents and visitors
5) Increase Wilhelmshaven's visibility as a gateway to the Wadden Sea heritage site and as a stopping point on the coastal cycling route along the North Sea coast.

The reading of the sea dike as a kind of artificial mountain range extending for hundreds of kilometers to the east and to the west of Wilhelmshaven forms the basis of the design expression. Here at the center of the Wadden Sea biome and in the largest city immediately adjacent to the natural World Heritage Site, the relentless horizontality of the sea dike expresses itself for a few short kilometers as a piece of land art with a mountainous profile. (Fig. 16.7) This artificial topography is constructed with dredging material

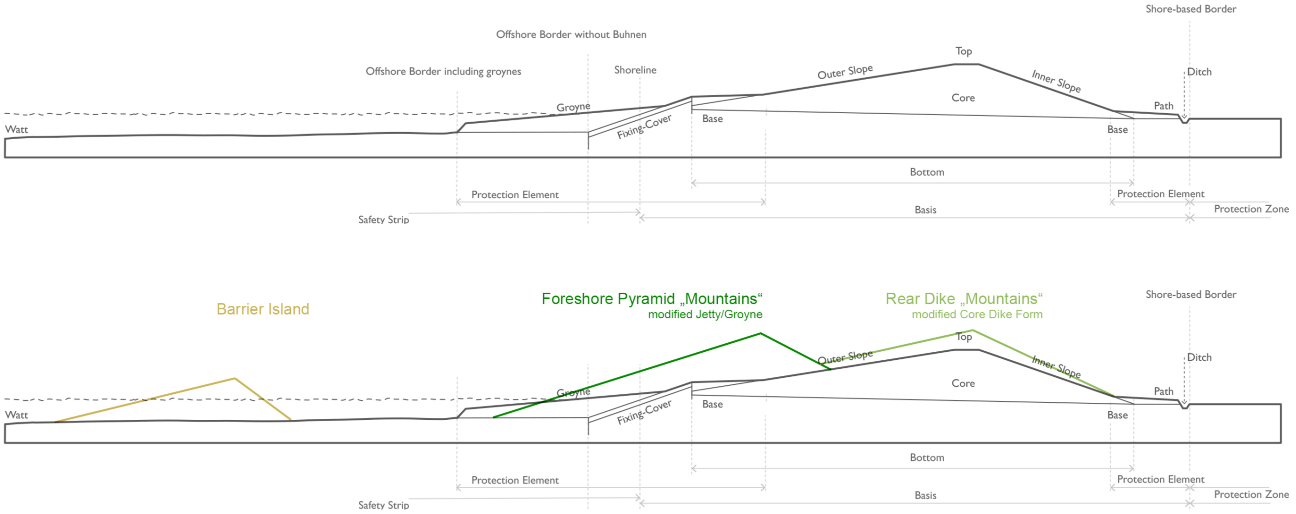


Figure 16.5: *(below)* Typical sea dike profile near Wilhelmshaven with proposed modifications to this dike typology along the Wilhelmshave sea dike. Drawing top, Sebastian Beutel with data from NLWKN 2007, 44. Drwaing bottom - modifications by Joseph Claghorn.

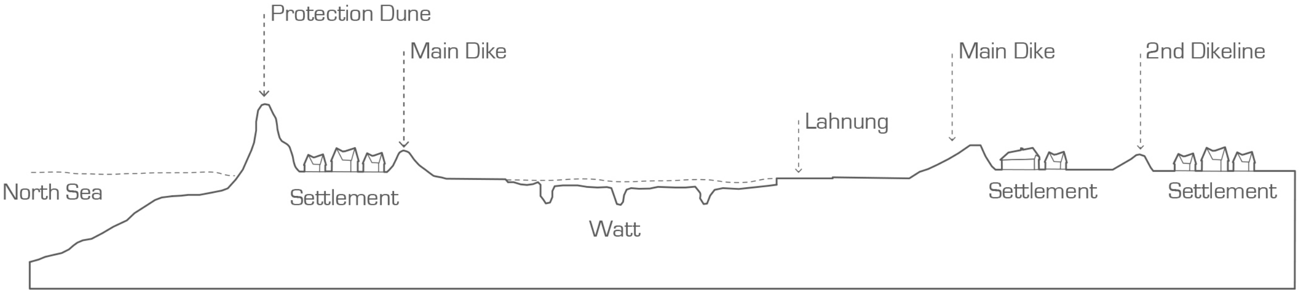


Figure 16.6: *(above)* Coastal protection is a many layered system, with natural barrier islands and dunes together with artificial dikes and Lahnungs working together to blunt the impact of powerful winter storms.
Drawing Sebastian Beutel with data from NLWKN 2007, 14.

obtained by an ongoing project to expand Wilhelmshaven's standing as a deep-water port capable of handling imports and exports from the world's largest ships.

The proposed topography of the dike itself has two types of forms (see Fig. 16.5) First, a series of pyramidal "mountains" strengthen the dike's foreshore and replace the jetties or groynes intended to push the strong tidal toe current at the foot of the dike away so as to reduce erosion and increase the dike's overall structural integrity. The "saw-tooth-like" pattern produced also reintroduces areas of deposition, creating habitat niches for plant and small aquatic species at the foot of the dike, and for human users along the upper reaches of the dike. Next, a second series of "mountains" with a rhythm dependent on the rhythm of the jetties/pyramidal "mountains" at the dike's front are created. These "mountains" enhance the dike's protective function, but also introduce a degree of formal variation to transform the minimalistic dike into a sculptural piece. These rear "mountains" also structure paths of circulation from the dike's water edge to the top of the dike. From here, users can visit viewing platforms, return to the water, or move to the dike's rear edge where the entrances and exits are found.

In addition to the two types of forms in the dike proper, a third series of forms comprising a series of offshore artificial "barrier islands" break up larger waves in the bay before they threaten the dike and are also intended to serve as permanently protected habitat for indigenous and migratory seabirds. (see fig 16.5, 16.6) These islands can be seen as land art pieces in their own right, with flocks of birds becoming part of a sort of living sculpture in the sea. To test these design ideas, algorithms are introduced to test variations of repetitive, largely geometric, constructed design measures, along with other algorithms to explore emergent form, including how constructed interventions will interact with natural forces through time to reshape the landscapes adjacent to the dike.

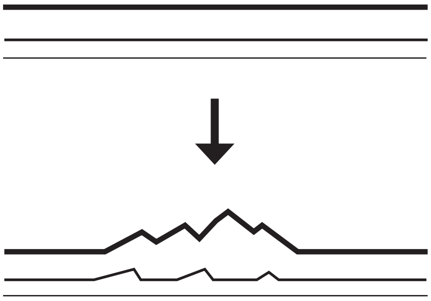


Figure 16.7: *(above)* Concept drawing. The relentlessly linear dike landscape of Lower Saxony's coast, acting as a kind of artifical dune or mountain, is reinterpreted in the Wilhelmshaven to improve the dike's protective function, to diversify human and natural ecologies, and to serve as a new landmark for the city.

16.5. Algorithmic Landforms – Deterministic Geometric System

The goal of the first set of algorithms is to create a deterministic process linking the various elements of the proposed dike landscape together such that as many elements as possible can be generated with a minimum amount of initial user input. Variations of the forms can then be studied and tested. The rhythm of the forms is derived from the observation that along the dike as now constructed, a series of jetties or groynes along the structure to minimize the toe current gradually increase in size and structural weight as one moves from west to east from the shallowest reaches of the Jade Bay—where currents are relatively weak—to its mouth, where the current has become very strong. (see Fig. 16.8) In this proposal, as introduced in the previous section, the jetties are transformed into pyramidal "mountains" whose form pushes the water away from the dike, creating niches of calm water next to the dike in the process. It is unclear how big these forms need to be, however, and several alternatives may need to be tested. For this reason, developing a model with a parametrically changeable set of relations can be argued for.

The algorithm takes a single user defined curve as an initial input, which corresponds to the back of the dike as it now stands. From this, the algorithm first generates the pyramidal forms at the front of the dike that serve as the "jetties." The user can change the rhythm of the pyramids as well as the amount of protrusion into the bay so that they gradually increase in size corresponding with the increase in toe current. (Fig. 16.9) Next, the algorithm creates the topography of the rear "mountain chain" that expands the dike's core and structures pedestrian and vehicular circulation (for maintenance and rescue vehicles) along the dike. This rhythm is dependent on the rhythm of the foreshore "mountain chain." Lastly, also dependent on the rhythm of the pyramidal jetties, the algorithm creates the offshore "barrier islands" which can brunt the impact of waves during major storms, and which also are intended to be colonized by sea birds.

Once these fundamental geometries are drawn, first in 2D, a second series of algorithms generates the 3-dimensional topography. The topography above water is generated through a process explained in the next section, while simply offsetting some of the fundamental forms from the previous step serves to generate topography in the intertidal zone. A second alternative would be to make a more sculptural topography in the intertidal zone using a process similar to §A7.2 with a high degree of random variation at each underwater step. The effect would be that minimalist triangular forms

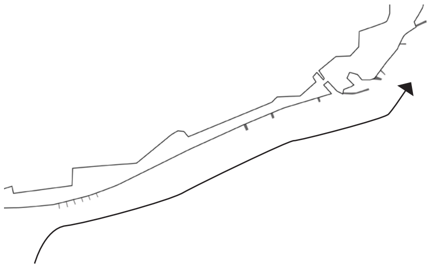
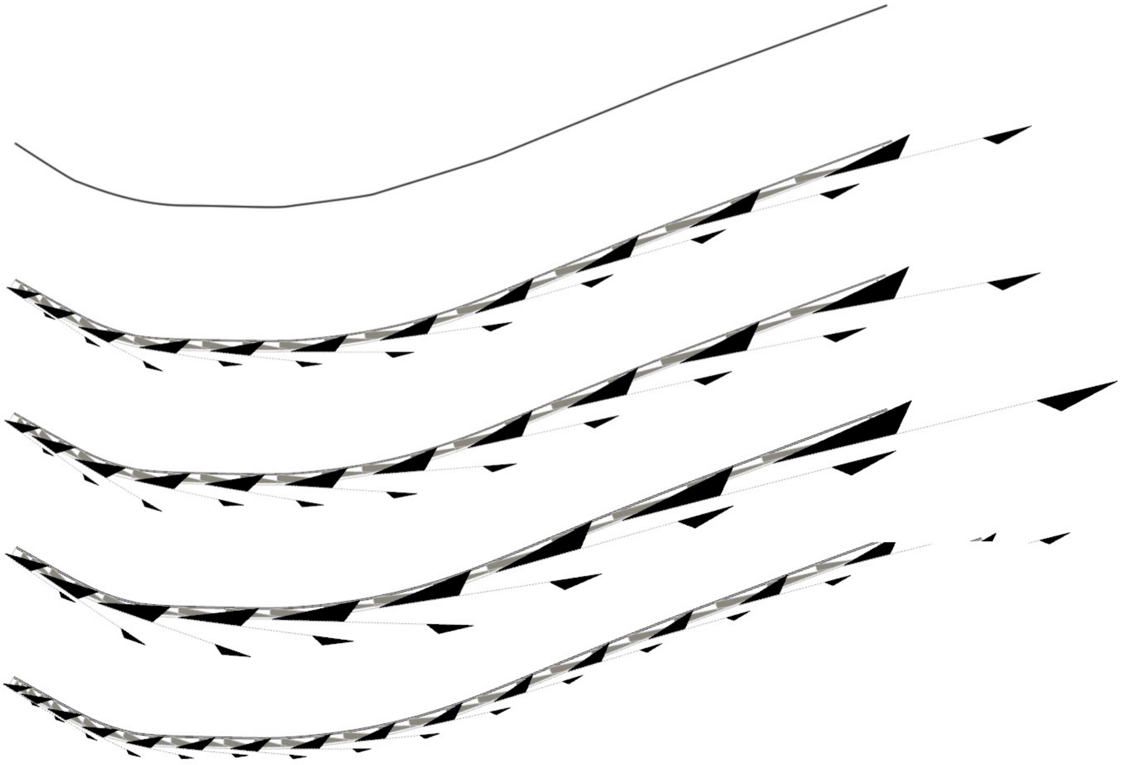


Figure 16.8: *(above)* Jetties increase in size from west to east in response to stronger tidal currents near the dike.

Figure 16.9: *(below)* Potential variations of the dike's forms and parts. Using a single input curve (top), variations are generated with the foreshore mountains



dominate the landscape during periods of high-water, while more “baroque” and dynamic forms are revealed during periods of low tide. (see Fig 16.12) These folded forms in the intertidal zone increase the surface area and potential niches where certain species might be able to establish themselves.

16.6. Landform shape from the topological skeleton

In the previous case study, the process of modeling the topographical surface or mesh from existing data, such as contour lines, was introduced (§15.5). Here it was shown how using the “skeleton lines” of a terrain—the lines corresponding with the ridges and valleys in the landscape—could improve the process of terrain modeling. “Skeleton lines” can also be used to simplify the process of three-dimensional landform creation in a design context, where the user inputs a two-dimensional outline of a shape to be modeled with nearly any conceivable form or dimensions and a three dimensional terrain can be generated from this with only a few additional inputs, such as landform slope and landform tilt. In this particular case study, the landforms along the dike are derived from the two-dimensional footprints with such a process.

To key to this process is to find the “skeleton lines” of a shape, lines known in topological mathematics as the *medial axes.* Both regular and irregular shapes have such axes except for the perfectly symmetrical case of the circle, where the medial axis is a single point. (Fig. 16.10) Various methods have been derived to find the *medial axis*, but the simple and effective method used here is taken from a description devised by Daniel Piker.[12] The method takes the outline of the shape to be converted into a topography, and dives this outline into a number of points, with more points creating greater accuracy in the end, but using more computational resources. A “Voronoi diagram” is then drawn (§A8.1) with each of these points designated as the center point of a Voronoi “cell.” (see Fig 16.11) the edges

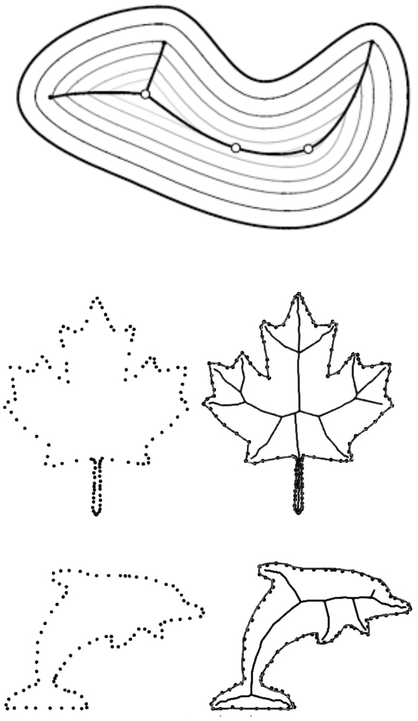
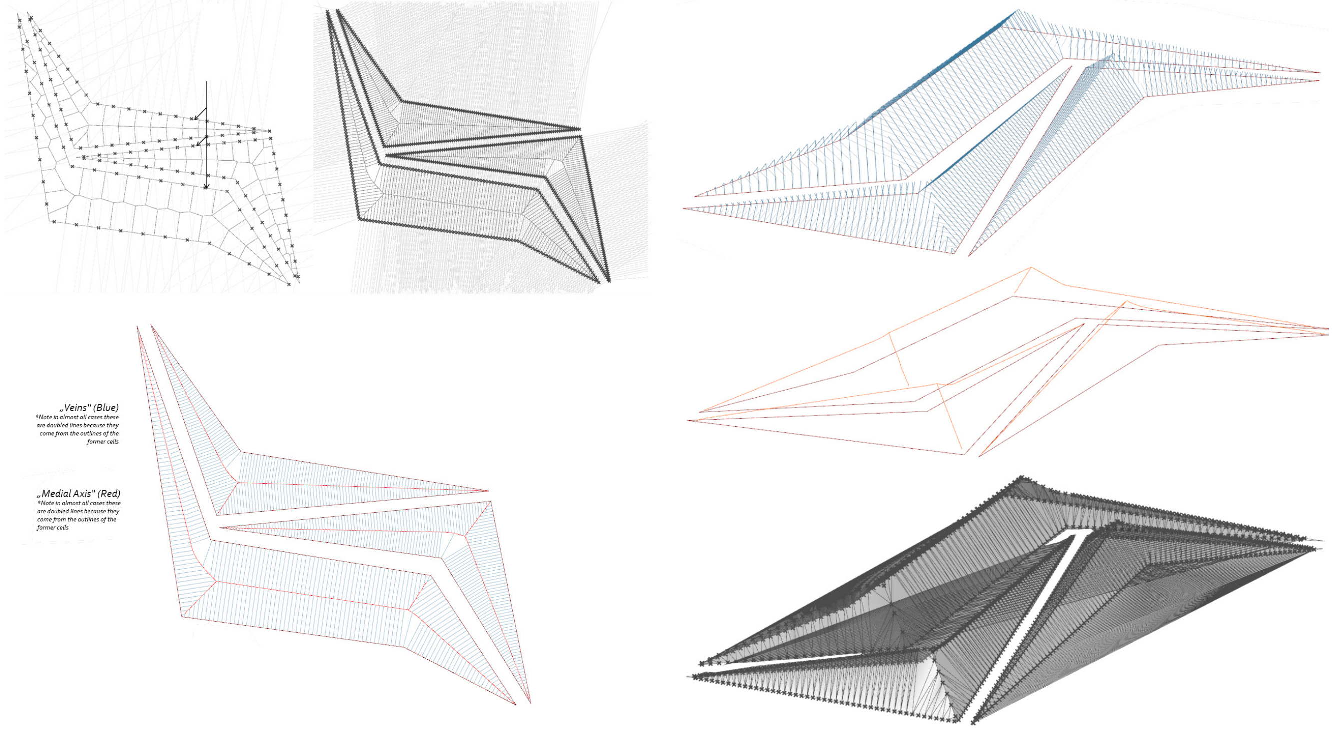


Figure 16.10: *(above)* Irregular shapes with their medial axis.

Figure 16.11: *(below)* Steps in algorithm to create terrain from medial axes.



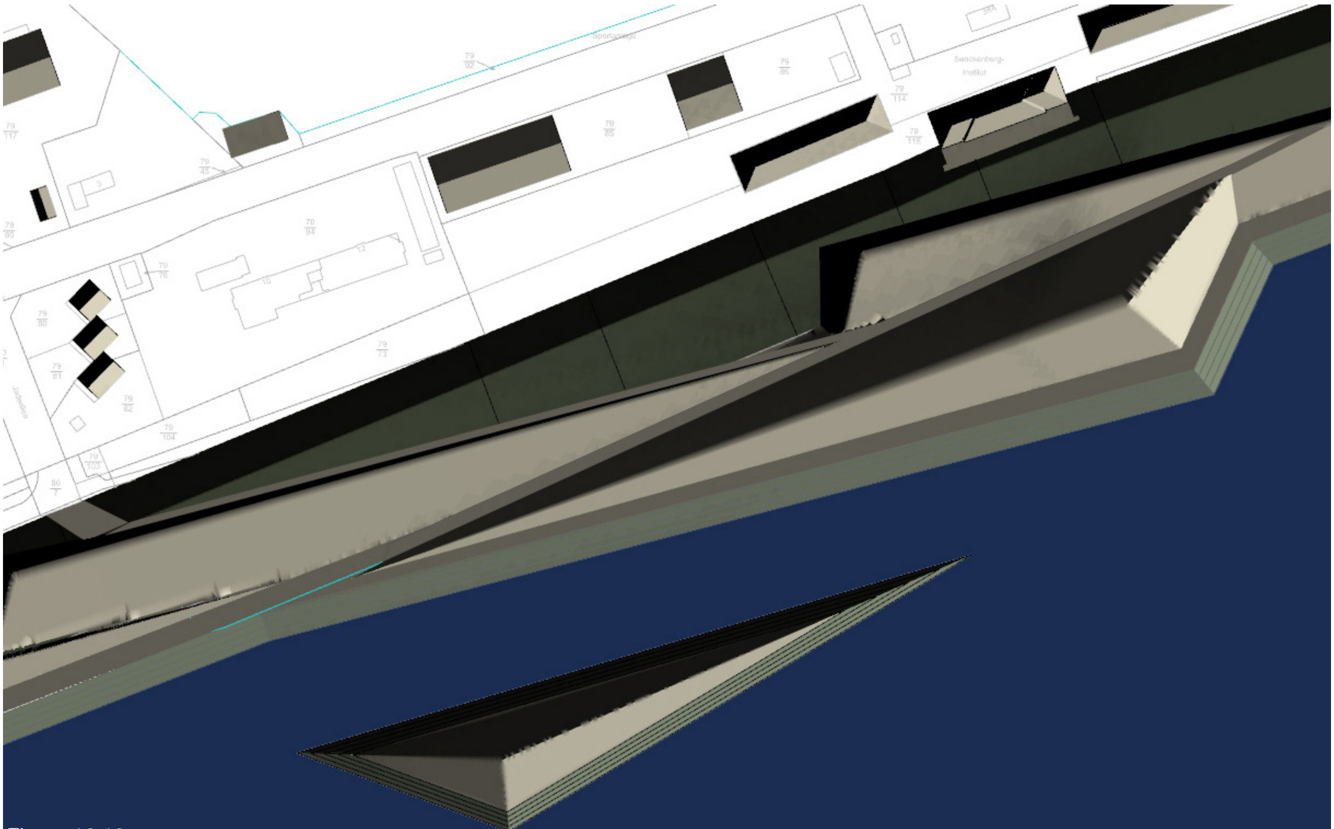


Figure 16.12
Typical "Module" Plan View

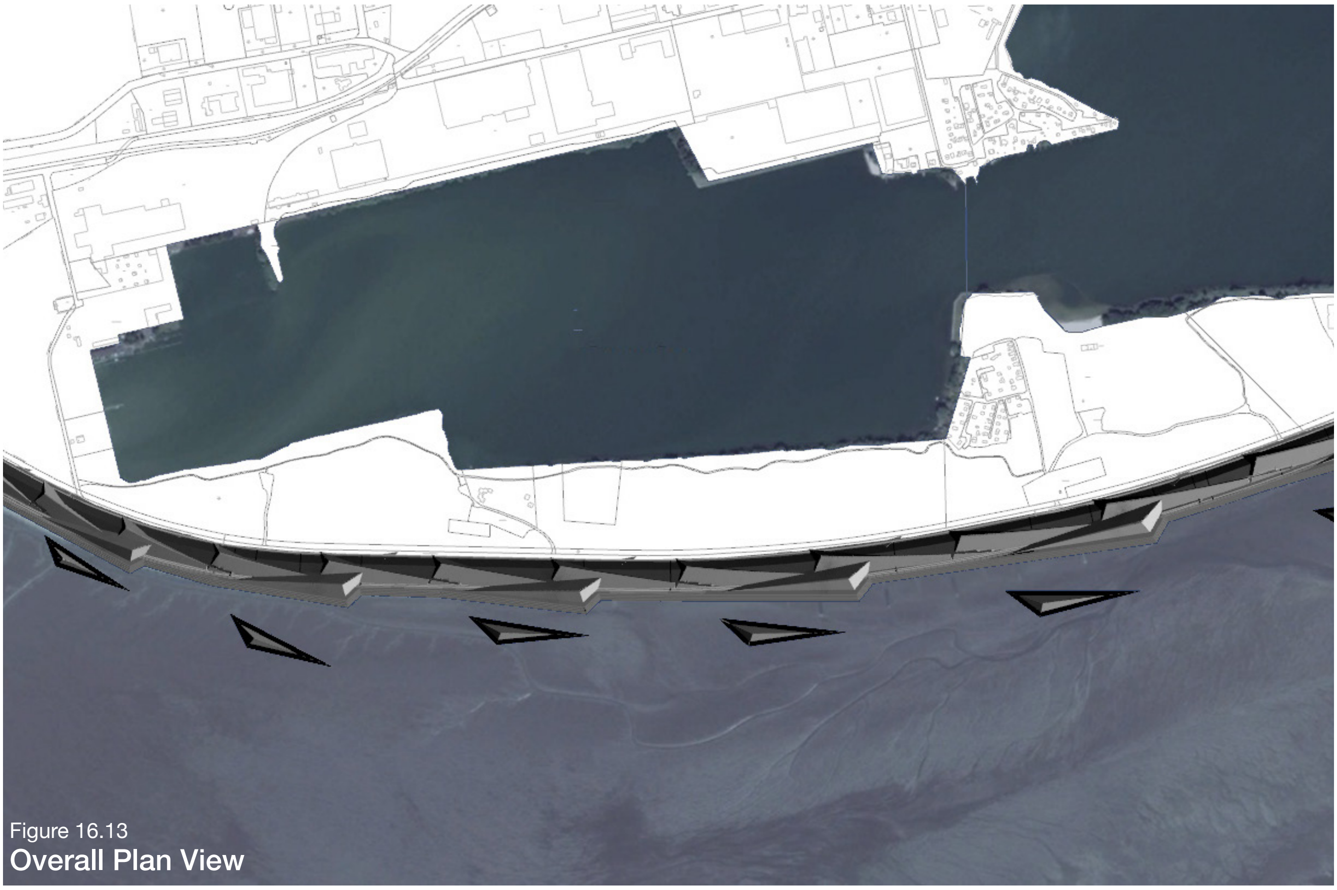


Figure 16.13
Overall Plan View

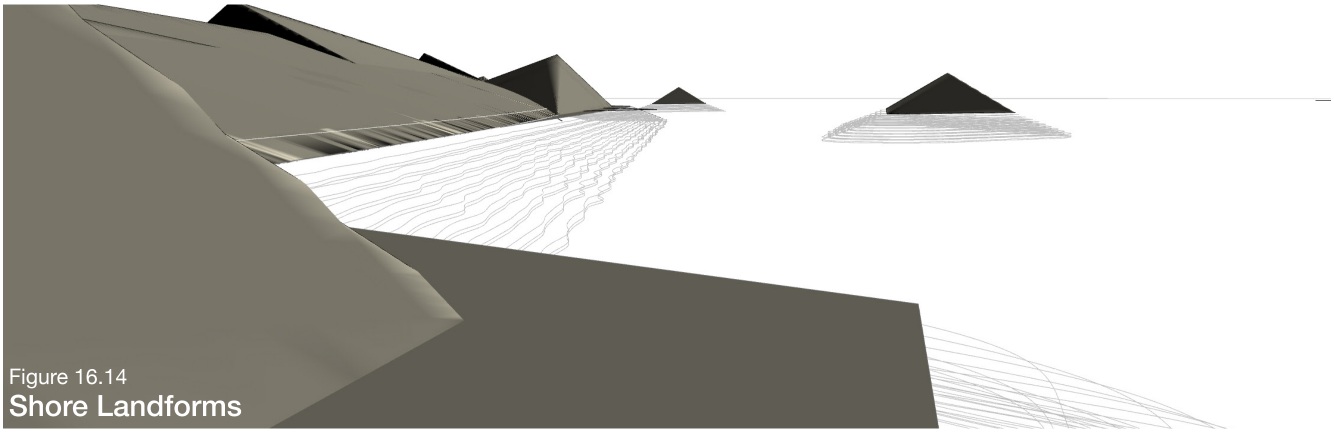


Figure 16.14
Shore Landforms

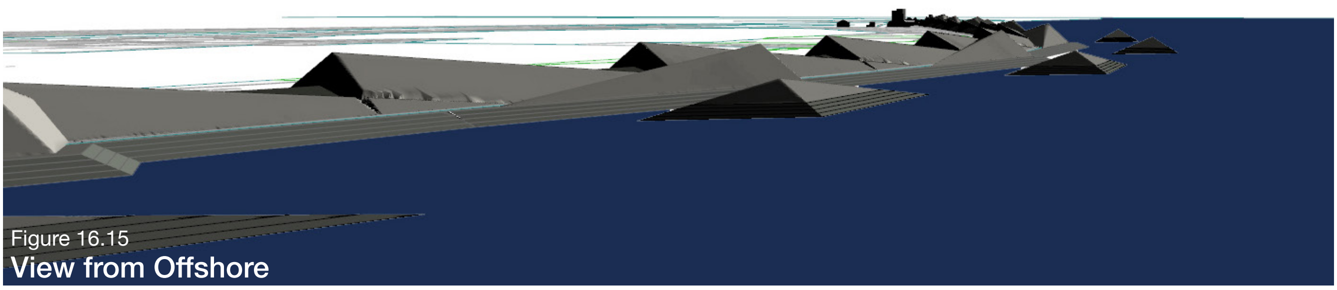


Figure 16.15
View from Offshore

of the Voronoi diagram outside of the original shape are then discarded. The remaining lines are then exploded, that is they are divided into smaller segments at each vertex of the Voronoi diagram. These lines are then reclassed based on whether they touch the original form or not. Any line not touching the original form is part of the medial axes, while lines touching the edges comprise the topological skeleton's "ribs."

The three-dimensional topography can now be generated by simply measuring the distance of each segment's end points to the original outline shape. The points are then moved in the Z axis an amount corresponding to this distance multiplied by an adjustable parameter relating to the landform's slope. Points on the shape edge, with zero distance from the edge, are not moved at all in the Z direction. Additional adjustments can be made to the algorithm to produce outcomes with more complex slope rules, such as a form with a steeper slope on one side compared to another, but such methods will not be elaborated here. Using one of various terrain surface or mesh generation techniques, the algorithm can now generate the three-dimensional form by using either the medial axes, the "skeleton ribs," or a combination of both.

16.7. Algorithmic Landforms – Emergent Sand Dunes

Behind the dike, in land intended for a new public park, a second landform strategy is explored. In contrast to the formalist, deterministic logic of the engineered dike landscape, the landforms in the public park are shaped by the logic of an emergent process. The idea for a park itself with forms inspired by coastal dunefields on the Wilhelmshaven site was initiated and proposed by a student team in the Fliegerdeich studio in 2016, Weixiao Xie and Mengyao Xing, but the design and implementation here is the work of

Figure 16.12: *(opposite page, top)* Detail of one of the dike's modules. Paths near the pyramidal „mountains" were post-processed in photoshop to help understand the circulation system.

Figure 16.13: *(opposite page,bottom)* Overview plan of the algorithm's results, with an aerial image of the mudflat to show how new forms fit with existing tidal dynamics. (§16.9)

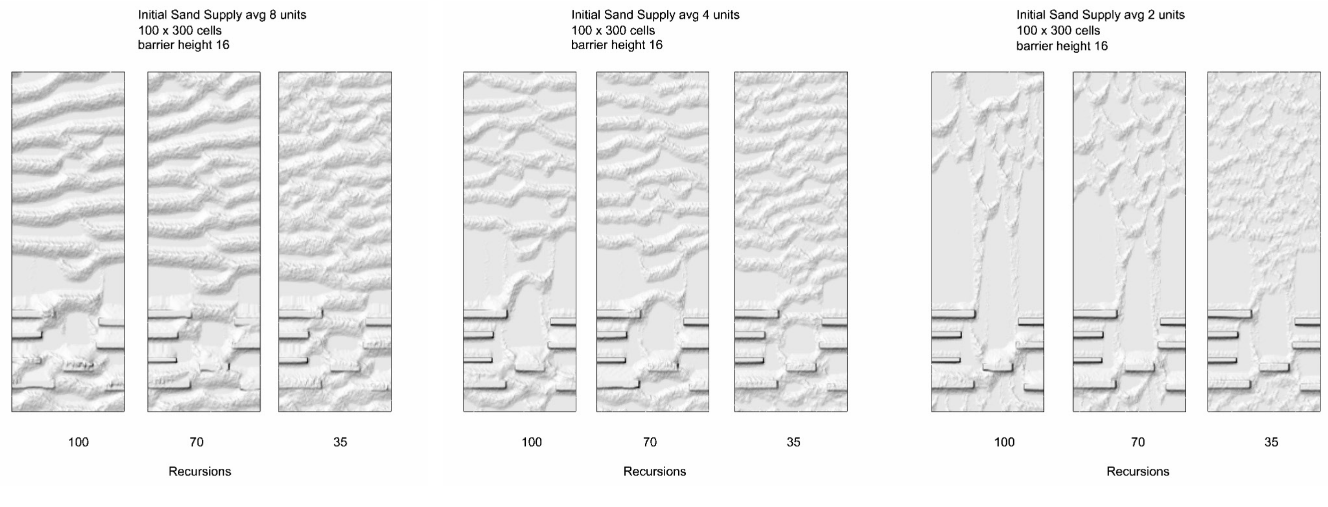
Figure 16.14, and 16.15: *(above)* Perspectives of landforms produced through the algorithmic process described in §6.5 and §6.6. No post production has been done on these images and all three-dimensional forms are generated according to the algorithmic production rules so that the viewer can clearly see the limits and potentials of the algorithm.

Figure 16.14 at top represents a perspective on the dike's main foreshore path, while Fig 16.15 below this represents an overall impression of the dike's mountain chain, the first view a bicyclist approaching Wilhelmshaven along its dike would experience the author. The development of the algorithmic method was informed by an excellent study of sand dune morphology by two students in the Landscape Urbanism program at the Architectural Association in London, Anastasia Kotenko and Niki Kakali who in their "Aeolian Sand Odyssey," under the direction of Alfredo Ramirez and Eduardo Rico, adapted the logic of Werner's cellular automaton to various irregular starting conditions, allowing also for the introduction of fixed barriers to sand movement which would in turn have an effect on the evolution of the sandscapes morphology.[13] It is unclear what the exact algorithmic methodology they used was, but a fairly simple method is proposed by the author here, which may or may not share similarities with Kotenko and Kakali's method.

In this method, the landforms evolve in a cellular sandscape based on the algorithm described in §A13.2 with two major variations. The first variation is that now wind direction can be set according to a variable parameter, and the direction of the prevailing wind can also be altered from one run of the algorithmic loop to the next. A change in the wind direction alters the order in which sand moves from one cell to its neighbors in Phase II of the script described in §A13.2 A wind from west to east, for example, moves sand from one cell to the next in the X direction only, while a wind from the southwest to the northeast moves sand to the cell in a diagonal direction.

The second major variation in this script's logic is that obstacles are now introduced into the sandscape. The sandscape here is based on a one-meter grid, with a single "stack" unit of sand representing 20cm of material to maintain the 1:5 ratio used in §A13.2. To account for obstacles in the dune field, the footprint of the obstacle—a wall, raised path, a building, or another type of obstruction—is drawn as a two-dimensional curve. Any grid points within this curve are sorted through a dispatch component into a second class of geometry. Instead of receiving an initial random and ultimately variable height value based as the sand cells do, they are assigned a fixed minimum height value to certain cells based on the presumed height of an obstacle. These cells cannot lose height through the avalanching process as described in §13.2, and can never have a stack value below the fixed obstacle height, but sand is allowed to accumulate on top of them. They also cast a wind shadow just as a sand landform would with a shadow angle of 15° and interact with the dunefield in all other ways. The results of a several small initial test are shown in Figure 16.6. Barrier walls with gaps towards the middle are placed towards the bottom of the simulation. Three different

Figure 16.16: *(below)* Studies of an evolving sandscape with a series of linear barriers. Each study represents a variable amount of initial sand.

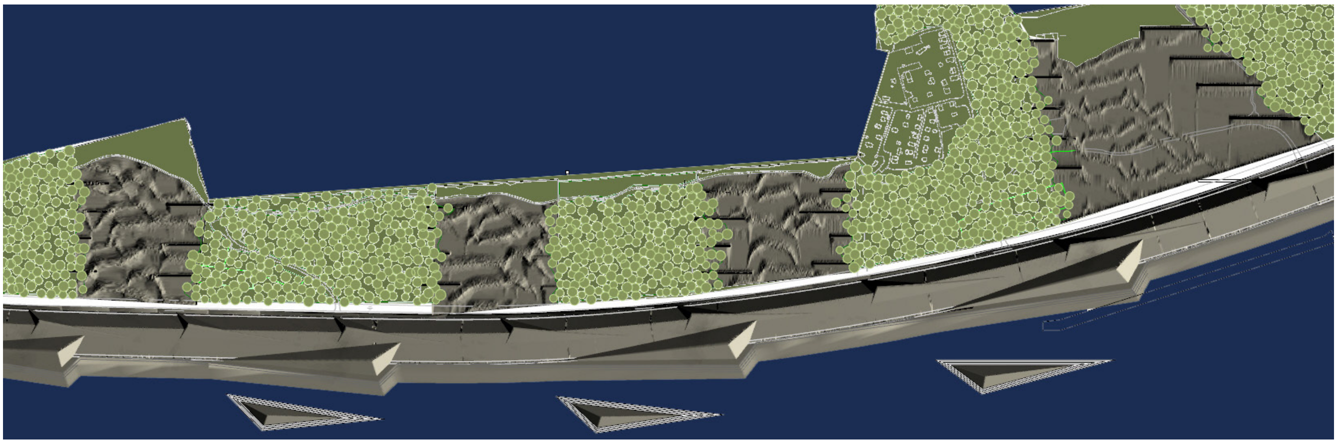


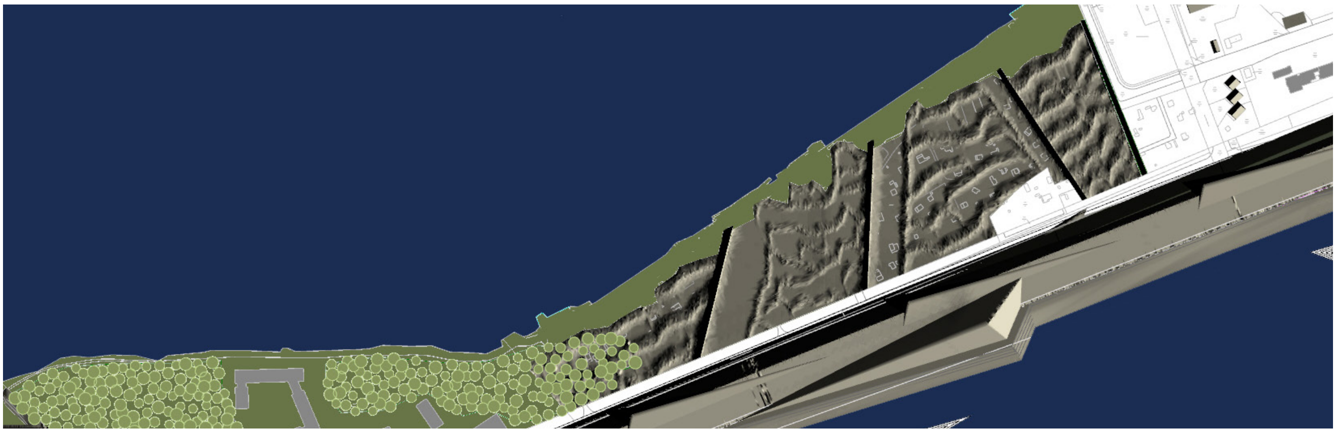
amounts of initial sand are tested, and the evolution of the dunefield over a period of 35, 70, and 100 recursions is shown.

Next, this methodology was applied to the whole site. Here, two different strategies for evolving the dunefield were tested. In the western part of the site, the park alternates between forested areas and open dunefields. The rhythm is determined partly by existing conditions and partly by the rhythm of landforms in the proposed alteration to the adjacent dike landscape. On the interface between forest and dunefield, a series of stabilizing walls parallel to the water and perpendicular to the anticipated prevailing wind direction are erected. The stabilization here will help trees become established, which will have the further effect of increasing the stability of the dunefield at the edges through time. In the four clearings shown in the top image of Figure 16.17, the amount of initial sand in the sandscape varies from west to east leading to the most significant changes in dunefield morphology. The initial average sand inputs are 2m, 1,5m, 1m, and 0.5m in the various clearings respectively. The form shown in the drawings represent the evolution of the dunefield after 85 iterations. The dunefields could be allowed to evolve naturally through time, or robot controlled construction equipment could grade the site to correspond with the height of the dunes in the Rhino model, representing a speeded up state in the dunefield's long-term elevation.

In the eastern part of the site, a different strategy was used to structure the dunefields, Instead of constructing walls parallel to the sand ridges, here they are generally perpendicular to ridges at a variety of angles. (Fig. 16.7, bottom) These walls represent raised paths of movement through the dunefield, and have an effect nevertheless on the dunefield's longterm evolution. Each larger "cell" created by the paths has a variable amount

Figure 16.17: *(below)* Evolved sandscapes applied to the Wilhelmshaven site. The image at the top towards the west of the site has four areas with barriers parallel to the prevailing wind direction, while the four sand regions to the east have barriers gernally perpendicular to the wind direction.





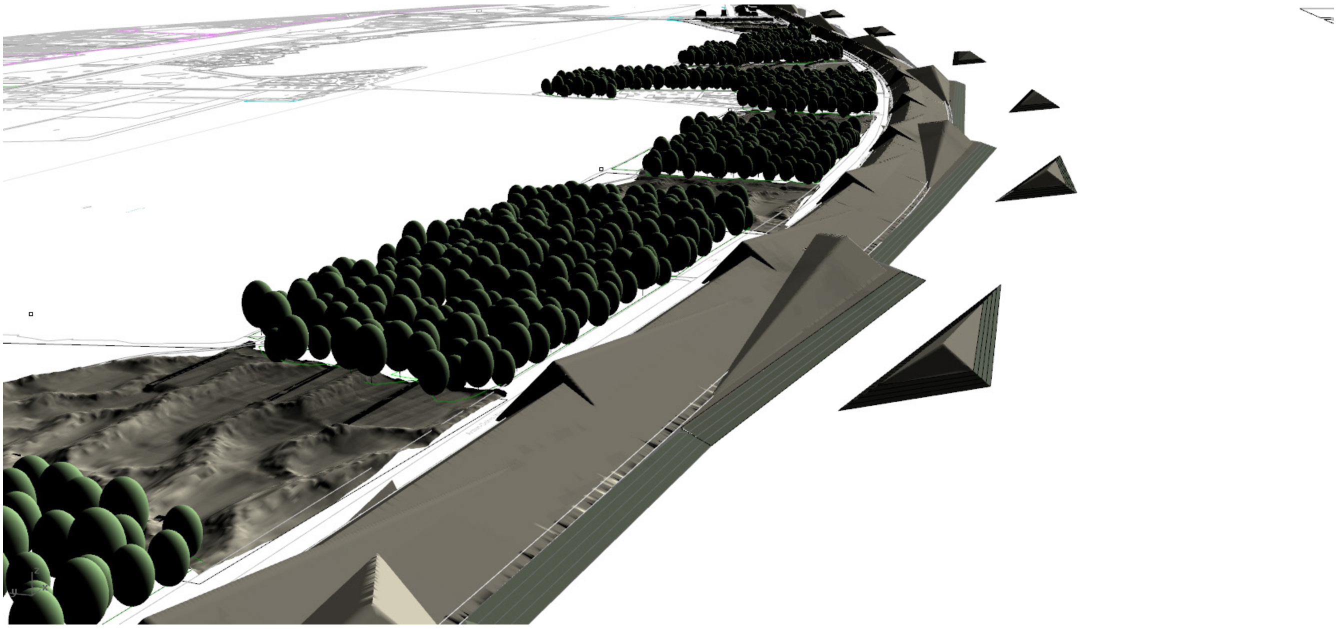


Figure 16.18: *(top)* Bird's eye view of the proposed landform interventions as described in this chapter.

of initial sand, leading again to changes in the long-term evolution of the dunefield's morphology. While the "dunes" here could be allowed to evolve through time as the dunes in the western part of the site, here it is proposed to construct the landforms as artificial dunes, planted with lawns, to increase their usability by human users and allow for the insertion of various types of program. Here then, the designer uses the logic of a natural process to in the end create fixed or "frozen" forms with the morphology of a thing found in nature.

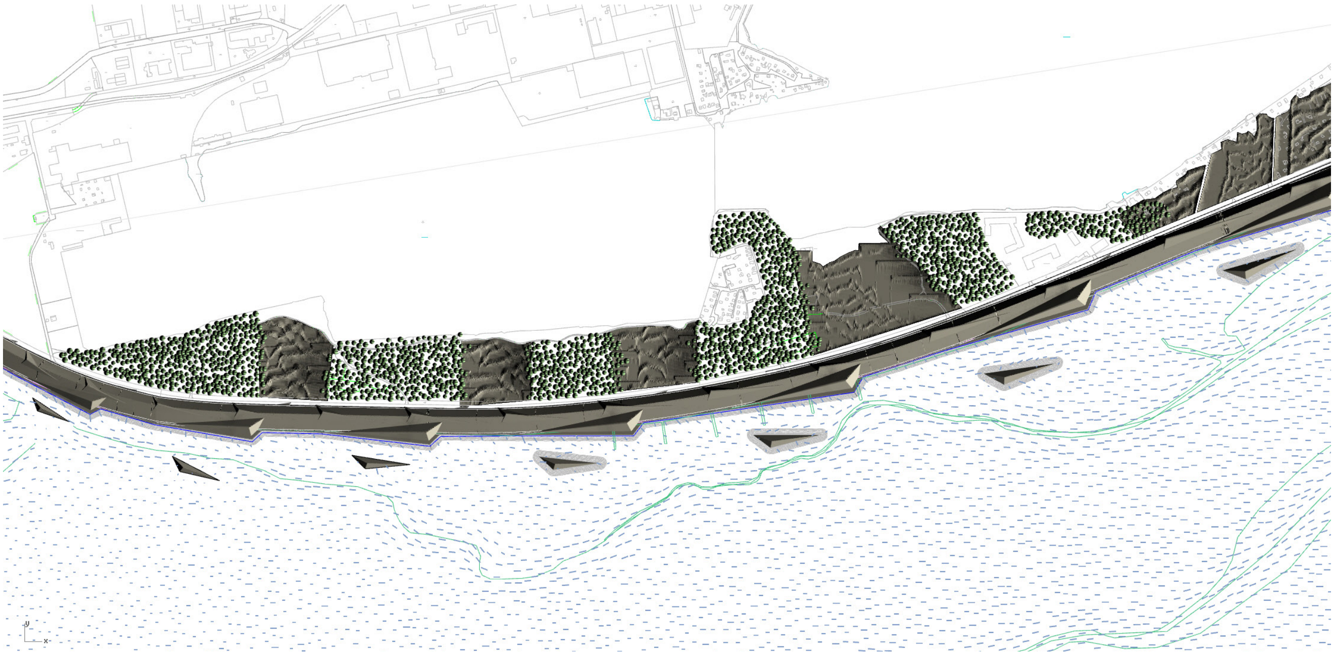
16.8. Fluid Studies

A final major goal of this case study was to explore the implications of the various re-engineered dike and barrier island forms introduced in §16.5 and to see what their impact would be on the tidal dynamics and on the processes of sediment transport and deposition near the dike. The goal was to speculate on how new mudflat channels might form, where new ecological niches, such as salt marshes, might be able to establish themselves, or where waterside areas usable by the dike park's users, such as sand beaches, could be constructed. This information would be used to test the various configurations proposed in §16.5 in an attempt to choose the best or most performative series of forms, or to change the underlying topological relationships between elements entirely. This goal was inspired by preliminary results other landscape architects have had with experimenting with computational fluid dynamics systems, notably with Aquaveo, ANSYS, and Autodesk CFD as introduced in §11.4. The author experimented with several programs, notably Aquaveo and RhinoCFD, but over the course of this research, however, it slowly became apparent that a moderately convincing study would not be possible within this dissertation's scope, and a much more focused research program would need to be developed to test the applicability of such models in landscape architectural projects. The author proposes several reasons why this is the case, and echoes many of the findings Roberts and Moosavi who reported on some initial successes with a comparable CFD study in the context of landscape architecture, but who encountered many of the same problems.[14]

A first barrier is encountered with selecting and learning the appropriate software. Many computational fluid dynamic programs are available, but these are targeted towards engineers working with highly regulated workflows where variables can be tightly controlled, such as analyzing the movement of fluids in machines and pipes, or the movement of air around precise descriptions of an airplane or automobile body. In contrast, the systems landscape architects work with are much less precise, and have a much higher degree of uncertainty. The CFD program Aquaveo specializes in situations with higher degrees of uncertainty and riparian, estuarine, and coastal contexts, but as noted earlier, the version of Aquaveo designed for coastal dynamics is very expensive, and trial versions generally have too short of a license period to attain any degree of fluency in the software. Another possibility is using the open-source program Delft 3D, but this program is even more user-unfriendly and requires an extensive amount of prior expert knowledge to operate. In other words, to produce convincing CFD studies for landscape architecture, a committed line of research into this software's potentials would need to procure funding to buy the software with specific goals and expertise in mind, and would require dedicated commitment to learning the software, most likely through professional training courses. This points to a second major difficulty, as noted by Roberts and Moosavi, which is the learning curve for the software, which requires an extensive background in mathematics and physics to understand the variables at play.[15] While it is possible to obtain "results" by playing around with the software, these results are not altogether convincing. Assuming one has a good grasp of the software and its internal workings, a second group of obstacles arises—obtaining precise information with which the model can operate. For the modeling of coastal dynamics in the Wilhelmshaven site, it became apparent one could not analyze just the area near the dike, but that one would need precise bathymetric data for the entire Jade Bay as well as measurements of the currents entering and exiting the water body. Such information is available but to obtain this information with the precision needed for the CFD study, it again is only made available to researchers with a well-defined research agenda.

Ultimately, the task of modeling the water dynamics with a scientifically sound *teleological* process had to be abandoned. For the purposes of representation, however, an adaptation of the algorithm presented in §11.3 was devised for the Wilhelmshaven site. This representation is based

Figure 16.19: *(bottom)* Proposed interventions will have an impact on shore dynamics. The appropriateness of the interventions could be tested with better fluid dynamic models. Here a simple adaptation of §A11.3 shows only general flow directions for representational purposes.



on the observation that perhaps the best representation of the tidal dynamics on the mudflat was expressed through the traces of the channels on the mudflat itself. Translating this information from the site, tracings of these channels are used to define a series of input vectors, which increase in force from west to east. The constructed dike and barrier island landforms provide a second set of vectors which interrupt or resist the flows in the bay. Finally vectors near some of the constructed landforms are manually drawn to indicate a small number of areas where expected movement of water across the flat should be altered. The results of this process are shown in Figure 16.19.

16.9. Reflection

The Wilhelmshaven site is large and complex, and social, political, administrative, and technical factors not accounted for in this proposal would naturally call into question many of the proposals here. Many other factors would need to come into play were this proposal to be seriously developed. The focus with the measures is also, within the scope of this dissertation, focused on expressing a limited number of processes algorithmically, and as a result, design moves which would lend themselves more to an analog approach are not explored.

Regarding the two major series of algorithmically generated landforms, however, several observations can be drawn which contribute to the reflections in the first part of the thesis. The geometric landforms of the dike are generated through a formalist process characterized by a strong interior logic, but their performative aspects cannot yet be determined as the dialogue with their context, the field of information in which they unfold, cannot yet adequately inform the design process, at least algorithmically, and be used to judge the appropriateness of the forms. Were better information on the tidal dynamics available, and had the computational fluid dynamic tests been successful, achieving this goal should be possible. Here this thesis echoes the observation by Robers and Moosavi that "while it is possible to test whether a model or form 'works,' it is difficult to experiment with how systems and forces being simulated can be harnessed for the purposes of performative design outcomes."[16] Regardless, the designer has strict control at all times of the internal relation between forms, perhaps at times too strict, and over the final formal expression. While the algorithm is helpful for initial studies to test variation, as only one of these possible variations would be conceivably built in the end, the overall usefulness of the algorithmic method is unclear. In other words, the forms could just as easily be derived and place based through an analog decision making process.

The second series of landforms are generated through a process, which unlike the engineered dike landforms, have a weak internal mechanism of formation, with the ultimate form emerging based largely on exterior relation. Here the biggest design challenge or difficulty is in determining the arrangement of the forms and structures which bound the dunefield. In this study, the decisions on the placement of barriers, walls, and other control mechanisms of the dunscape were made quickly and without a strong governing logic. Were this project and methodology to be transferred into reality, a more rigorous logic for these elements as well might need to be implemented, as the emergent dune structure itself is not strong enough to organize space in a landscape architectural context. In general, however, the emergence of form in this context, once the internal workings of the algorithm are refined, is a satisfying experience and shows promise for the use of similar methods in other design contexts.

Endnotes

1 „Wer will nicht deichen, der muss weichen,“ English: “Whoever does not want to build dikes must step aside.”

2 David Blackbourn, *The Conquest of Nature: Water, Landscape, and the Making of Modern Germany* (London, W.W. Norton, 2006), 124-132.

3 *Ibid,* 134-144.

4 Stadt Wilhelmshaven. “Entwicklung: Einwohnerzahl Wilhelmshavens seit 1853.” Graphic. (2016). www.wilhelmshaven.de/statistik.

5 Plan-werk Stadt: Büro für Stadtplannung & Beratung. “Endbericht: Gesamtstädtischer Zukunftsdialog Stadtumbau Wilhelmshaven.” (Wilhelmshaven-Bremen: Stadt Wilhemshaven, 2005), 16-30.

6 *Ibid,* 73-76, 92.

7 Rainer Beckershaus, “Die Zukunft liegt im Süden,” (Wilhelmshaven: Initiative Südstadt).

8 R. Boyd, R. Dalyrmple, and B.A. Zaitlin, “Classification of clastic coastal depositional environments.” *Sedimentary Geology,* 80 (1992), 139-140.

9 Jens Enemark, “Executive Summary,” in *The Wadden Sea, Germany and Netherlands (N1314) – Extension Denmark and Germany*. vol. 1 (Wilhelmshaven: Common Wadden Sea Secretariat, 2012), 9.

10 *Ibid.*

11 *Ibid.*

12 Daniel Piker, “Medial Axes / Voronoi skeletons,” *Space Symmetry, Structure: Journeys in the Apeiron* (blog), 5 Oct 2009. spacesymmetrystructure.wordpress.com/2009/10/05/medial-axes-voronoi-skeletons/#more-834.

13 Anastasia Kotenko and Niki Kakali, “Aeolian Sand Odyssey.” Master thesis. (Architectural Association Landscape Urbanism, 2014). issuu.com/aalandscapeurbanism/docs/aalandscape_urbanism_aeolian_sandwa.

14 Thomas Roberts and Sareh Moosavi, “Leveraging the Dredge Cycle at the Gippsland Lakes: Simulating with Autodesk CFD.” *Journal of Digital Landscape Architecture*, 2 (Berlin: Herbert Wichmann Verlag, 2017), 42-53.

15 *Ibid,* 49..

16 *Ibid.*

Chapter 17 – Oostvaardersplassen

“I am speaking here of a landscape architecture that has yet to appear fully, one that is less preoccupied with ameliorative, stylistic, or pictorial concerns and more actively engaged with imaginative, enabling, and diversifying practices—practices of the wild*.” – James Corner*[1]

17.1. Introduction – Case Study Oostvaardersplassen

This section represents the third of three in-depth case studies to test strategies for applying algorithmic methods to specific landscape sites and problems. In its broader context, this case was originally conceived as a dual to the ideas and dilemmas introduced in Chapter 5 Von Neumann |Alexander, addressing the role of computational technologies in the contemporary management of nature and of human societies, touching on the ethics of technocratic oversight and control. It also seeks to draw inspiration from concepts revolving around individual freedom on the one hand and crowd intelligence in the other.

Fig. 17.0: *(opposite page)* A herd of Konik horses on the Oostvaardersplassen in late March, 2017.

In the case study itself, the focus is on developing algorithms and methods associated with an ecological planning project in the Dutch province of Flevoland located between the cities of Almere and Lelystad. Here on land created a mere half-century ago is one of Europe’s largest and most prominent “rewilding” projects in a large protected area known as the Oostvaardeersplassen. Despite some successes and widespread publicity, the project currently suffers from animal overpopulation and as a closed ecological system is experiencing deteriorating environmental conditions. To revitalize the large populations of grazers, various proposals including introducing predators have been suggested. The most realistic proposal involves connecting the reserve to other protected spaces in the Netherlands to create an open ecological system comprised of protected patches and corridors of movement.[2] Despite progress in articulating the planning vision and widespread support, the planned connective corridor project is on hold because of opposition from a few landowners, whose land would need to be appropriated to implement the plan as currently proposed.

The inspiration for the case study stems from a small article published by the author in Princeton University’s *Pidgin 9* in 2010. In the article, it was speculated that the ideas promoted in landscape planning and ecology, especially as developed by Richard Foreman, could be integrated with the then current discourse on computational design through “a digital model designed to deal with the complexity of ecological networks alongside the complexity of local real estate markets (along with other potential networks) [that] could replace the master plan, searching for opportunities to create a new hybrid ecology.”[3] In such a way, “the DNA of the human/natural ecology becomes the province of designers, where large and complex spatial systems are consciously manipulated for social, economic, or environmental ends while simultaneously preserving the rights of the individual to variance within the greater framework without endangering the whole project."[4] This chapter tests some of the speculations made in this short 2010 piece to reflect on the feasibility of such an approach.

17.2. Oostvaardersplassen Background

The Oostvaardersplassen is a 60 square kilometer protected area on the Netherland's 1000 square kilometer Flevoland polder, reclaimed from the IJsselmeer sea inlet with work beginning in the 1920s and being officially completed in 1968.[5] It represents the last major piece of land in the Netherlands to be polderized and at nearly 1000 square kilometers, the Flevoland Polder also represents the largest artificial island in the world.[6] Originally planned for industrial development, the land fell into disuse during a real estate downturn shortly after the polder's inauguration, and was soon colonized first by Greylag Geese, whose grazing behavior prevented establishment of forest through ecological succession which might have been expected under such conditions, and in turn by a number of other rare and migratory bird species who thrived in the open, wetland habitat.[7] [8] Since the land at the time was experiencing no significant developmental pressures and owing to the biological diversity of the waterfowl which were establishing themselves on the site, it soon came under environmental management for nature conservation and was designated a *Staatsnaturrmonument* in 1986.[9]

During the course of its environmental management, it was decided the Greylag Geese would not be enough to halt the processes of succession in the long term so it was decided to introduce large, grazing ungulates into the project to further maintain the open character of the land. Although initial proposals imagined bringing domestic cattle in to graze the site on a transient basis, under the direction of ecologist Frans Vera, the somewhat controversial decision was made to instead make the reserve home to large herds of wild and semi wild herbivores, most notably Heck cattle and Konik horses, who would instead inhabit the reserve year round with no significant human intervention into their life cycles.[10] These breeds of cattle and horse were descendants of an idealistic "reverse breeding project" to restore ancestral, pre-domesticated versions of these common farm animals. In the specific case of the Heck cattle, it was an attempt to "reverse engineer" the extinct aurochs, the much larger and more ferocious ancestor of the docile cow which had been in decline for centuries, but only passing into extinction in the early 1600s.[11] The thinking was that the genes of the aurochs are latent in domestic cattle today, and if breeders began selecting cattle for criteria such as size and aggressivity instead of, for example, docility and capacity to produce milk, the Pleistocene species could be bought back from extinction.[12]

Figure 17.1: *(above)* Some of the fauna of Oostvaardersplasen in good times and in bad. Joseph Claghorn *(top, middle)* and the *De Nieuwe Wildernix, (bottom)*

The Heck cattle program fit well within the "rewilding" goals of Vera and many others associated with the Oostvaardersplassen polder. These radical ecologists offered a critique of standard models of ecological conservation which sought to freeze nature in its current state, conserving for example heathlands and other cultural landscapes in their present, degraded state, or using the Europe of a few hundred years ago as the ecological "baseline" to which a landscape should be returned. Instead the proponents of rewilding propose a baseline much deeper in history—the Europe at the end of the last Ice Age–before human agriculture, forestry, and animal domestication began to radically alter Europe's landscapes.[13] With such an ambitious rewilding project so close to a major core European metropolis, however, this "wild experiment" eventually came into conflict with other interests. In the first years the populations of herbivores thrived, but as the reserves managers had "no targets, no models and no explicit action plan,"[14] the *laissez-faire* attitude of the reserves managers, eventually led to heated conflict with traditional ecologists and with certain segments of the public at large. As the herbivore populations thrived, they eventually multiplied to a point near the ecological carrying capacity of the reserve, and the natural, but some would argue inhumane process of starvation and disease began to set in. Animal rights activists sued the reserve managers, comparing animal welfare against, as Vera laments, an "agricultural benchmark."[15] Vera and his managers argued the animals, much like the vast herds of ungulates in the Serengeti, lived lives of freedom with its accompanying rewards and risks.[16] The counter argument portrayed the animals as captive prisoners, animals who "were not found in the wild, nor did they arrive of their own accord."[17] Activists began releasing "grainy" footage of decaying animal corpses and "affective" scenes of emaciated, starving animals with "iconography of captivity and implicit references to concentration camps."[18] Ultimately, a court ruled in the reserves favor, arguing the reserve managers no longer "exerted 'factual power' over the animals,"[19] but the critique remains with Callon et. al. in *Acting in an Uncertain World: An Essay on Technical Democracy* arguing that the reserve "is neither 'secluded' enough to qualify as science nor 'wild' enough to be democratic."[20]

17.3. Expanding the Reserve – The Oostvaardersland Project

To address the actual and perceived criticisms of the Oostvaardersplassen project, an ambitious strategy was devised in the early 2000s to expand the reserve, connecting the area through a new 1.8 square kilometer corridor to the Horsterwold a 37 square kilometer region on Flevoland's southern edge representing the largest deciduous forest area in the Netherlands.[21] (Fig. 17.2) This would address criticisms that the animals were being held "captive" in the Oostvaardersplassen reserve since they would now be free to move to the relatively sheltered forest environment during the cold winter months and would have more area to range and expanded options for foraging as well. As an ecological land planning strategy, it did not represent a radical departure from mainstream ecology, being in essence a fairly direct adaptation of Richard Forman's concept of "patches" and "corridors," with the largely open wetland to the north and the largely sheltered forest ecosystem to the south representing two existing "patches," which would then be connected with a new corridor.[22] The strategy also envisioned future connections to additional patches even further afield, including large mixed forest areas in the Netherland's center (Fig. 17.3) and eventually extending into Germany.[23]

Despite widespread publicity and promotion by government ministers, the scheme which should have been inaugurated in 2014 was put on hold. A major driving factor was that the farmers, specifically the 22 landholders who would have been forced to relocate had the project moved forward. Although the project was still being promoted by government ministers when the author first visited this case in 2010, the reflection written at the time on why the Oostvaardersland project specifically, and other rewilding projects in general, faced significant headwinds, is worth repeating here:

> "[The] reluctance to move on the part of the farmers, despite the fact that the recently reclaimed ground that they occupy has not been in their families for countless generations, and is only maintained above the water-table through an ongoing and expensive public works investment, hints at the difficulty in realigning the bounds of human occupation in other areas where a deep generational connection to the land *is* felt, and where the landscape is maintained not as part of a broader public works effort, but through the considerable efforts of the farmer himself. In other

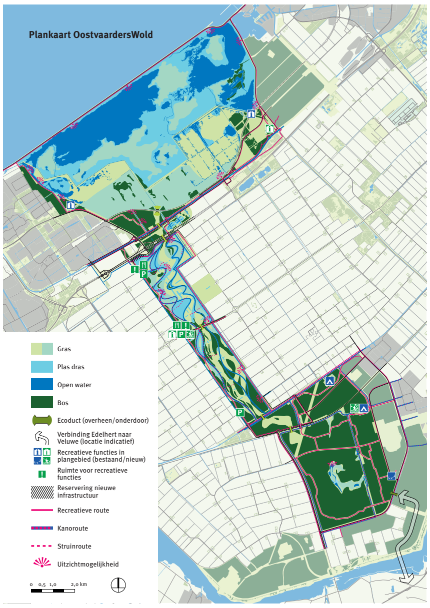


Figure 17.2: *(above)* The Oostvaardersland proposal with the planned ecological corridor, Oostvaarderswold.

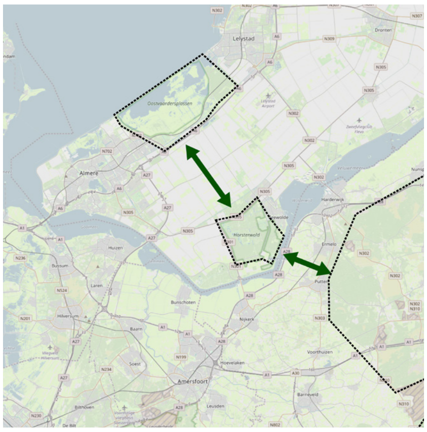


Figure 17.3: *(above)* Long-term connectivity strategy.

> words, if the state cannot evict a landowner from artificial ground, how can it evict a landowner from ground that has existed since time immemorial? In the past, the state has been able to justify such evictions with the logic that they serve a greater public interest. As the rights of the individual are held in ever greater regard, however, especially in the west, the burden of justifying this greater public interest with regards to property seizure has become increasingly heavy."[24]

As mentioned in the introduction to this case study, the mediation of individual rights and freedoms with global concerns we share as a common society is one of the most significant challenges facing our current society. Both Von Neumann and Alexander saw this tension between the local (the freedom of the individual) and the global (the needs of society), as a significant challenge. While Alexander may have advocated an approach along the lines of what was proposed in the Oostvaardersland project as the way forward, that is where the bounds of human occupation are separated from the bounds of animal occupation, Von Neumann may have argued that the systems are to tightly interconnected to separate. The human footprint has expanded too much, according to von Neumann, to sustain even ourselves in the long term, let alone the other species with which we share the planet.

17.3. Design Approach

To address these concerns, as has been argued at other parts of this thesis, landscape architects and planners can become involved in a larger planning process which is much more adaptive and which takes in the needs of a range of stakeholders, including non-human species. Much as Tom Verebes proposes in regards to "computational urbanism," where he suggests that the computer can become a tool for mediating in a more democratic way between the needs of various actors,[25] this case study offers a small test of how computational methods can be applied to this on the side of ecological planning.

This model begins with the assumption that "continental scale implementation of rewilding as imagined and performed at [Oostvaardersplassen]" is unrealistic as the abandonment of productive lands in areas with currently high agricultural productivity would, as Lorimer and Driessen point out, "demand the intensification (or continued global outsourcing) of agriculture and the abandonment of the forms of agriculture currently practiced elsewhere."[26] Furthermore, while wild reserves should continue to play a role in overall land-use planning, the general segregation of the cultured and the wild landscape into two categories strictly walled off from each other also stifles the potential for potentially beneficial symbiotic or hybrid conditions characteristic of open and non-linear systems. By allowing the agricultural landscape between Oostvaardersplassen and the Horsterwold to interact with the movements of animal agents, both the animal system and the agricultural system could benefit from each other, with one potential benefit hearkening back to traditional systems of crop and field rotation.

Before the advent of commercial fertilizers, maintaining long-term soil fertility was dependent on regular infusions of nitrogen into the soil. While farmers may not have understood the chemistry involved, they realized that soil fertility and crop yields increased after a fallow period where the field was used as pasture. This is owing to the fact that animal manure is a rich source of nitrogen, with animals being a vector for nitrogen transport through an ecosystem. Depending on the crop grown, fallow periods as pasture are recommended for fields for approximately one third of the time, but a variable and dynamic regiment rather than a strict rotation is ideal.[27] If fallow periods of various fields are coordinated throughout the region such that they link together to create a dynamic and changing animal corridor which finds a new path dedicated to movement between the Oostvaardersplassen and the Horsterwald each year, both farmers and animals could benefit from this arrangement. The animals benefit from increased habitat and range. The farmers would benefit as the animals would replenish soil fertility naturally by moving nutrients from the dynamic ecosystem of the wetland to the farmer's fields by way of their manure. This would also improve water quality in the area in the long term, since the use of artificial fertilizers could be decreased which artificially inflates the amount of free nitrogen in aquatic systems with long term detrimental impacts.

Drawing inspiration from Lansing's analysis of the Bali rice terrace landscape through the use of a cellular automaton model, (§5.11) which analyzed the emergent patterns of coordination among farmers engaging in local interactions with their neighbors, this case study instead proposes to use a modified cellular/agent system not to analyze, but to manage and coordinate the series of local and global interactions. The model, using a logic similar to the path-finding algorithm presented in §A12.3, attempts to find a new ecological corridor or movement at regular seasonal intervals. Farmers can opt in or out of the system on a temporary or a permanent basis as long as a significant majority agree to participate, but their participation can be further encouraged through various forms of subsidies.

17.4 Building the Model – Open Source Data

In contrast to previous two case studies, where base data was provided by the respective municipalities, this case relies on the use of open-source, user generated data as a backdrop. In the vein of the "wiki" movement inspired by the work of Alexander and as described in §5.9, the platform openstreetmaps.org represents the largest single source of user-generated and freely reusable mapping data in the world. Much as the collective intelligence of thousands of users on Wikipedia vets and verifies data far exceeding the scope of an encyclopedia edited by a small team of professionals, the data in OpenStreetMap (OSM) can often surpass the accuracy of data provided by platforms such as GoogleMaps. This is especially true in certain countries and in rural areas. While it is beyond the scope of the present research to explore this subject in depth, the generation of crowd-sourced maps is having a significant impact on how data is shared and used for applications with marginal economic incentive, but where good information is nevertheless critical.[28]

The Netherlands is undoubtedly one of the most carefully and comprehensively documented countries in the OSM platform with nearly every building, canal, and field in the country, along with hundreds of other useful data types continuously mapped and updated. A comparison of the GoogleMaps view of the study site, where only a few roads and canals are shown, in contrast with a screenshot of the OSM data, where every farm outbuilding, field boundary, path, is mapped, along with countless other landscape features are mapped, is quite striking. (Fig. 17.4) This collective map, to use Meyer's term, represents a "figured ground" where landscape is not a negative space, but an active field. (See §2.9) Early in the course of this thesis research, the author developed a methodology to use Timothy Logan's Grasshopper's Elk plugin, a convenient tool for importing open source mapping and topographical data into Rhino, to build three-dimensional models of various landscapes. (Fig. 17.3) Using this methodology with a

Figure 17.3: *(above)* Models of Rossiniere Switzerland, Ecoteaux Switzerland, and Prospect Park generated from open-source data.

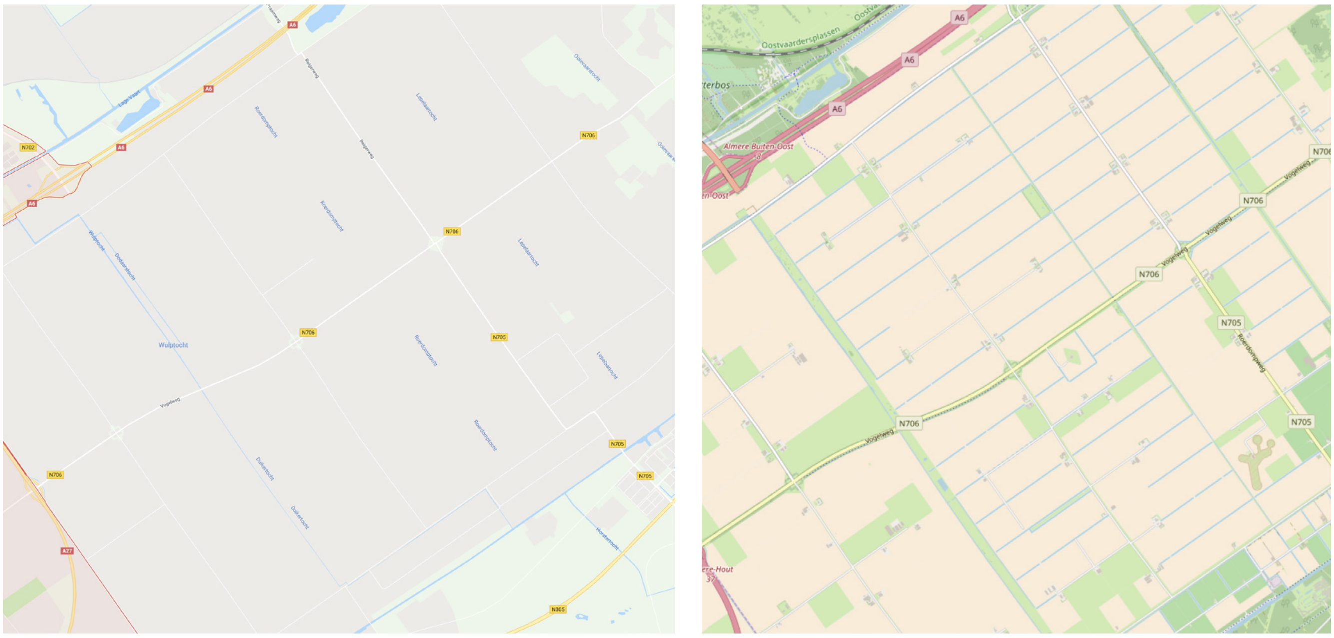


Figure 17.4: *(above)* Comparison of data for the site from GoogleMaps, left, and OpenStreetMap, right.

few adaptations, a context model for the Oostvaardersland site was created for this study. (Fig. 17.5) A few edits were made to the base data from OSM before this process took place, especially to ensure the field's cell structure was properly represented, but otherwise the methodology developed for other sites worked quite well for Oostvaardersland. Topography was not accounted for as the Flevoland site has very little topographical variation that would be significant for this study.

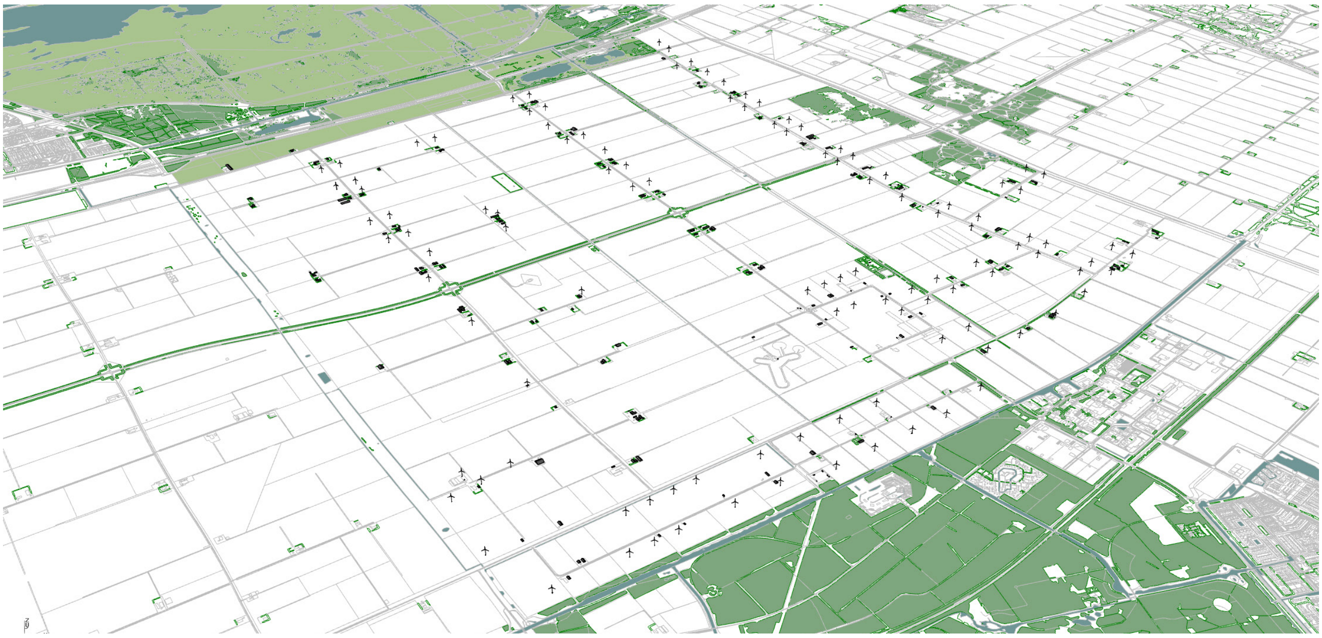
17.5. Defining the Cellular Topology

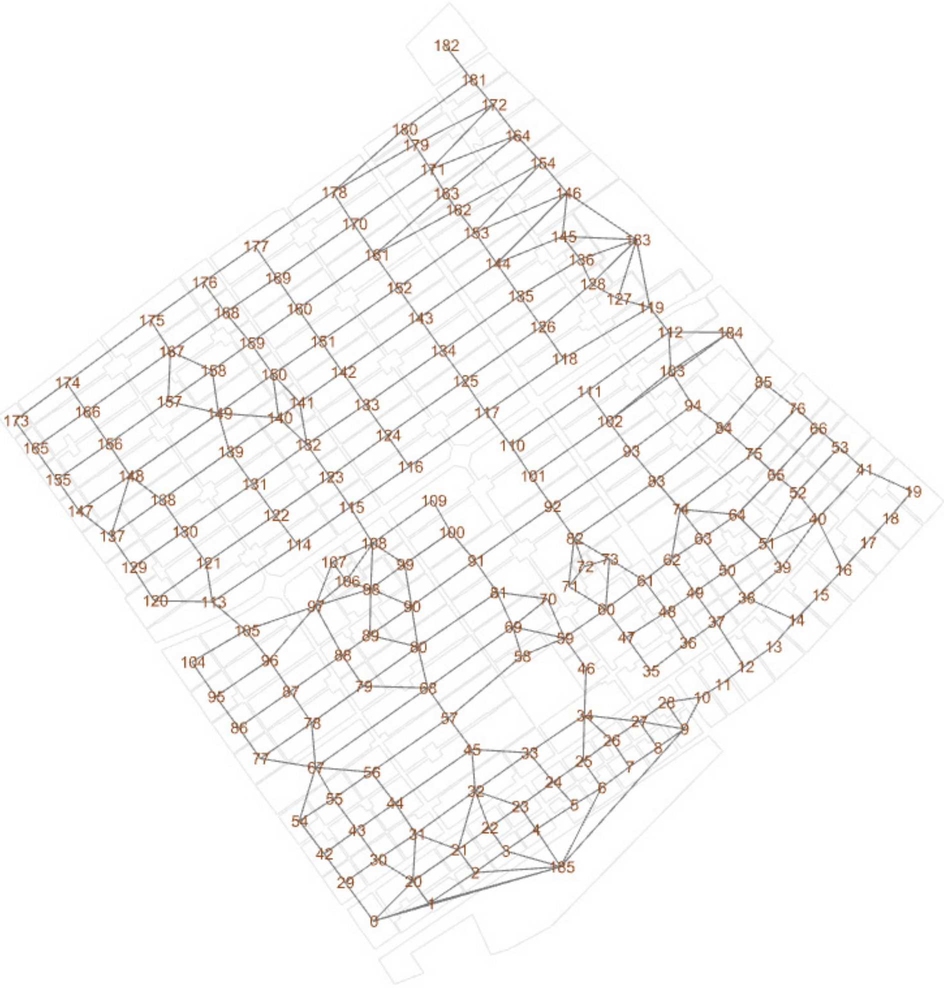
After importing and developing a base model, an early design task was to define the configurational or topological relationship between the various cells in the landscape. In a classic cellular automaton, the basic Von Neumann or Moore neighborhoods (§6.13) are used to define relations between cells in a uniform grid. Despite the largely geometric nature of the landscape in the project area, however, a more complex and nuanced network needs to be defined. At a basic level, the relationship between cells uses a Von Neumann neighborhood, i.e. movement can happen on the linear boundaries but not on the diagonals between cells. Where a large cell abuts two or more smaller cells, more than one possible path of movement in that direction is possible. Where the boundary between two cells has a significant physical obstacle between them, such as a road, a decision needs to be made if and how movement across the obstacle can be accomplished. In the study area, many of the roads are minor agricultural streets with only a minimal amount of local traffic on them. Here cross movement of the herds should not be an issue and would require only the installation of cattle guards to keep the herds from wandering into the road network. There is, however, a minor highway which transects the middle of the site which needs to be accounted for. Traffic volume is not high enough to merit an expensive wildlife bridge, but a system may need to be installed with traffic lights which stops traffic when herds of animals are crossing the highway. Since these crossings could require infrastructural improvements, only four out of the ten possible cell adjacencies are considered a valid crossing point.

To define the topology, each field or cell is given a unique identifying number. The topology needs to be defined manually by inputting into a

Figure 17.5: *(opposite page, top)* 3D model of the site imported from OSM data

Figure 17.6: *(opposite page, bottom)* Topological structure between fields or “cells“ of the study area constructed through manually entered spreadsheet data.

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spreadsheet next to each cell's identifier a list of all the other cells with their identifiers that cell can connect to. This task is a bit tedious but in this particular case, took about an hour and a half of time. Once the topology is defined cells can be later excluded from the matrix as explained in the next section, but adding a cell later can create problems with the identifier numbering system introducing error if not carefully checked. It is hence better to include all possible cells and connections at the beginning and later turn them off at a later point rather than the other way around. The final topological structure for the cell matrix is shown in Figure 17.6.

17.6. Cellular System for Ecological Management and Agent Movement

The core goal of this project and the algorithm's primary goal is to establish a dynamic corridor through the cellular matrix, following a hybrid cellular automaton-agent based logic with a path-finding mechanism conceptual similar to §A12.3. The studies here were done with the assumption that the corridor would be updated every year, but the cycle could be changed so that it updates seasonally, once in the fall and once in the spring, or every two years. The advantage of updating it more frequently is that any individual field is not taken out of service for too long, but other factors might argue for a longer cycle, such as two years, as will be discussed shortly. For the sake of consistency, however, the text will refer to years when referring to iterations of the algorithm.

In the first year, every cell participating in the program is assigned a probability of being chosen, with the schematic representation here demonstrating a scenario where each cell has a baseline probability value of

Figure 17.7: *(upper row, bottom)* First steps of the corridor finding algorithm

102	103	104	105	106	107
96	97	98	99	100	101
90	91	92	93	94	95
84	85	86	87	88	89
78	79	80	81	82	83
72	73	74	75	76	77
66	67	68	69	70	71
60	61	62	63	64	65
54	55	56	57	58	59
48	49	50	51	52	53
42	43	44	45	46	47
36	37	38	39	40	41
30	31	32	33	34	35
24	25	26	27	28	29
18	19	20	21	22	23
12	13	14	15	16	17
6	7	8	9	10	11
0	1	2	3	4	5

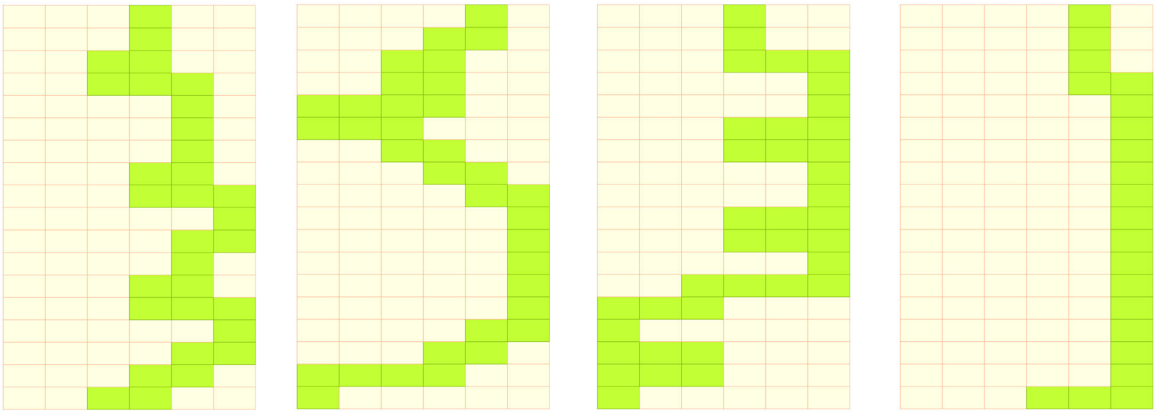


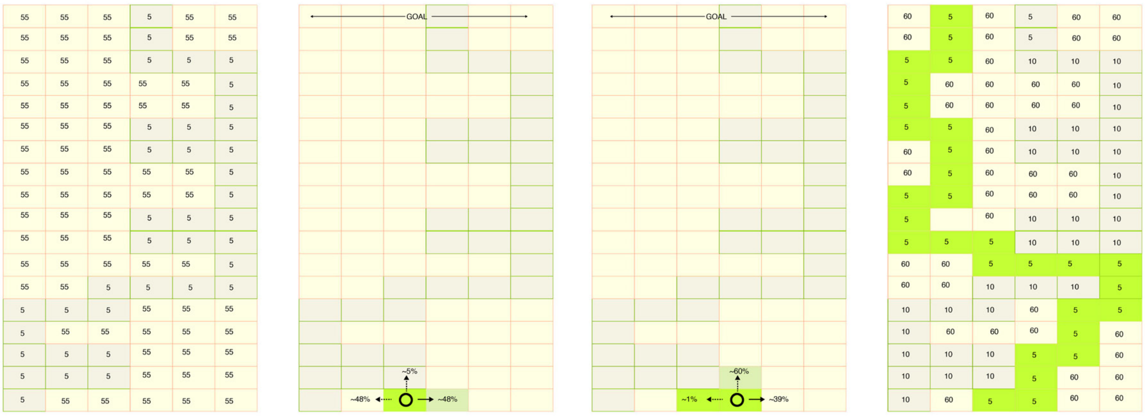
Figure 17.8: *(lower row, bottom)* Potential results after running the corridor fiding algorithm in its first year.

"50." Starting from the bottom of the cellular matrix, the algorithm rolls the dice and picks a cell. This cell is now "activated," but its probability of being selected again is reduced to "1." It is not reduced to "0" so as not to enter into a condition where the path-finder gets stuck. In other words, it can backtrack if it has to. The algorithm from her examines all the neighbors and based on the probability, selects one of the neighbors in either a lateral direction, or forwards towards the goal, but never backwards. (see Fig. 17.8). This process repeats in this method, selecting a cell based on the probability rules described until the corridor reaches one of the cells in the final row of the matrix, ending the corridor generation. Four of many possible outcomes of the first run of the algorithm are shown in the schematic representation in Figure 17.9.

In subsequent years, the probability rules become more complex. Cells selected in the previous year have their probability reduced, in this case to "5" while cells not selected have their probability increased by "5." (See Fig. 17.10, 1). This alters the calculus of the path-finding "agent." While it is unlikely a cell will be selected twice in a row, sometimes this is inevitable , as shown in Fig. 17.10, 4. After the corridor for the year is completed, the process repeats, with cells selected in the year having their probability reduced, and cells not selected having it incremented. Through time, cells which have not been selected for several years then, become significantly favored over other cells. The evolution of the matrix when taken out of its abstracted version and applied to the actual Oostvaardersland site through several years is shown in Figure 17.8.

For cells that need to be temporarily or permanently taken off line, the computer generated probability matrix can be overridden and an value of "0" can be assigned to the cell. This means it will not be selected under any

Figure 17.7: *(upper row, bottom)* Corridor finding algorithm in its second year.



55	55	55	5	55	55
55	55	55	5	55	55
55	55	55	5	5	5
55	55	55	55	55	5
55	55	55	55	55	5
55	55	55	5	5	5
55	55	55	5	5	5
55	55	55	55	55	5
55	55	55	55	55	5
55	55	55	5	5	5
55	55	55	5	5	5
55	55	55	55	55	5
55	55	5	5	5	5
5	5	5	55	55	55
5	55	55	55	55	55
5	5	5	55	55	55
5	5	5	55	55	55
5	55	55	55	55	55

60	5	60	5	60	60
60	5	60	5	60	60
5	5	60	10	10	10
5	60	60	60	60	10
5	60	60	60	60	10
5	5	60	10	10	10
60	5	60	10	10	10
60	5	60	60	60	10
5	5	60	60	60	10
5		60	10	10	10
5	5	5	10	10	10
60	60	5	5	5	5
60	60	10	10	10	5
10	10	10	60	5	5
10	60	60	60	5	60
10	10	10	5	5	60
10	10	10	5	60	60
10	60	5	5	60	60

Figure 17.8: *(lower row, bottom)* Corridor finding algorithm applied to the site in years 1, 2, and 30.

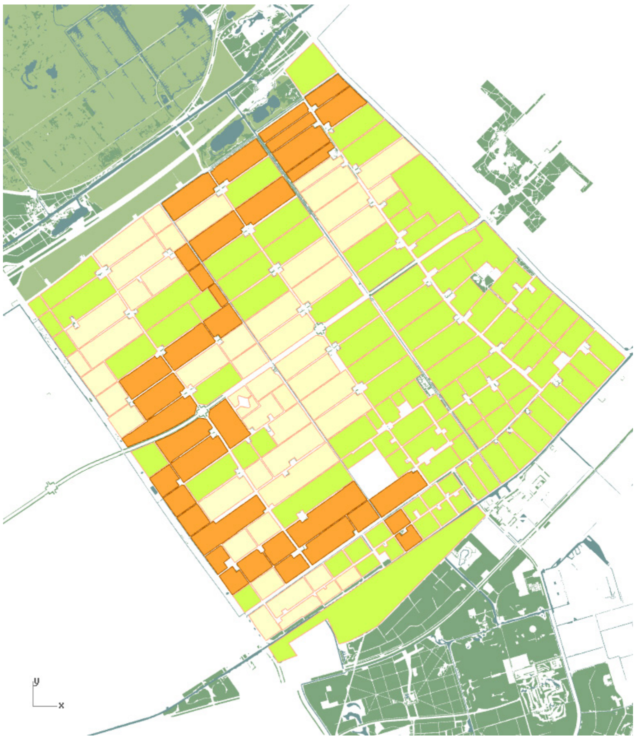


Figure 17.9
Year 2

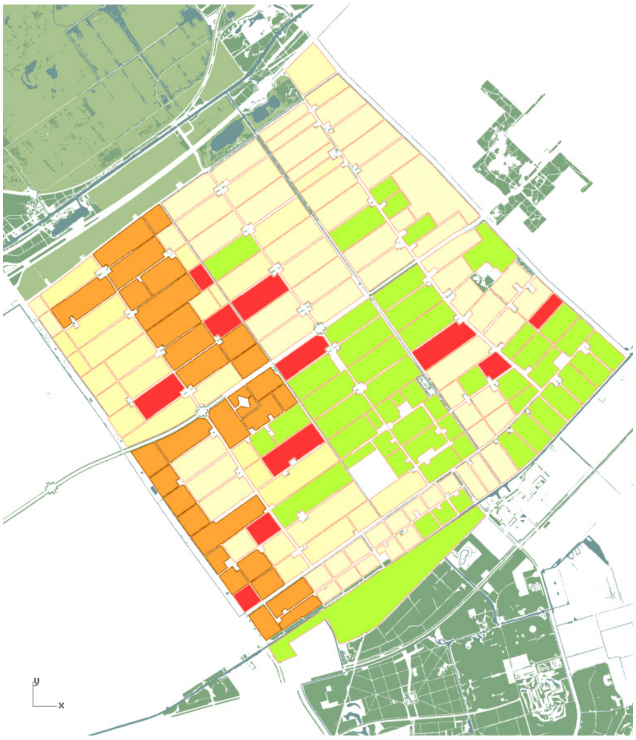


Figure 17.10
Year 2 - Cells Excluded

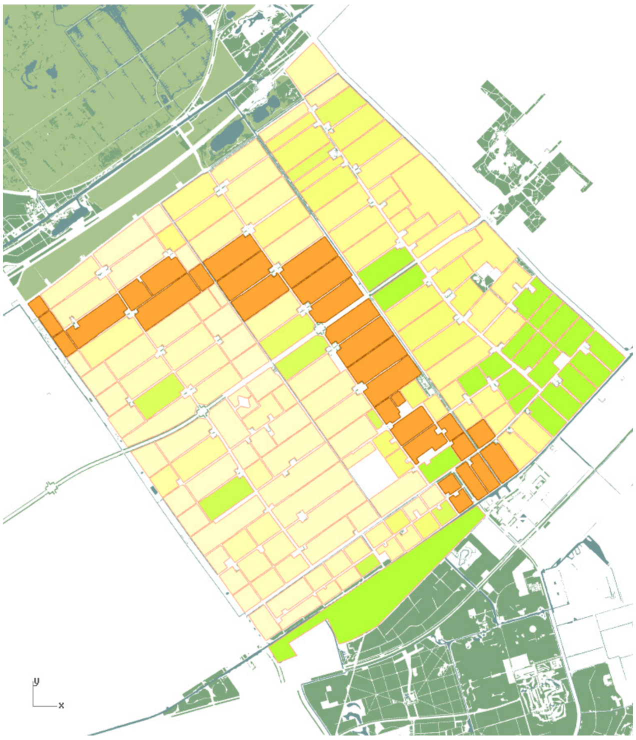


Figure 17.11
Year 10

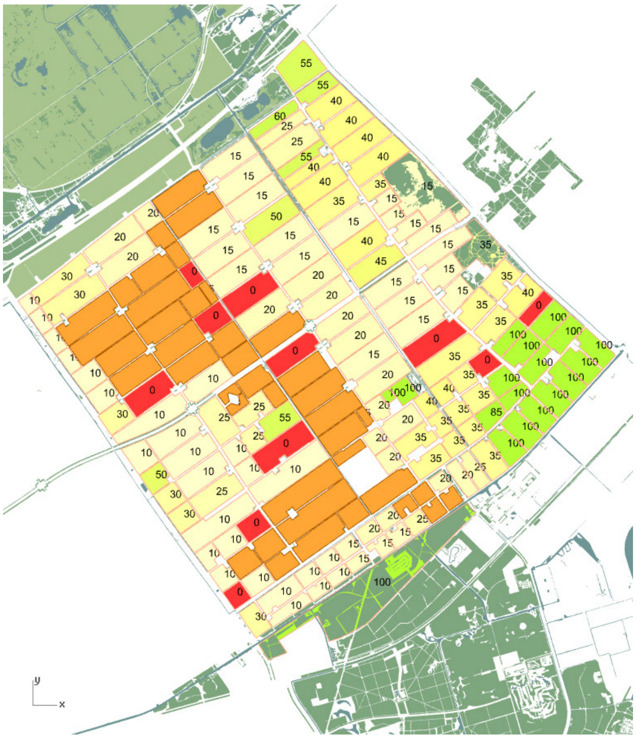


Figure 17.12
Year 30 - Relative Probabilites for Next Year

circumstances. (See Fig. 17.10) Running the algorithm many times indicates certain cells tend to be selected much more than others. Compensatory incentive programs for the farmers take this into account, and much as in the case of an insurance policy, provide yearly subsidies to the farmer in an amount proportional to this probability. If over the course of time this system falls out of balance, the subsidy amounts could be revisited. One also notes certain cells are selected with a very high frequency while others are not selected at all. This knowledge can be used to exclude certain cells from the program, such as the cells in the southeast corner of the study area as indicated in Fig. 17.12, while considering permanent conservation status for a limited number of cells which are regularly selected as this indicates their importance to the overall functioning of the system.

17.7. System for Plant Growth and Succession

The computational model represents a kind of brain for the project, but implementing the proposal would still require the construction and installation of a significant amount of physical infrastructure and especially the boundaries for the landscape cells or rooms would need to be strengthened. A significant amount of temporary fencing would need to be deployed each year to control animal movement and to keep them out of the agricultural fields, and permanent cattle guards would need to be installed at the connections which cross roads. Existing waterways and canals would help define landscape rooms to a certain extent, but as a long-term strategy for delimiting space, shallow strips at each field's edge are encouraged to remain in an unplowed state to encourage the spontaneous growth of hedgerows. Not only would these reduce the need for deploying temporary fencing as the hedges become established and begin to act as barriers, in the long-term they would increase the biological diversity of the landscape by providing beneficial habitat to a number of species, would shelter the landscape from strong winds, would reduce the pumping load for the polder in the summer months when they would transpire water from the nearby canals, and would increase the aesthetic appeal of the landscape.

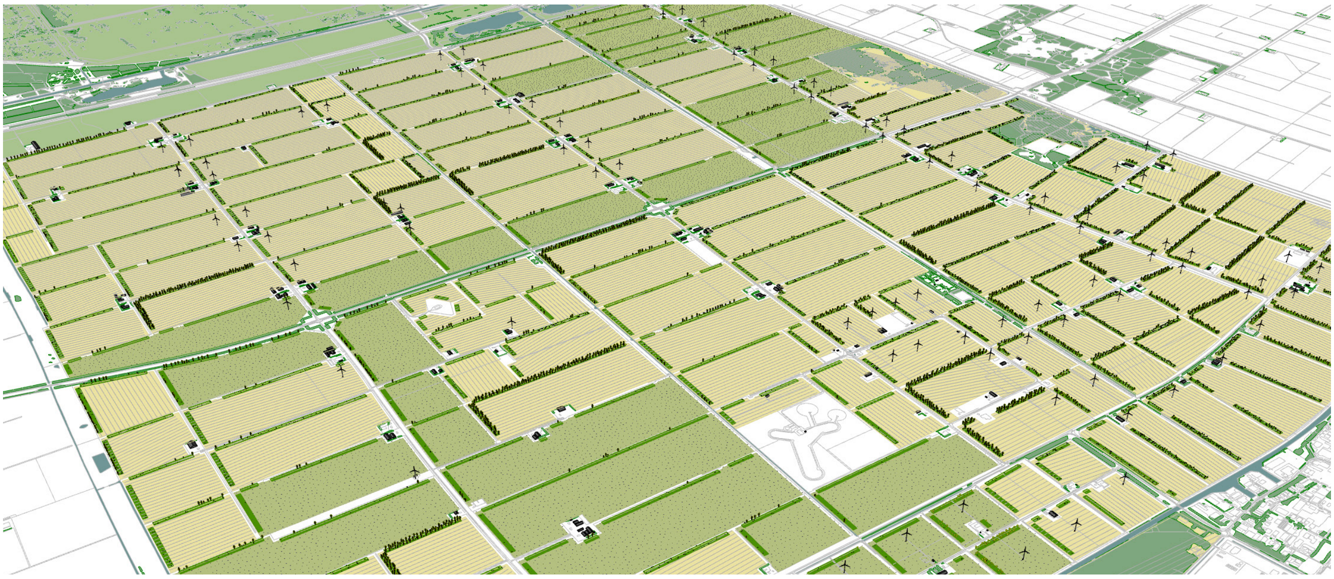
To simulate the establishment of the hedges over time, the cellular matrix was combined with an adaptation of the model of ecological succession described in §A14.2. In this adaptation, the trees grow and establish dominance with respects to their neighbors just as they do in §A14.2, but young trees have a chance of being grazed by passing ungulates in years where the cell which they abut is part of the dynamic ecological corridor. For the purposes of the simulation, it was assumed 80% of plants younger than 5 years old would be culled each year, preventing establishment of the hedgerows. The results of this algorithm are reflected in the birds eye views of the site. (Fig. 17.3) While the algorithm is not developed to the point where this would reflect the actual process of plant establishment in the zones designated as hedgerows, the algorithms still presents a useful visual cue of the frequency with which a particular cell is selected. Cells with dense hedges bounded by mature trees represent cells infrequently grazed, while cells with sparse hedges are under heavier grazing pressure. This might indicate to the designer, however, that additional plant establishment and protective measures may need to be taken in these areas in order to establish the hedges.

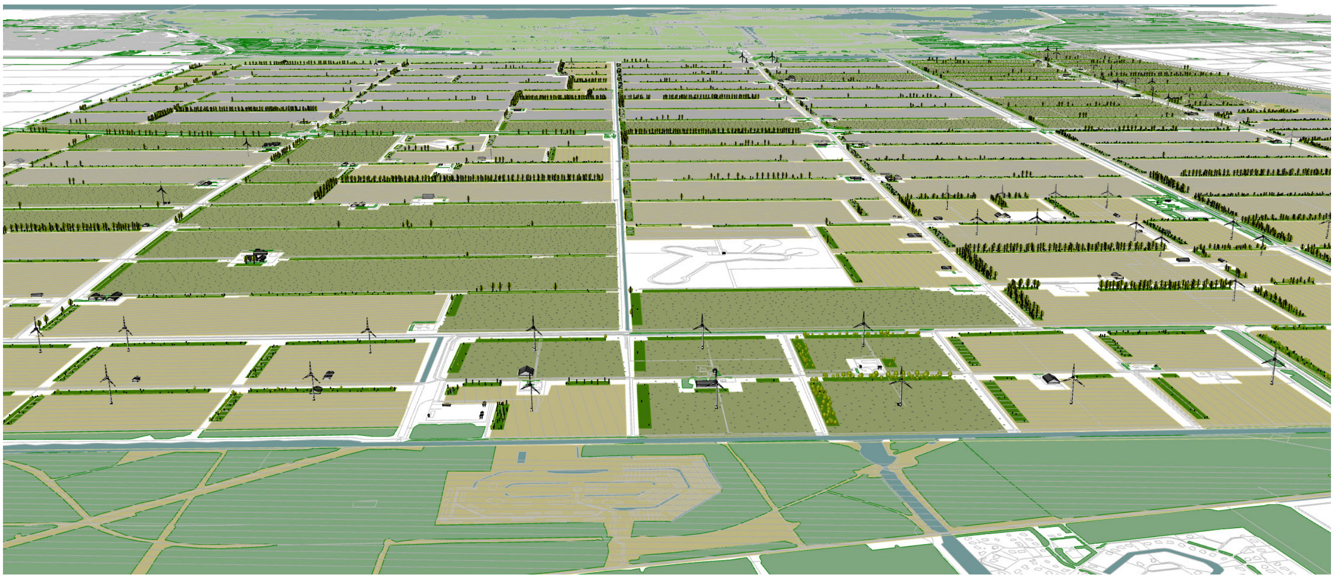
Figure 17.9: *(opposite page, top left)* Scenario after 2 years.

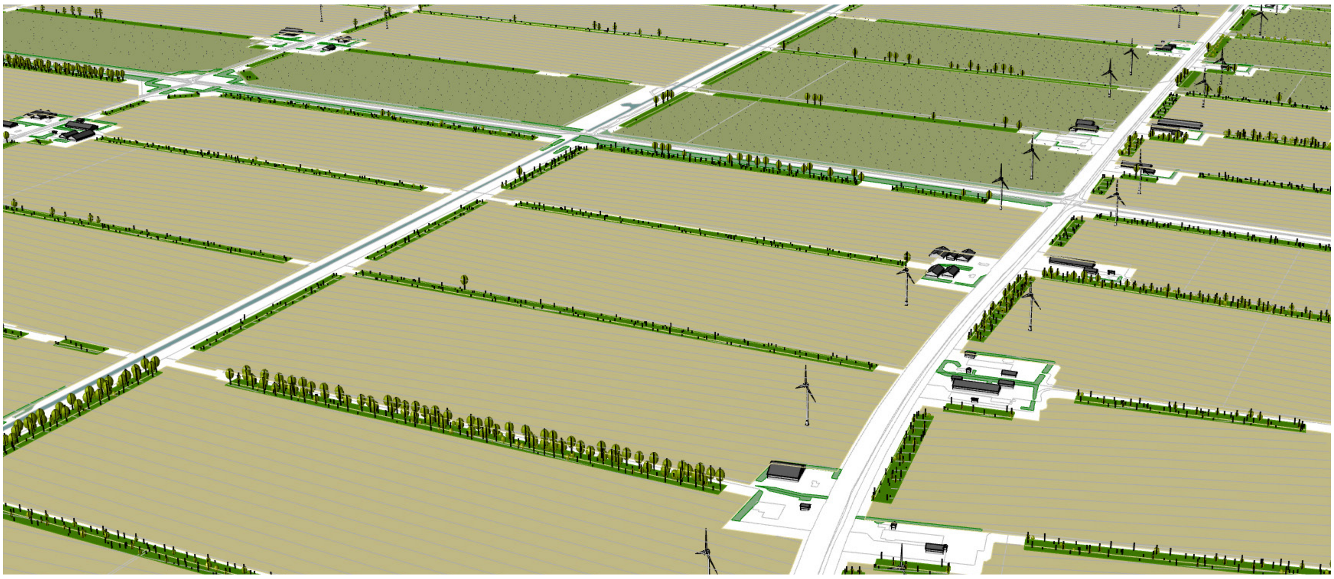
Figure 17.10: *(opposite page, top right)* Cells can be taken out of the matrix by designating their probability as zero, red.

Figure 17.11: *(opposite page, bottom left)* Landscape after many years

Figure 17.12: *(opposite page, bottom right)* Probabilities of cells being selected after many years.







17.8. Reflection

This proposal represents an initial hypothesis for a future in which technology is used to help mediate the complex and at times problem fraught relationship between human beings and other animals inhabiting the earth's biosphere. The model for a technologically mediated relationship between human life and wild life, however, would need to be developed with a full range of actors in mind, and all parties would need to buy into the concept. The need to make room for the *wild*, even this close to the centers of the "civilized" West, however, as argued by George Monbiot in *Feral* is a moral imperative; how can we in the developed world demand conservation of wildlife and a halt to expansion of the human footprint in the less developed world when we ourselves are unwilling to make room for the wild near our own homes?[29] In the end, however, the proposal here does not advocate a pure "rewilding" strategy, but advocates instead the development of a hybrid landscape where farmers and birdwatchers, tourists and the reverse-engineered aurochs, high powered windmills and Serengeti-like herds can meet and rub shoulders. It is the Anthropocene meeting the Pleistocene. To borrow Lorimer and Driessen's description of Oostvaardersplassen itself, this proposal represents:

> "A nature reserve for the Anthropocene in the sense that it is willingly presented as a made site for knowing and experimenting with an unknown future. It is uninhabited and uncultivated, but it is not purified. It is hybrid in the sense that it is a knowing co-production of multispecies agencies. It serves as the inspiration and catalyst for the proactive 'development' of 'new natures' under a distinctly Dutch mode of conservation."[30]

The proposal is also intended to stimulate discussion regarding concepts of agency and control, order and wildness, and the responsibility or the apathy we show as designers towards the needs of the other species who call earth home. Landscape architects, as the discipline on the boundary between the ordered and the engineered on the one hand, and the ambiguous, indeterminate, and the emergent on the other, are well-positioned to address these challenges. As Edward Wilson argues in *The Diversity of Life,* for the tide of environmental degradation to be challenged:

> "Parcels of land will have to be set aside as inviolate preserves. Others will be identified as the best sites for extractive reserves, for buffer zones used in part-time agriculture and restricted hunting and for land convertible totally to human use. In the expanded enterprise, landscape design will play a decisive role. Where environments have been mostly humanized, biological diversity can still be sustained at high levels by ingenious placement of woodlots, hedgerows, watersheds, reservoirs and artificial ponds and lakes. Master plans will meld not just economic efficiency and beauty but also the preservation of species and races."[31]

With this goal in mind, where technology and especially computational methods can play a role in mediating between these complex and sometimes conflicting dynamics, it should be embraced. Where it itself serves as a destructive or counterproductive force, it should be resisted, but not out of ignorance, but with a critical and well-informed alternate stance.

Figure 17.13: *(opposite page)* Birdseye views of the site after 50 years

Figure 17.14: *(opposite page)* Fauna cross a road near the study site near Horserwold.

Endnotes

1 James Corner, "Ecology and Landscape as Agents of Creativity," in *Ecological Design and Planning*, George Thompson and Frederick Steiner, eds. (Chichester: Wiley, 1997), 105.

2 Province of Flevoland, "Oostvaardersland: Strengthening the economy and ecology of the Netherlands," PDF leaflet. (Provincie Flevoland, 2010). wildexperiments.files.wordpress.com/2011/05/oostvaardersland-brochure.pdf. Accessed 13 April 2018.

3 Joseph Claghorn, "Recreating the Primeval Wilderness: The Case of the Aurochs," *Pidgin 9* (Princeton: Princeton School of Architecture, 2010), 194.

4 *Ibid,* 195.

5 Frans Vera, "Large-scale nature development: the Oostvaardersplassen," *British Wildlife* (June 2009), 31.

6 Jamie Lorimer and Clemens Driessen. "Wild experiments at the Oostvaardersplassen," *Transactions of the Institute of British Geographers* (2013), 173.

7 *Ibid,* 172.

8 Vera, 31.

9 Lorimer and Driessen, 172.

10 Vera, 32-33.

11 Mieczyslaw Rokosz, "History of the Aurochs (*Bos Taurus* primigenius) in Poland," Animal *Genetic Resources Information* 16 (1995), 11.

12 Claghorn, 188-190.

13 Lorimer and Driessen, 172.

14 *Ibid,* 175.

15 Vera, 35.

16 *Ibid.*

17 Lorimer and Driessen, 174.

18 *Ibid,* 177.

19 Court decision as cited in Lorimer and Drieseen, 174.

20 Lorimer and Driessen, 177.

21 Province of Flevoland, "Oostvaardersland," 5.

22 Richard Forman and Michel Godron, *Landscape Ecology* (London: Wiley, 1986).

23 "Structuurvisie Oostvaarderswold" (Lelystad: Provincie Flevoland, 2009), 18.

24 Claghorn, 192.

25 Tom Verebes, ed. *Masterplanning the Adaptive City: Computational Urbanism in the Twenty-First Century.* (London: Routledge, 2013).

26 Lorimer and Driessen, 179.

27 Fred Magdoff and Harold van Es, *Building Soils for Better Crops,* 3rd ed. (Brentwood, MD: Sustainable Agriculture Research and Education, 2009), 118-124.

28 As only one example, within 48 hours of the 2015 Nepal earthquake, 2000 OSM "arm-chair crisis mappers," using aerial imagery as a base were able to add 3 million pieces of data to the map of Nepal's poorly charted rural areas. Within five weeks, 1.4 million buildings were traced and over 13,000 miles of road were mapped, proving invaluable to the disaster response. Courtney Rieger, "A Review of the Capacity for OpenStreetMap Software in Humanitarian Disaster Response: A Case Study Investigating the Humanitarian OpenStreetMap Team Response to the 2015 Nepalese Earthquake." *Meeting of the Minds Graduate Student Journal* 1. (University of Lethbridge, 2017).

29 George Monbiot, *Feral: Rewilding the Land, Sea and Human Life* (London: Penguin, 2013).

30 Lorimer and Driessen*,* 178.

31 Edward Wilson, *The Diversity of Life* (London: Penguin, 2001), 301-303.

Summary Part III

In contrast to Parts I and II of this thesis which can primarily be characterized as "research *about* design" and "research *for* design" respectively, the goal of Part III was to test some of the thesis' earlier assumptions in the context of specific project case studies, and is an example, as such of "research *by* design. (§0.4) Like Parts I and II, Part III of this thesis also sought to address one of the major research questions, specifically the inquiry: To what degree can landscape architects improve the performative aspects of landscapes and fulfill the ambitions of the systems thinking paradigm through algorithmic design? The research proposed that this could be done at the intermediate scale by creating meaningful connections between algorithmic "objects" or patterns, characterized by their own internal formal relationships, and an informational "field" expressing important characteristics of sites. These informational data points enter into a dialogue with the form-giving algorithmic patterns in a recursive and evolutionary process, progressing the landscape into possible future states. Three case studies exploring the productive, *performative* potential at the intermediate scale were conceived and tested.

The three case studies all had successes and failures. The Medellin case study was part of a much larger research project, which helped inform and direct the process overall and which promoted the in-depth study of methodologies with the goal of delivering specific products. In comparison with the other two cases, this grounded the project more strongly in reality and the process also helped to clearly define the algorithms that were ultimately used. The algorithmic method for dealing with the very large amounts of data available in the settlement was also crucial to delivering the final graphic and modeling outputs, and if nothing else, the work on this case study demonstrates the fact that algorithmic methods have become essential in almost any endeavor dealing with such huge sets of data. To bring this case study to the next level, more carefully developed computational methods for introducing indeterminacy not through computer generated randomness, but through a democratic, participative, and ultimately socially constructive model, could be a productive avenue of future research. (See also §7.6) In other words, means should be developed to allow others to interact with the processes at play and become digital co-authors as envisioned by Carpo.

The Wilhelmshaven case study was perhaps the least convincing of the three, partly due to the disappointment of not attaining a sufficient level of fluency with the appropriate software specifically for performing the computational fluid dynamic calculations originally envisioned. (see §11.4, §16.8) While many software programs for performing CFD calculations exist at the present time, they are generally inaccessible to landscape architects—at least if they want to achieve convincing results—and also require a high degree of accuracy with the base information. This may still prove to be a productive avenue of future research; here a very strong cross-disciplinary and goal oriented team would need to be formed to demonstrate to what degree CFD simulations can be judged useful for landscape architects. The emergent dune study using the cellular automaton, however, was a fascinating algorithm to explore and while not a perfect predictor of future landscape evolution, it does help generate plausible landforms with can react with the context. This along with other successes with cellular automata models would encourage the author to explore more research in this direction, especially with the CAESAR model introduced in §13.5 as an alternative to complicated CFD packages.

Finally the Oostvaardersplassen case was highly rewarding, but the algorithmic methods used in reality might be of limited usefulness to the actual *performative* design of the landscape. The models of ecosystem succession, for example, were grossly simplified and serve more as an innovative way of producing a believable *representation* of the character of future vegetation rather than serving as a tool to make informed design decisions. The core algorithm which produces the randomly generated path each year is also a simple mechanism lacking a high degree of algorithmic complexity, and its decision-making capacity should ultimately be based more on the complexity of the informational context—its inputs—than on its own internal random logic. Ultimately, however, the case was successful insofar as it sought to bring into view questions of freedom, individual agency, paternalistic control, and collective responsibility with respect to technology rather than developing a comprehensive and realistic model for "rewilding" a specific landscape. Furthermore, some of the logics introduced as well as the concept of flexible and adaptive planning, should prove a productive avenue of research in the coming years. Additionally, if the case is thought provoking, maybe it can be described as performative, but true performative design in such a context needs more exploration.

In conclusion, the author believes that the performance hypothesis explored in Part III still needs more testing. To do this most effectively, the formal strategies developed in Part II would need to be supplemented with better methods of information gathering, better and more complex models of landscape and ecosystem development, and better methods of engaging indeterminate informational fields, especially in the context of user-informed co-authorship, to truly reach a *performative* algorithmic process. Should these barriers be overcome, strategies for transferring the products of a digital design process into the real world also need to be considered. Constructability of large-scale landscapes, perhaps using a number of emergent technologies and new robotic tools, could also be explored in the context of algorithmic design. These potential future research directions will be discussed with additional detail in the next Chapter. (§18.5)

Chapter 18 - General Conclusion

18.1. General Summary of Thesis Structure

This thesis began with three guiding research questions, structuring the text into three general parts—a theoretical context for algorithmic design in landscape architecture, a catalogue of algorithmic patterns for landscape architectural design, and a series of algorithmic applications to landscape architectural projects. These three sections, in terms of their research methodology, were characterized as a section of "research *about* design," a section primarily characterized as "research *for* design," with the final section characteristic of "research *by* design." (§0.4) Summaries of the key findings as well as each section's relationship to the three guiding research questions were presented in the concluding summaries following each of the three major parts. In this general conclusion, a few concluding remarks relating to the overarching topic of this dissertation will be presented. As offered in §0.2, this research proposed that **the algorithmic manipulation of space has the potential to change the practice of landscape architectural design**. The introduction then promised to reflect on what those potentials mean. This will be done by 1) enumerating several of the potential benefits for landscape architects to using an algorithmic design method, 2) reflecting on several specific challenges for landscape architects using an algorithmic design method, 3) proposing a brief series of recommendations for integrating algorithmic design into landscape architectural practice, and then 4) outlining some of the important directions for future research stemming from the process of research and writing this dissertation. The general conclusion will then conclude with a few final thoughts on some of the larger societal issues stemming from the increasingly pervasive influence of algorithms on contemporary society.

18.2. Potential Benefits for Landscape Architects Using an Algorithmic Design Method

Contemporary landscape architecture is a wide-ranging discipline born out of the arguably much narrower and more specialized legacy of garden art and design. Over the course of its development as a professional discipline, however, its most ambitious practitioners have set a much more aspiring and consequential agenda for the field than its humble beginnings or its limited public visibility might suggest. It has sought to engage a wide range of issues, engaging questions germane to art, such as philosophical questions of memory and meaning on the one hand, to engaging social and environmental issues surrounding the livability of our cities and our planet on the other. Algorithmic approaches, this thesis argues, can serve to deepen the engagement of landscape architects' approaches to a number of contemporary questions and fulfill many of the ambitions of contemporary landscape design discourse. Four specific benefits of adopting algorithmic methods in both pedagogy and practice as identified in this research are described here:

1) The use of algorithmic methods can deepen the "Systems Approach" to design: As introduced in Chapter 1, landscape architectural discourse in recent years has largely embraced the "systems approach" to design problems. (§1.8) For the rhetoric surrounding the systems approach to design to move beyond mere lip service, however, algorithmic design *can* be a valuable tool. The process of axiomatizing design problems forces the designer to consider how various elements in a system are related, to consider specific parameters and their weighting, and also to consider what important elements may not be accounted for in the model, but which may be consequential. It can facilitate the process of bringing a design problem into the "discursive realm" (§2.3, §5.8) where it is then open to manipulation and refinement. The process of scripting and coding forces a degree of discipline upon the designer and helps avoid the crutch of vague or subjective generalizations. The early successes of GIS in landscape architecture at larger, planning scales can be informative in this regard when algorithmic approaches are used at smaller to intermediate scales. (§1.11) A degree of caution should be introduced here; just because a systems approach has been used does not necessarily make it a good approach, especially when the design of the system needs to be compromised or adjusted to work with the tools at hand or with the limited coding experience of the designer.

2) Algorithmic literacy fosters interdisciplinary collaboration: Those dealing with the science and behavior of complex systems have increasingly come to rely on computer models and simulations to gain knowledge about how these systems operate and their consequences for the future of the built and natural environment. (§1.5, Part II Summary) Engineers are also increasingly using such models to study the suitability of their proposals and interventions. (§11.4, §11.5) Part II of this thesis proposed that landscape architects could adopt many of the means and methods developed in these disciplines to deepen their own design proposals. This process does not need to operate only in one direction, however, and landscape architects with a degree of literacy in algorithmic methods are better positioned to judge the suitability of models developed by those in other disciplines. At the same time, they are better positioned to give constructive feedback and suggestions for improvement of models developed in a collaborative setting.

3) Algorithmic experimentation enriches the formal vocabulary available to landscape architects and deepens discourse surrounding "shallow form " and "deep form": A recurring issue within landscape architectural theory and practice revolves around the suitability of specific formal expressions to a particular design context or problem. This discourse expresses itself in many ways, with this thesis introducing the binaries of "shallow form" vs. "deep form," (§2.5) categories such as "formal" and "informal," or *designed/created* vs. *emergent* form. (§3.9-§3.13) A key theme of this dissertation has revolved around the difficulties and overlaps in such categories. Algorithmic experimentation allows the designer to rethink these categories and shift the discourse. In a computational context, the specific distinction between *ontogenetic* and *teleological* approaches to creating form was introduced (§6.9) which shifts the discourse away from the visual reception of the forms as being "ordered" or "disordered" and instead focuses on the processes of their generation. Also introduced were the Deleuzian concepts of *smooth spaces* vs. *striated spaces* (Chapter 9) where the manifestation of particular patterns points towards certain types of hierarchical, formational, and relational processes being at work. While the algorithmic process does not exactly parallel the processes at work in such spaces, an honest effort to model and code the processes at play can provide hints that can reveal the larger forces at work. A well-considered algorithmic process of formal generation may also provide hints as to how a particular design expression can be implemented in a constructed project. (e.g. §15.7)

4) Algorithmic methods can speed up landscape "evolution" and optimize form in rapidly changing contexts: Another reoccurring theme in this thesis revolves around the notion that landscape architecture is fundamentally a discipline which speeds up or slows down processes as they unfold in time. (§2.12) Several thinkers introduced in the text proposed that designers need to evolve new forms and patterns to deal with the rapid advances of modernity (§2.3, §5.6, §5.8) and to create on a much-abbreviated timescale spaces with the resilient characteristics and complexity. Computation is one tool that may help achieve this vision (§5.12) through a process of simulated evolution. This may allow the designer to both project potential optimized future states onto the present through tools such as genetic algorithms, (§A14.3) or to identify present configurations that might lead to preferred future outcomes by simulating how a process may unfold through time. (e.g. §A14.2) This idea holds enormous potential but needs to overcome significant hurdles as discussed in the next section. This can be done through convincing tests that can only be the product of future practice and research.

18.3. Specific Challenges for Landscape Architects Using an Algorithmic Design Method

Despite the promising potentials presented here, designers wishing to explore or exploit the potentials of algorithmic landscape design should be aware of the limitations of relying on such methods, and significant hurdles need to be overcome. Four critical issues for consideration as identified by this research are as follows:

1) Designers must make critical decisions regarding the "boundary conditions" of algorithmic models: A simulation or model typically has three levels of detail or interactions. First is the internal logic or structure of the system. Second are local interactions. The methodology proposed in the Summary of Part I proposed a mediation between the internal formal relations of design "monads" or "patterns" and a local, informational field. There is, however, a third level of interactions that is much harder to account for—the level of global interactions. Algorithms based purely on internal interactions are often relatively easy to program, but typically are uninteresting in the context of landscape design and fail to model or simulate to any degree processes in the landscape. Local interactions can also be easy to account for and when accounted for will increase the believability of the system, but the system only approaches realism when global interactions are accounted for as well. These are very hard to program, and a number of intelligent assumptions must be made by the designer or programmer for these to be meaningful.

An issue closely related with the topic of local and global interactions is the issue of boundaries. Boundaries can refer to physical boundaries or perhaps more importantly to conceptual boundaries. What is included in a simulation and what is excluded is a fundamental question. (§5.8, §6.9) For practical purposes, a boundary typically needs to be drawn around a simulation or model, but such hard boundaries almost never exist in a real system. The boundary can have significant implications for the modeled system, however, and significantly alter results. Further complicating the matter is the fact that boundaries in the real world typically operate on many different levels and on many gradients, with varying levels of porosity.

2) Simulations must be recognized as "simulacra" and not as true representations of reality:
As argued by Kwinter, simulations tend to be more telling or revealing than models. They may offer hints as to future directions and "offer the possibility of apprehending developmental patterns of extraordinary and unprecedented depth and abstraction, offering tantalizing glimpses of the very free-form structure of time itself (chaos, complexity, self-organization)."[1] The predictive power of simulations, however, needs to be met with a great deal of skepticism as "no computer on earth can match the processing power of even the simplest natural system."[2] M'Closkey and VanDerSys remind us in the opening editorial to the *LA+ Simulation* that the word "simulation" fundamentally means to "feign, to pretend, or to give false appearance"[3] and that a great deal of care needs to be taken to not confuse the representation with the reality. This problem is not unique to algorithmic simulations, M'Closkey and VanDerSys argue, and pervades many other aspects of the discipline's representational tools as well. But because of the mysticism often surrounding computational methods, this distinction is often lost by end users, clients, or even the designer herself/himself when the result is computer generated. At the same time, most educated individuals recognize from their own experience that advanced mathematical simulations of well-understood phenomena lacking fundamental agency, such as those used in weather forecasting, cannot predict with a high degree of certainty far into the future. We might know that it will be sunny next Thursday based on weather simulations, but we cannot say if it will be sunny a year from today with any confidence based on a computer model. Simulations of systems with intelligent agents, involving actors and complex decision-making, must be met with an additional degree of critical scrutiny. In the end, the user has to judge not whether the simulation is thoroughly accurate, but whether it is useful. Both the accuracy and the usefulness depend to a large degree on addressing some of the issues in the first point above regarding boundaries.

3) The ambiguous qualities of landscape often do not lend themselves to algorithmic certainty: A third major consideration is that the computer is fundamentally a binary machine, not with its 0s and 1s, but with its If-Then And-Else statements. (§6.5) As Meyer argues, (§2.9) binary categories which have governed western thought for generations do not work well with landscapes, with their dynamic topological complexities and with their ambiguity of space. This may also point to a fundamental problem with algorithmic approaches. In classic algorithmic models, all questions have to be answered with a "yes," a "no," or with "roll the dice." Introducing a wide-range of exceptions or ambiguous categories can be incredibly difficult to program and of dubious logical clarity. In such instances, careful reflection on the ambiguous or variable qualities of landscape is needed before an algorithmic method of dealing with these complexities can be introduced.

4) Not everything of importance in a landscape can be easily quantified or measured, and hence cannot be algorithmically manipulated: In addition to the ambiguous uncertainty or variable nature of landscapes, many of the intrinsic and important qualities of a landscape do not lend themselves easily or at all to quantification. Carl Steinitz, who has spent a career pioneering the use of algorithmic methods at larger scales, is fond of a quote attributed to Einstein in this regard: "not everything that can be counted counts, and not everything that counts can be counted."[4] (see §15.3) These aspects include personal experiences, memories, and histories associated with the landscape, as well as certain atmospheres and cultural/semantic associations. Alexander von Humboldt, who obsessively measured every aspect he could of the landscapes he visited, including even the blueness of the sky, describes certain landscapes with adjectives that denote their unquantifiable characteristics—*unvermessbar*. At the same time he describes how unquantifiable and un-measureable quantities are also what give the landscape its magic.

18.4. Recommendations for Integrating Algorithmic Design into Landscape Design Practice

It is a hope of the author that the findings of this dissertation can ultimately be used to inform the decision-making of those interested in integrating algorithmic methods into their own landscape architectural design practices. To most efficiently exploit the potential benefits of algorithmic or computational design thinking and to avoid potential traps in deploying such methodologies, no boilerplate workflow can be proposed. Based on the research in this thesis, however, several general recommendations can be made. These recommendations will need to be adapted to an office's existing design philosophy, design goals, project interests, and workflow. All of the four issues mentioned here should be taken into serious consideration.

1) The algorithmic design process should be informed by parallel experimentation using more traditional methods: Algorithmic models should be seen as a part of a larger design process, transparent and open to scrutiny, and not as an overarching, dictatorial schema. The creative process has long been described as being iterative; recursive might be a better word in this context, as the process should build on past lessons learned with each time step rather than simply producing a series of unrelated options. To do this in a productive way often means frequent shifts between representational tools for exploring, testing, and design ideas often leads to better results than by following a linear methodology. In §11.2, the creative processes of the artist Leonardo Da Vinci, architect Lebbeus Woods, and landscape architect Herbert Dreiseitl were introduced as models of individuals who frequently shift between more scientific, research-based perspectives and artistic exploration. These are not parallel and unrelated tracks, but the two methodologies inform each other in turn. Likewise, this thesis introduced the idea in §1.12. that computational methods should not be seen as a substitute for analog techniques, but that the various "instruments" can complement each other to create a better end result. Studies by hand following an algorithmic logic in the spirit of "instructional art" (§1.7) can help a designer develop a more robust and creative computational logic without the added technical challenges associated with programming software. Likewise, the products of software experimentation should not bee seen as a final design, but should be open to further refinements using other techniques. Finally, strategies need to be found to get results "out of the computer" whenever possible, whether through physical fabrication, 3D/CNC printing, or other means. This allows the design to be perceived in a new light, and also forces thinking regarding topics such as constructability and the methods of implementation. The Medellín case study presented in Chapter 15 should offer additional insights into how algorithmic methods and other methods can work together.

2) The algorithmic design workflow should feed into a collaborative process: The internal design process also needs to be considered in terms of collaboration with other teams with varying levels of expertise and/or with the end users, such as public and community groups. In many ways, the need for interdisciplinary collaboration may force landscape practices to adopt algorithmic tools more so than they may have were it not for such collaborations. This thesis has intentionally avoided the large topic of Building Information Modelling (BIM) which is addressed in considerable depth by Wallis and Rahmann in *Landscape Archtiecture and Digital Technologies*,[5] but most BIM software makes liberal use of algorithmic methods, or at least offers the user to engage in various types of simple scripting and coding. Landscape architects who educate themselves in these methods will be better positioned to be leaders of interdisciplinary teams rather than followers struggling to catch up to the curve, as argued above in §18.2.2. In this vein, however, landscape architects should not feel they have to do *everything,* and could, for example, avail themselves of experts with specific expertise in computer science to more quickly and efficiently program algorithms to address a specific design problem. Again, a degree of literacy in what may or may not be possible in this regard will help the designer set more reasonable expectations. In this way, landscape architects of the future may increasingly hire computer programmers as consultants on projects in much the same way they might hire a plant scientist or an ecologist, depending on project needs. Finally, for landscape architects with an interest and an aptitude for computer programming, opportunities to establish "hybrid-practices" may exist. This collective expertise may be kept in-house, but considerable opportunities also exist to consult with a number of more traditional practices who do not keep such capabilities in-house.

3) The adoption of algorithmic methods with a primary eye towards increasing productivity should be met with a degree of skepticism: Many practices looking to integrate algorithmic design into their practices do so with the hope that it will allow their workers to become more efficient. A commonly touted benefit of algorithmic approaches is that it allows the user to quickly generate variations and alternatives. While technically true that by changing a few parameters, an infinite number of alternatives can be generated quickly, in practice most variations within a single algorithm are largely inconsequential and fail to generate new or surprising results. As pointed out in Donella Meadow's book, *Thinking in Systems*, changing numbers or input parameters is often the most inconsequential way to change a system, and creates the false illusion that something is being done while nothing of consequence is actually changing.[6] To generate truly meaningful variations or scenarios, structural or topological changes have to happen within the algorithm, something that is incredibly hard to program an artificial intelligence to do. Maybe Sanford Kwinter put it best when he described the futile efforts of the "deadheads" who amaze themselves with the "395th glorious variant of the same digital meatball," whose efforts should be better spent trying to uncover patterns of complexity. (§1.14) This does not mean that algorithms cannot be used to generate a range of alternatives, only that to get true variation, a lot more thinking and coding needs to be done than simply pressing a button to generate a new alternative.

In a similar vein, another touted benefit of algorithmic approaches is that a particular code can easily be transported from one project to another. In Chapter 6, the concept of the design pattern or the "object" was introduced. The argument is that these patterns, like building blocks or Legos, can be easily transported between applications. Again, while it is often beneficial to transport snippets of code from one application or project to another, especially when they are well-written and organized as discrete "objects" requiring few inputs or outputs, (§6.3) each problem or project in practice needs to have much of its code and internal logic redesigned each time from the bottom-up. This is especially true when the algorithms are doing anything more than simple cosmetic operations, such as when they are interacting or relating to each other in a meaningful way.

In commercial software design, the process of debugging a program is by far the most time consuming aspect of development. Every conceivable use and abuse of a program needs to be tested, and corresponding modifications in the code need to be made. In the context of a design practice, there is minimal time for such debugging operations and it would be hard to convince a client to pay to debug an algorithm on one project so that it can be used on others. Many software engineers also take a very cautious approach to reusing code, even when they generally subscribe to the "object-oriented" programing approach. Kelly argues that each of these "objects" carries a small bit of "intelligence" and that as functions become structurally interconnected, "emergent properties" in a negative sense of the word, that is in the form of unintended software defects, colloquially known as "bugs," can appear. Small errors or unnoticed errors in an object can appear when it appears in another context, leading to the necessity of a costly and expensive debugging process. Often it is better to start from scratch rather than reusing snippets of imperfect code.[7] That being said, projects using algorithmic methods in the end may require *more* upfront investment than those relying on more traditional methods. Offices who adopt these methods with unrealistic expectations or for the wrong reasons may walk away disillusioned.[8]

4) The focus of adopting algorithmic methods should be on enhanced creativity: The previous point made an argument against the oft-touted selling points regarding enhanced productivity that many expect to reap from increasingly automated algorithmic workflows. Several issues surrounding the transportability of algorithmic methods between projects were likewise presented, with technical considerations and limitations being described in some detail. An additional consideration would be that is also unlikely that a large degree of portability would be even desirable from a creative standpoint. A certain project or formal expression may be visionary at first, but variation and replication can quickly become boring and derivative, especially if the forms are playful explorations lacking deeper substance and meaning. If landscape architects start creating dunefields everywhere based on the process described in §A13.2 and §16.7, or parks with paving patterns based on Grasshopper Vectorfields, they risk becoming unfashionable and neglected like so many other recent examples of digital experimentation in the landscape. Guattari makes a fundamental point when he states that: "My insistence on the need for aesthetic paradigms is based on an attempt to stress the importance of perpetual reinvention - of always starting from *tabula rasa* … The alternative is entrapment in deathly repetition."[9] Digital experiments are a worthwhile endeavor, as hopefully this thesis has conveyed, but they need to be part of a larger program of experimentation. Again quoting Guattari: "What it requires is the promotion of innovative practices; the proliferation of alternative experiments which both respect singularity, and work permanently at the production of a subjectivity that is simultaneously autonomous, yet articulates itself in relation to the rest of society."[10]

Part II of this thesis presented a series of algorithms of increasing complexity and in Chapter 9, a distinction between algorithms that generate patterns indicative of "striated spaces" vs. algorithms suggesting the processes of "smooth spaces" was made. The section proposed that while more difficult to program, methods with logics deriving from smooth spaces, such as agent-based models, may offer more creative potential for landscape architects to describe the ambiguities, complexities, and topological variability of landscape space, especially in contrast to architectural space, which is perhaps better described with algorithms indicative of "striated" space. For practices looking to unlock the creative potentials of algorithmic design in a landscape context, effort and research in this direction, in the author's opinion, may in the end bear the most fruit.

18.5. Future Research Needs in Algorithmic Landscape Design

The themes related to algorithmic landscape design presented in this dissertation have been very broad and wide-ranging. As such, many topics were not explored to the degree that they could have been. At the same time, these gaps indicate many potential avenues for future research. The points enumerated thus far in this general conclusion should give some insight into areas showing a degree of promise, but it would be impossible to present an exhaustive list here. Nevertheless, four major areas of interest to the author that may be especially productive directions for future research include the following:

1) Methods for co-authorship in digital environments need to be developed: One of the most promising benefits of computational design, as presented by Mario Carpo, is the opportunity for collective authorship. He asserts that "all that is digital is variable, and all that is digitally variable is potentially open to interaction, communality, and participation." (§7.6) With the interest in mediating between the wants and needs of a multiplicity of actors in democratic societies, a robust dialogue surrounding participatory methods has emerged in landscape architecture in recent years. The potential for exploring the intersection between community engagement strategies, especially as communities around the world become increasingly computer literate, and computational design in this context should be obvious. A recent essay "Computation and Participation in Design" by Andrea Hansen Phillips proposes just that, and gives an overview of nascent efforts in this direction. Since there is low economic incentive for professional software developers to develop these tools for specific applications, landscape architects trained in coding and those engaged in hybrid-practices are starting to fill this gap.[11] Such methods could enrich any design proposal, but in the context of this research, both the case study in Medellín (Chapter 15) and in Oostvaardersplassen (Chapter 17) would especially benefit from algorithmic tools for facilitating more active engagement with the affected actors.

2) The potential applications of CFD models to landscape architecture need more testing and intuitive physics models for experimentation need to be developed: One of the biggest disappointments in the course of this research was the failure to adequately develop a model using Computational Fluid Dynamics software to test the consequences of specific infrastructural interventions on the forces and flows in dynamic landscapes, especially in the context of the Wilhelmshaven case study. (§11.4, §11.5, §16.9) Part of the problem is that such software has largely been written for highly controlled, high-budget experimentation in the context of the aerospace and automotive industries. Some software packages are moving to applications at broader scales, such as Delft3D, but to make a convincing test of this methodology, a well-funded collaboration between landscape architects and experts in the use of this software would be welcome. As described in §11.4, some practices are already establishing such cooperation (Mosbach, Rahm, and Transsolar), but examples of this being implemented on specific sites are still lacking. To aid in experimentation, however, landscape designers could devise tools which make use of simplified CFD algorithms, such as that devised by Jos Stam for use in gaming,[12] which while lacking the scientific rigor of professional CFD packages, could help in the conceptual design process. Trans-disciplinary collaborations to verify the assumptions and results of these experimental tests, however, would still need to be formed for use in the later phases of project design.

3) Methods for implementing the products of algorithmic design on real-world sites, especially at the larger scale of landscape, need to be investigated: The discourse surrounding algorithmic design in architecture has been strengthened and grounded through a parallel discourse into methods of digital fabrication. To date, however, most of these tests have been at very small scales, partly since the output tools—3D printers, laser cutters, CNC mills, or robotic arms—can only produce results at limited sizes. These methods can also be very time extensive, with 3D printers taking hours to produce even small objects. To ultimately build such algorithmic architecture at larger scales, conventional methods have to be used, requiring a great deal of customization and expense. At the scale of landscape, however, the means and methods may be very different than those that architects use. Already, some promising research in this direction involves methods such as stakeless grading, whereby robotically controlled equipment is used to do heavy site-work using GPS coordinates referenced to a digital model,[13] or the method of robotic tree planting, where fleets of drones fly over ecosystems to be restored, determining where specific species should be planted determined by an algorithmic process, after which a second drone actually plants the trees in the specific pattern.[14] Landscape architects could also adopt methods from precision agriculture, an increasingly digitally managed approach to one of humanity's oldest professions, which robotically manages the agricultural regime according to data collected regarding the minute intricacies of sites.[15]

4) Adaptive and Relational Landscape Masterplanning: A final major research direction proposed by this thesis stems from the concept of the adaptive landscape masterplan, inspired by the Computational Urbanism of Thom Mayne and Tom Verebes. The Oostvaardersplassen case study in Chapter 17 is an example of this concept, but there is much more room for exploration in this direction. This theme has been returned to repeatedly, especially in in §2.12 and §5.12. and is described above in §18.2.4 as a potentially rich avenue of future research. Specific methodologies were proposed or explored in §3.11, §3.12, §5.11, and §10.4. This is also a strong component of Eduardo Rico and Enriqueta's methodology known as the Relational Urban Model to make planning decisions in new towns in the developing world.[16] More examples of such models specifically addressing the planning and evolution of landscapes should be proposed, and examples of both adaptive urban and landscape planning put into practice through on-the-ground implementation need to be pursued.

18.6. Broader Technological and Cultural Considerations

In conclusion, the role of the algorithm in the field of landscape architecture has been explored in this thesis in many dimensions, hinting at but not directly addressing several important societal and ethical questions which are intertwined with the digital-algorithmic paradigm. A fuller exploration of these questions is beyond the scope of this thesis, but this does not mean that the need to explore and address them is not urgent. The consequences of living in an increasingly data-driven society, mediated not always directly by bad actors, but often by imperfect algorithmic processes, needs to be carefully and critically considered. Developments in this direction are happening at an accelerating rate, and advances in machine-learning are increasingly taking the development of the algorithms themselves out of human hands and out of the realm of human scrutiny. Algorithms designing algorithms.

Many questions will arise as algorithmic methods become pervasive both in landscape architectural practice and in the broader society. Will computational technologies and artificial intelligence ultimately liberate us, or will we become their slave? Will the relationship between "robots" and humans be one essentially of cooperation, or of competition? This is not meant to invoke a dystopian scenario from science fiction. Already thousands of workers see emergent computational technologies as a threat to their livelihood, and this trend is only set to increase. So far, the effects have been in jobs that require performing numerous routine tasks, but eventually artificial intelligence will also touch upon the lives of those in other fields, and eventually even in the creative fields such as design. Some take solace that those in the creative professions may be largely insulated by the increasing mechanization of society; Alexander, for example, felt that computers could not work with his patterns, as human creativity requires invention. Artificial intelligence is however, moving in the direction where algorithms *learn* and early demonstrations point to the possibility that they can even engage in creative processes. Computers running "genetic algorithms" (see chapter 14), for example, can create musical compositions and design products.[17] Answers to these questions, ultimately, will strike at the core idea of what it means to be human.

Leaving aside these existential questions, issues surrounding the distribution of the benefits and the risks associated with these emergent technologies also need to be addressed. The competition of the future may not be between robots and workers directly, but through those who *own* the robots and workers. We are already seeing this in GDP and employment figures. Perhaps this phenomenon is most starkly manifest in the seemingly absurd overvaluations of technology firms in comparison with more traditional enterprises. As just one extreme example, the company WhatsApp made headlines just a few years ago when the company which employs fifty-five people was sold for $19 billion dollars. This leads to the absurd valuation of $345 million per employee, but this is not the amount that each employee of the buyout received.[18] Numerous other examples abound. Owing to the relatively small size of the profession, automated landscape design will unlikely be a target in the near future of overzealous techno-capitalist interests, but in their own lives and their own practices, landscape designers need to carefully reflect on these trends, and rather than ignore developments with which they are uncomfortable, move to steer and lead the discourse in positive directions. The best way to confront the absurdities of technologies and the emerging dominance of algorithmic paradigms in society, however, are not to ignore them, but to critically engage them, embracing what improves societies and environments, and challenging what is destructive. Ultimately, it will be up to landscape architects ourselves to discover, invent, and apply algorithmic and computational methods in ways that benefit our communities, our broader society, and the global environment in which we live.

In closing, the perspectives of two thinkers introduced earlier in this text could be again considered: the optimism of Leibniz, who may have said of computation that it represents "the last effort of the human mind, and, when this project shall have been carried out, all that men will have to do will be to be happy," (§4.4) in contrast to the measured pessimism of Burnham, who struggles with the dilemma that "it appears that we cannot survive without technologies potentially just as dangerous as the dilemmas they are designed to solve," and who feels that "systems theory may be another attempt by science to resist the emotional pain and ambiguity that remain an unavoidable aspect of life." (§1.9) With a sense of critical reflection on these two viewpoints, it is the belief of the author that landscape design professionals should be in a better position to approach the promises and perils of algorithmic design, and to steer the dialogue and experimentation surrounding computational methods in a way which moves these towards more socially, ecologically, and artistically productive ends.

Endnotes

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7 Kevin Kelly, *Out of Control: The New Biology of Machines, Social Systems and the Economic World* (New York: Basic Books, 1995), 198.

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Appendecies

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Figure 7.6: author's original drawing
Figure 7.7: author's original drawing
Figure 7.8: author's original drawing
Figure 7.9: author's original drawing
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Figure 7.15: author's original drawing
Figure 7.16: author's original drawing
Figure 7.17: author's original drawing
Figure 7.18: Tiger Bush in Niger, US Geological Survey, sciencedaily.com
Figure 7.19: author's original drawing

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Figure 8.0: Photo Joseph Claghorn
Figure 8.1: author's original drawing
Figure 8.2: author's original drawing
Figure 8.3: author's original drawing
Figure 8.4: author's original drawing based on concepts of Peter Stevens in *Patterns in Nature,* 37-50.
Figure 8.5: Harvard Mathematics Department
Figure 8.6: Donella Meadows *Thinking in Systems* (London: Earthscan, 2008), 19. Images courtesy of Donella Meadows.
Figure 8.7: author's original drawing

Figure 8.8: author's original drawing
Figure 8.9: John G. Bartholomew, *An Atlas of Economic Geography*, 1914. Rome2Rio, 2016.
Figure 8.10: omitted for copyright reasons
Figure 8.11: omitted for copyright reasons
Figure 8.12: author's original drawing
Figure 8.13: author's original drawing
Figure 8.14: author's original drawing
Figure 8.15: author's original drawing
Figure 8.16: author's original drawing
Figure 8.17: D'Arcy Thompson, *Growth and Form*, a new edition (Cambridge: The University Press, 1945), 1062-1064.
Figure 8.18: author's original drawing
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Figure 8.21: author's original drawing
Figure 8.22: author's original drawing
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Chapter 09

Figure 9.0 Photo Joseph Claghorn
Figure 9.1: Courtesy of Google Earth
Figure 9.2: Courtesy of Google Earth
Figure 9.3: Robert Ulanowicz. *Growth and Development,* 101.
Figure 9.4: Corner and Maclean. *Taking Measures Across the American Landscape*, p. 48.
Figure 9.5: Google Earth
Figure 9.6: Stan Allen, "Field Conditions." From Points + Lines: Diagrams and Projects for the City (Princeton Architectural Press, 1999).
Figure 9.7: Top - www.ec.gc.ca/biotrousses-biokits/default.asp?lang=En&n=F0B7344C-1
    Bottom: Alexander von Humboldt, Chimbarazo
Figure 9.8: Forman. *Landscape Ecology Principles in Landscape Architecture and Landscape Planning*, 16.
Figure 9.9: author's original drawing, after Allen.
Figure 9.10: author's original drawing
Figure 9.11: author's original drawing
Figure 9.12: author's original drawing
Figure 9.13: author's original drawing
Figure 9.14: author's original drawing
Figure 9.15: author's original drawing
Figure 9.17: author's original drawing
Figure 9.18: author's original drawing, after Karres en Brands

Chapter 10

Figure 10.0: Photo Joseph Claghorn
Figure 10.1: Ulanowicz, *Growth and Development,* 159.
Figure 10.2: S. Bohn, S. Douady, and Y. Couder. Four sided domains in hierarchical space dividing patterns. *Physical Review Letters* 94 (American Physical Society, 2005), Fig. 1, Fig. 6, Fig. 7.
Figure 10.3: author's original drawing
Figure 10.4: Lindenmayer and Prusinkiewicz. *The Algorithmic Beauty of Plants.*
Figure 10.5: Parish and Müller, "Procedural modeling of cities," SIGGRAPH '01 Proceedings of the 28th annual conference on Computer graphics and interactive techniques. (New York: Association for Computing Machinery, 2001), 302, 305. Image used with Permission.

Figure 10.6: author's original drawing
Figure 10.7: author's original drawing
Figure 10.8: author's original drawing
Figure 10.9: author's original drawing
Figure 10.10: author's original drawing
Figure 10.11: author's original drawing
Figure 10.12: author's original drawing
Figure 10.13: author's original drawing
Figure 10.14: author's original drawing
Figure 10.15: author's original drawing
Figure 10.16: author's original drawing
Figure 10.17: author's original drawing
Figure 10.18: Source: Wikiart.org, except 3. abcgallery.com & 4. paintingdb.com
Figure 10.19: author's original drawing
Figure 10.20: author's original drawing

Chapter 11

Figure 11.0: Photo Joseph Claghorn
Figure 11.1: Leonardo Da Vinci Sketchbook.
Figure 11.2: Lebbeus Woods. <Lebbeuswoods.wordpress.com/2010/12/18/slipstreaming-2/>, 18 Dec 2010. Courtesy Princeton Architectural Press, Lebbeus Woods Estate.
Figure 11.3: Image courtesy of: earth.nullschool.net – Screenshot 15 April, 2018.
Figure 11.4: Catherine Mosbach and Phillipe Rahm competition entry for Taichung Gateway Park, 2011.
Figure 11.5: Design by b720 Arquitectos. Photo credit: frankblacknoir Wikimedia commons, 2008.
Figure 11.6: Photo Jamin Grau, Joseph Claghorn
Figure 11.7: author's original drawing
Figure 11.8: author's original drawing
Figure 11.9: author's original drawing
Figure 11.10: Author's algorithmic adaptation based on Schwenk, *Das sensible chaos,* 30.
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Figure 11.14: author's original drawing
Figure 11.15: author's original drawing
Figure 11.16: author's original drawing
Figure 11.17: original source unknown: Slideshare.net
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Chapter 12

Figure 12.0: Photo Joseph Claghorn
Figure 12.1: Source unknown
Figure 12.2: Andrew Adamatzky, "Approximating Longest Roads in USA and Germany with Slime Mould"
Figure 12.3: Craig Reynolds, top 3 images, author's original drawing bottom image
Figure 12.4: Nikolay Nikolov Popov, "How Can Netlogo be Used in the Landscape Architectural Design Process."
Figure 12.5: author's original drawing
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Figure 12.8: author's original drawing

Figure 12.9: author's original drawing
Figure 12.10: author's original drawing
Figure 12.11: author's original drawing
Figure 12.12: author's original drawing
Figure 12.13: author's original drawing
Figure 12.14: author's original drawing
Figure 12.15: author's original drawing
Figure 12.16: author's original drawing

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Figure 13.0: Photo Joseph Claghorn
Figure 13.1: Szabó, Józef. "Anthropogenic Geomorphology: Subject and System," 7.
Figure 13.2: Study for Bass River Park, Copyright Stoss Inc. Image courtesy of Chris Reed.
Figure 13.3: Josine Lambert and Eugenio Darin, *The Riparian Land-shaping Machine,* (AA Landscape Urbanism: 2014), 35.
Figure 13.4: Beaman, "Landscapes After the Bifurcation of Nature," 437.
Figure 13.5: Courtesy of PARKKIM, *Mud Infrastructures,* photographer: Jong Oh Kim.
Figure 13.6: author's original drawing
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Figure 13.12: author's original drawing
Figure 13.13: author's original drawing
Figure 13.14: author's original drawing
Figure 13.15: author's original drawing
Figure 13.16: Image used with permission. Richard Huggett, *Fundamentals of Geomorphology,* 2nd edition. (London: Routledge, 2007), 7.
Figure 13.17: author's original drawing
Figure 13.18: Image courtesy Hans Beyer. Hans Theobold Beyer, "Implementation of a method for hydraulic erosion," TU Munich, 2015.

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Figure 14.0: Photo Joseph Claghorn
Figure 14.1: author's original drawing
Figure 14.2: author's original drawing
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Figure 15.0: Photo Joseph Claghorn
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Figure 15.5: Echeverri, Werthmann, et al. *Rehabitar la montaña,* 253.
Figure 15.6: Echeverri, Werthmann, et al. *Rehabitar la montaña,* 227.
Figure 15.7: author's original drawing
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Figure 15.14: Pinedo, et. al., 201.
Figure 15.15: author's original drawing
Figure 15.16: author's original drawing
Figure 15.17: author's original drawing
Figure 15.18: Roman Früh and Marten Urban, "Re-making Medellin" Studio Project, 2012. Based on techniques described in Studer and Zeh, *Soil Bioengineering, Construction Type Manual,* 234-235.
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Chapter 16

Figure 16.0: Photo Joseph Claghorn
Figure 16.1: "Entwicklung von Jadebusen und Weserdelta; Verlandung seit 1300 entstandener Wasserflächen ab 1500 nur indirekt über die Abdeichung dargestellt." CC BY-SA 3.0, created by user Ulamm, 2014.
Figure 16.2: "Jade, Elb- und Weser-Mündung," *Justus Perthes See Atlas.* Gotha: Justus Perthes, 1906. Public domain.
Figure 16.3: Student created image: Marianne Cabanis, Aranzazu Ceron Herrera, Lenka Podolakova, Mengyao Xing, 2016. Base data from Wadden Sea World Heritage Center.
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Figure 16.5: Student created image: Sebastial Beutel with data from NLWKN 2007, 44.
Figure 16.6: Student created image: Sebastial Beutel with data from NLWKN 2007, 14.
Figure 16.7: author's original drawing
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Figure 16.18: author's original drawing
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Figure 17.0: Photo Joseph Claghorn
Figure 17.1: Photos Joseph Claghorn and film still from De Nieuwe Wildernix, 2013.
Figure 17.2: Provincie Flevoland, “Ostvaardersland: Strengthening the economy and ecology of the Netherlands.”
Figure 17.3: author’s original drawing
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Figure 17.13: author’s original drawing
Figure 17.14: Photographer unknown. “Cycling in Almere.” www.vvvalmere.nl/en/fietsen.

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Eidestattliche Erklärung

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Hannover, 12 Sep 2018 Joseph Claghorn