Material Computation for a New Equilibrium in Architecture
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MATERIAL COMPUTATION FOR A NEW EQUILIBRIUM IN ARCHITECTURE

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ABSTRACT

Morphogenesis defines the schema of natural material formations as a set of merging self-organized behaviours, rules, relative forces, and limits of materialization that analytically characterize a spatial arrangement within a specific environment for achieving an equilibrium state. However, in architecture, material organization, which acts as a threshold to space, has always been treated as a secondary component in design processes. This attitude has reduced the capability to generate an architecture that is intelligently aware of its functionality and of its environment. Transforming computational models of biological systems into the computational logic of material organization found in architecture would produce an architecture that is a product of full interactions between those material logics and space. This inquiry elaborates a set of biological computational frameworks to cultivate stratified developments of knowledge-based architectural prototypes of complex hybrid-structure material morphologies as contextual schemata.

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To my mother, whose voice I first did hear

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Introduction

When architecture is considered as a material practice, materiality is emphasized as an inextricable component of it, both in materiality's theoretical and technical developments. In one sense, materiality may be used to rationalize a virtual form, equivalent to layering a geometrical construct. However, materiality does not simply refer to substance. It also suggests a model of thought. In this sense, its computational frameworks make use of computational models of natural systems. The organizational capacity of materiality is analytically envisaged by infusing morphogenetic and evolutionary schemata. These schemata include natural materials' computational interactive-based behaviours, tendencies and characteristics that are deeply embedded in their finest structures. The schemata are merged and coupled at an anatomical scale in order to manifest form as an intensively integrated deployment relative to the space that material defines. This developed spontaneous organizational capacity as a whole achieves a state of equilibrium based on feedback. In this process, which is equated with Frei Otto's form-finding experiments, materiality is an inseparable constituent of the design process. It signifies natural organizational processes. The work of Frei Otto and his design-intuitive experimentation with soap bubbles, which resolved a physical form-finding method for woven textiles and fixed-node meshes, illuminates a comprehensive re-stratification of material systems. The work of Antonio Gaudí and his hanging chain models for the design of Sagrada Família in Barcelona also incarnates these architectural strategies. More recently, Achim Menges and Sean Ahlquist's intensive research prototypes and pavilions display highly integrative material culture.

In architecture, material organization is defined as formulating materials' attributes into factors that integrate space. These attributes carry matter's characteristics, and they correlate with embedded inner-connected rules and elements. These formulations of attributes merge reciprocal inner-connected interactions between both a material construct,

which has both deterministic and indeterministic parameters, with spatial factors' forces (external and internal). This initial process itself has a high degree of computational complexity, which has been known to confuse most designers. The computational and mathematical models of complex biological systems have demonstrated that solving extremely complicated interactions can be facilitated through employing a combination of simple and yet expandable rules. Thus, this thesis elaborates upon natural material formation's logic in order to integrate those interactions into computational logics of material organizations in architecture.

This thesis initially elaborates upon the use of a panoply of recent innovative technological hardware, desktop computers, to envisage and calculate sublime complex material organizations in various domains. *Simultaneously, within the focus of this thesis, a scientific dynamo is developed from a biological space to cultivate and generate a framework for material computation in architecture from a constellation of accumulated system qualities, natural material processes, and intellectual concepts.* (Kwinter, 1994) These cogitated schemata, these multidisciplinary domains with complex pedigrees profoundly rooted in computer science, mathematics, system science and philosophy and their lineage is traced from biology, as a single organizational entity that constitutes an integrative dynamic transition state in architecture both technically and theoretically.

This calibrated reciprocal maturation of both theoretical and technical amelioration effectively critiques the classical mechanism of linear systems and their deductive methodologies. Then, it deciphers the retrograde nature of authority driven from Phenomenology in order to circumvent and actually obliterate an ideological over-coding arising from dogmatic typologies in a biological interactive domain in architecture. This means that, similar to the science of biology, where its development assures that the dynamics of information in living organisms has gained control over the dynamics of energy (which, in classical terms, derives

nonliving systems), this inquiry aims to exploit the dynamics of information in order to study a 'Transition State' in architecture. (Kwinter, 2008) (Holland, 1995)

In doing this, instead of speculating on descriptive methodologies, this thesis' scientific dynamo engages analytical explanations in order to de-pathologize nonlinear systems to cultivate a framework for interaction-based material organizations in architecture. This involves moving from mimetic representations of nature to modeling a wide variety of domains to illuminate the ultimate integrative capacities of anti-arborescent and anti-entropic¹ bio-extended sublime complex state apparatuses. This might enable our mental faculties to engage aspects of the natural world whose logic was formerly unattainable because they are too great and removed from modalities of designer's sense of intuition, as Sanford Kwinter puts it (Kwinter, 2008)

Moreover, this thesis aims to alter the material culture in architecture from a comprehension of simply mechanical inert terms into a more computed, controlled, responsive and, above all, interlinked behavioural organizational domains. What is important here is not to revolve around shape memory alloys, or microchip-driven material systems, but rather to develop a transcendental schema for deciphering and indeed de-territorializing de-stratified embedded rules within natural organisms by abductive lines of segmentation to create an interactive domain that evades and breaks off from the dogmatic over-coding dominating regime in current discourse in order to spontaneously re-contextualize an architecture which correlates various environmental agencies within its abstract machine's intelligence. (Deleuze & Guattari, 1987)

It is worth declaring that no abstract machine, in this case a computer, can outperform the simple intelligence of any living organism on earth. It is in the design-intuition

¹ Entropy persistently moves toward a deconstruction and simplification of everything, but the spontaneous capacity of living organisms (life) is anti-entropic: perpetually shifting toward a greater complexity and organizations as Buckminster Fuller put it.

sense that the author borrows the term 'learning machine' from Negroponte. The terms intuition, machine, and intelligence need to be elaborated in this inquiry. The faculty of intuition, by Kant's definition, shapes the state apparatuses of intelligence. The form of intelligence that author aims to develop within the machine (computer) is driven from cogitated transcendental schemata of morphogenetic processes and evolutionary systems. These cogitated schemata as models of thought consider that intelligence has integrative qualities. Integrative intelligence does not respond to the conditions which it confronts, but, it rather responds to causalities of circumstances in active domains. Its processes make models of arbitrary systems circumscribed behind situations they encounter, even de-territorializing co-parallel and recursive evolutionary processes in this author's humble opinion. This kind of intelligence decentralizes and re- contextualizes various state apparatuses in a degree of perfection. In other words, it is not about adaptation itself, which occurs in the twists and turns of evolutionary processes and their development. It is about a process that is unfixed but related in time and separated from Euclidian space and geometry. ***Here, by Kant's definition, intuition is neither synthetic and nor analytic. It deciphers analytical explanations of causalities, and it apprehends multiplicities of interpenetrating processes separated from space, time and external bodies in order to perceive form in snapshots of transition states which are in a ceaseless materialization flux in which it has codified into the abstract machine. It takes bursting fragments of perpetual anti-entropic features of life and develops a propensity to accumulate temporal dimensions into mapping probabilities as do some spatial parts of some spatial plants. This inquiry is about the faculty of intuition shaping the faculty of intellect to incarnate simultaneous temporal multiplicities of ideas (in various levels of strata of mind) into object, geometry, logic and materiality in architecture.*** (Kant, 1914) (Bergson, 1944) (Deleuze, Bergsonism, 1991)

It is worth also noting that this inquiry, which explores morphogenetic processes in

order to develop a pure intuition, thereby forming faculties of heterogeneous intelligences that are codified in abstract machine, ***does not assume an architecture akin to homogeneous thought about nature***. Similar to Alfred North Whitehead's proposal, here homogeneous thought about nature only empirically observes natural phenomena for further simplification. (Whitehead, 1971) But, there's a different approach that takes homogeneous thought about nature and incarnates an ingredient called thought. Such approaches are called heterogeneous thought about nature that involves thought itself as well. (Whitehead, 1971) This heterogeneous thought about nature is purely reflected in the work of Goethe and his transcendental schemata for metamorphosis. Therefore, ***here, being akin to natural systems, it alludes to heterogeneous thought about nature***.

Highly influenced by Kant's transcendental schemata, Goethe's formation and transformation (gestalt), and Darwin's evolutionary process, the author aims to not only implant these schemata in the mental faculties of transitional moments of his design-intuition exercises, but also to incarnate these complex, nonlinear anti-arborescent and sublime biological models into the fashioning of the structural metaphor of the narrative in this book as well. *"Arborescent hierarchical models that have spinal axiom theory develop an argument with a privileged viewpoint over-coding and dominating other regimes."* (Deleuze & Guattari, 1987) *Hence, there is no privileged point of view in this thesis. It is an analogue to connect multiplicities of ideas in various domains to architecture. Therefore, this thesis is not an argumentation which postulates a thesis, and develops several examples in order to establish a superior position in which it arrives at a fixed determined conclusion at the end. It does not attempt to inaugurate a deterministic epoch that sweeps everything else away because of a privileged central point of view. It can be read in any order. Chapters in this book ramify in a lateral way to create transitional states of connectivity without a central privileged position. It takes architecture into an infinite horizon with no hierarchical feature, middle, beginning*

or an end. It explores trans-disciplinary horizons to connect multiplicities from various domains of science; it becomes an assemblage of connectivity mapping a plane of organization as Deleuze and Guattari put it in their final chapter of 'A Thousand Plateaus'. (Deleuze & Guattari, 1987)

It is also worth noting that for illuminating possibilities and probabilities of mapping natural material systems' logics into material computation, this inquiry takes notes from the geneeses of sciences. Therefore, references from various disciplines are cited not as authorities, [in which this type of writings mostly appear in linguistic theories such as Hegelian absolutism], but they are instances of elucidations and clarifications for purposive purposelessness, as Kant puts it. In other words, in order to remove obscurities of expression, the author aimed to elucidate, communicate and deliver each topic, analytical explanations, and main concepts with the use of regimes of signs (language). It is perhaps as well to state explicitly that the reader might require some familiarity with concepts of nature. As nature's appearance is a complex system whose truth is rarely deciphered, concepts in this inquiry have not been fully elaborated in a simple linear manner. (Whitehead, 1971) This inquiry scrutinizes the genealogy of these intellectual concepts. In addition, in this inquiry, although mathematical notations have been avoided, their deducible logics have been analytically explained. The author has also aimed to evade any fixed conclusions, however doubtlessly his preformed opinion influenced his selection of materials that he has fashioned.

Chapter One: Computation

Introduction

It is evident that with the advent of recent technological hardware such as video display computers, the way in which we compute, perceive, realize, and visualize contemporary architectural form, space, material and structure is fundamentally different from the way these were previously understood. However, what is implicit here is not simply the use of the visualization power of computers, but to understand the processes and information which can be addressed with the computing power of this 'numerical calculator'. This addresses stages in which current architecture operates to depict how information can be inscribed in various domains in processes with the use of computation.

Why Computation in Architecture

Current architecture is in a stage of evolution where design is moving from a critique of technique to a critique of design. This means that, today, design thinking in architecture is not about adopting one principle or standard by which it may be judged¹ or decided, but rather it involves the formation of the arguments in both a technical computational manner and theoretical, material, and architectural veins. This means that multiple layers of consid-

¹ (Note: Inspire by Immanuel Kant's Critique of Pure Reason. Here the author briefly interprets Kant's judgment to elucidate mental faculties behind computational schemata of the learning machine)

According to Kant, Understanding and Judgment possess in-transcendental logic, a canon of objectively valid and therefore true exercise. They are comprehended in the analytical department of that logic. Analytical principals would be merely tools for measurements in the faculty of judgement. Analytical principals are instructions for judgment's applications into a phenomenon, and they eventually lead to a pure conceptions of the understanding. Here Analytical truth does not extend our knowledge.

Judging or critiquing architecture would not simply allude to analytical means and measures, but it would rather refer to organized information in a computational fallacy. Computation by this definition takes Synthetic A Priori [geometrical knowledge] and adds a different heterogeneous transcendental schema into it within a different realm to extend architectural cognitions beyond boundaries of our predictable possible experience. What the author means by this is that some of our knowledge begins with experience, but it does not arise from it. Here, A Priori is true statement, and Synthetic is empirical knowledge coming from our experiences. A heterogenous transcendental schema which includes pure intuition is a science of our own thoughts reflecting upon itself which takes our bio-extended capacities to incarnate various levels of information into a codification language within architecture.

erations, techniques, and information at various levels built into design processes are inextricable in architecture.

Learning Machine as a Response to Oversimplified and Disregarded Information

Arguably, issues and problems in current architecture are oversimplified on one level, even as they are disregarded on another. Therefore, current architecture falls into a middle ground of being ultimately generalist. In this approach, everything becomes a generalized idea, concept, and even data. Nicholas Negroponte in his early writing, *Toward a Theory of Architecture Machines*, succinctly defined this issue. He stated that ***'first, architects cannot handle large-scale problems, for they are too complex; second, architects ignore small-scale problems, for they are too particular and individual (and to them trivial).'*** (Negroponte, *Toward a Theory of Architecture Machines*, 1969) Furthermore, in some cases, to accomplish some of those considerations of details, architects have to neglect the issues on the other scale.

Negroponte offered the concept of the evolutionary machine that can be self-improving in that it enables

Figure 1 Negroponte's Interactive Machine, from <http://cyberneticzoo.com/robots-in-art/1969-70-see-nicholas-negroponte-american/>

the computing of various issues at different levels of the systems. (Negroponte, *Toward a Theory of Architecture Machines*, 1969) The implication here is that this machine can actually address several layers in a system, in terms of information built into design processes, and also in terms of the operation of an architectural system with computing power embed-

ded in it. (Negroponte, Jan.15.1973)

Computing methodologies have been adopted by several scientific disciplines ensuring numerous scientific advancements, whereas architecture has not advanced according to its capacity. John McHale emphasized this problem, and he argued for the application of the highest scientific and technological advancements. (McHale, 1967) Interestingly, he suggested using computers to re-conceptualize systematic thinking in architecture. (McHale, 1967)

Computerization vs Computation

A clear understanding of computation involves being able to distinguish between computerization and computation. In his writing, *The Death of Drawing*, David Ross Scheer clearly offers computerization as a tool for automation of what might have been traditionally manually processed. (Scheer, 2014) Scheer argues that computerization allows a better understanding of what has been designed through images or inputted data. (Scheer, 2014) The critical point here is that with Scheer's method, computers are used as a tool for storing preconceived data, concepts or even processes for the purpose of communication, visualization, and presentation. When doing this, designers ignore the computing power that computers offer. Kostas Terzidis, in his book *Algorithmic Architecture*, explicitly addresses this problem:

“The dominant mode of the computational mode of utilizing computers in architecture today is that of computerization; entities or processes which are already conceptualized in the designer’s mind are entered; manipulated, or stored on a computer system. In contrast, computation or computing, as a computer based design tool is limited. The problem with this situation is that designers do not take advantage of the computational powers of computers”. (Terzidis, 2006)

Computers as Modern Calculators (Cache)

Beyond using computers for coloring the video display, we can think about its computational power, the power that performs the calculations that enable mega organizations. Bernard Cache, French architect and philosopher, states that computers certainly increase the productivity of ideas, and that their use lets us *envisage second-generation systems in which objects are no longer designed but calculated.* (Cache, 1995) The emphasis here is on the computational power of this calculating tool.

Before Computers

For a clear comprehension of computers as a tool for calculating mega organizations, they should be studied in a historical context. The lineage of the first calculating tool can be traced back to the Egyptians' use of pebbles for addition and subtraction. Indeed, the word pebble is calculus in Latin. Contemporaneously, the Hindu-Arabic notational system was used for calculation. Later, the abacus (also referred to as a counting frame) was widely used for centuries by merchants. In 1673, Gottfried Wilhelm Leibniz developed the first mechani-

Figure 2 A Re-constructed Model of Charles Babbage's Difference Engine, from <http://www.theverge.com/2012/11/30/3709676/charles-babbage-difference-engine-gigapixel-images>

cal calculators. His notational system, also called pinwheel calculator and “living abacus” was arguably the foundation of virtually all digital computers. Possibly the very first advanced mechanical calculator capable of storing data within a mechanical memory was devised by Charles Babbage in 1834. Babbage’s Difference Engine as a first general-purpose computing machine had the basic architecture of modern computers. His machine had separate data and program memory, and operated on instruction-based principles, within which control units could make conditional jumps. (Wurster, 2002)

Modern Computers

The concept of the first abstract ‘universal machine’, which would follow a series of codes and instructions (algorithms) constituting a new generative system for the solidification of an argument, was introduced in a paper “On Computable Numbers” by Alan Turing in 1934. He also emphasized that one must differentiate between software and hardware with this machine. Indeed, John von Neumann, a genius who helped to design the architecture of all modern computers, based his main theories on Turing’s masterpiece. Arguably, today’s technological hardware and desktop computers operate in the same manner. Turing’s modern programmable computer was capable of computing by executing a program on a tape. (Wurster, 2002)

The advent of modern computers offered advantages such as efficiency and precision to several disciplines, thereby ensuring numerous advancements. However, before modern computers, calculating machines were used in aerospace and automotive disciplines for complex calculations. This new advanced technological hardware and modern personal computer initially offered new forms of accuracy and adequacy which allowed scientists to anticipate complicated nonlinear equations with huge amounts of data with deterministic and in-deterministic parameters in a fraction of the time of previous methods. This is what we now commonly refer to as simulation of the physical world. Concurrently, this efficiency

was followed by the production of technical blueprints that allowed for complex geometrical drawings to be visualized faster than they had been traditionally. Within architecture, computers are still being used as an accurate drafting machine for visualization of a preconceived concept to store information. But if architecture understands this numerical video display calculator's language, it can extend its capacities to reveal new territories within the discipline.

From Alberti's Machine to Sutherland's Graphical User Interface (Sketchpad)

For a clear understanding of computers and their implications as regards material organization in architecture, one must understand them within an architectural context. The very first graphical interfaces such as Sketchpad, GRASP and LOKAT for architecture were developed at MIT in 1960s. Sketchpad developed by Ivan Sutherland was the first procedural design based interface introduced to practice. Sutherland's innovative graphical user face (GUI) constituted new interactions between designers and computers. Designer would use a light pen to register points for constructing a geometry. "Construction of a drawing with Sketchpad was itself a model of a design process." (Ivan Sutherland) Sketchpad reflected the very first parametric and rule-based design interfaces. Current parametric rule-based design interfaces (surface population, geometry-based, hierarchical models) introduced through new software packages (Grasshopper, Generative Components) with recognized developers (McNeel, Bentley) from the CAD/CAM field are examples of parallel, but limited implementations of material systems into architecture. (Hensel, Menges, & Weinstock, 2010)

Although Sutherland's interface was used as a tool for drafting in the industry, it marked a convergence point in the discourse. Architects and engineers admittedly used this interface as an analogous tool to replace pen, paper, T-square and drawing board. In this way, it altered design thinking. This interface, which offered efficiency, speed, productivity, and was used as a "high-powered drafting machine", made the designer think about the pro-

Figure 3 Source: <http://i.ytimg.com/vi/fddOvhjyy8o/maxresdefault.jpg>

cess and actually construct the process in the initial stage of the design. (Reichardt, 1969) As Marshall McLuhan, paraphrasing Churchill, once said “*we become what we behold; we shape our tools and then our tools shape us*”. Sutherland’s interface legitimately accentuated three main points which reshaped designers’ thinking as well.

First, the necessity for co-operation with computers meant that designers had to think about process. Second, with the use of Sketchpad, designers had to solve the design step by step, and third, design had to perform like an entity behaving acutely like Alan Turing’s tape. The critical point here is that Sutherland’s interface explicitly altered what it was to be a designer in the same way that Leon Battista Alberti’s machine that devised perspective changed what it was to be an artist or in the way that his drawing documentation changed what it was to be an architect. Similar to Sutherland and Alberti’s mechanism, material computation, which algorithmically writes the space for the anticipation of interactions between materials’ logic and space and their design intuition, lets designers think not only about the process but also about the design of information within that process, underlining a transcendental moment in architecture. ***This facilitates an imminent rebirth in architecture and shifts design thinking into a new territory considering information forming processes. In fact, computation is actually an information-forming processes.*** (Burry & Burry, 2010)

Computation with Algorithm

In computational approaches, information and data is processed with simple yet expandable rules and scripts called algorithms. Then through iterative procedures it actually

evolves into what should become very particular and an operational system. (Terzidis, 2003)

Therefore, algorithms represent and define a series of instructions, rules and procedures with specific details. Here, the word algorithm refers to a precise method that explains how an interaction should take place. For instance, directions from point A to point B can be referred to as an algorithm. As there are multiple ways to get from one place to another, there are many ways to write algorithms. Hence, assumptions and decisions which succinctly define directions are some key elements in transforming a nonlinear computational logic of natural material formations into algorithms. (Reas, McWilliams, Barendse, & LUST, 2010)

The lineage of the term Algorithm

The lineage of the term algorithm as a procedural calculating method (a set of rules precisely defining a sequence of operations) can be traced back to a name of a Latin translation of a book written by Muḥammad ibn Mūsā al-Khwārizmī, a Persian materialist, mathematician, astronomer, and geographer. The title of al-Khwārizmī's book, On the Calculation with Hindu Numerals (in 825 AD), was translated into Latin as *Algoritmi de numero Indorum*, and eventually this evolved into the term Algorithm. However, the origin of modern algorithms can be traced back to the work of Axel Thue (String Rewriting Systems in 1914), David Hilbert (Entscheidungs problem as the Decision Problem), Gödel–Herbrand–Kleene (Recursive Functions), Alonzo Church (Lambda Calculus in 1936), Emil Post (Formulation one in 1936) and Alan Turing's Turing machines in 1936–7 and 1939.

Algorithms for Organizational Thinking

The most decisive key point in a full understanding of computation here can be captured in an understanding of organizations. In modern computers, numerical hardware is controlled by codes, similar to programs which are governed by rules called algorithms. Just like human languages, there are various programming languages; however, these

fundamentally differ in terms of operations. People's languages are cryptically demonstrative, and they inconclusively encapsulate multiple interpretations. On the other hand, computer algorithms are precise mechanisms for modeling thoughts that require designers to think procedurally within a system of rules. They explain a range of possible interactions and forms within decisive or indecisive domains. Implicit here is the understanding that a designer has to draw a diagram as a system that enables computable design possibilities within certain dynamics of information. This reveals new sets of domains that offer designers ways to explore unpredictable interactive properties that emerge from predefined rules and procedures. Indeed, what is important in material computation is understanding natural materials' nonlinear systems, and their behavioral interaction-based properties. **Therefore, the most powerful and challenging use of the computer is in learning how to make a simple organization (the computer) model what is intrinsic about a more complex, infinitely entailed organization (the natural or real system). (Kwinter, 2003)**

What is Material Organization

The core concept of understanding natural material organizations has two sides in computation. On one hand, one must understand natural systems in terms of their formal ramifications and configurations of branching parts in its materiality, structure and operation. On the other hand, one must learn how processes of materialization relate to the environment and performance. The first part indicates material's classification, and the second refers to embedded rules in relation to the environment. These two aspects are intimately interconnected with each other and have a relation to the environment.

Understanding Wild Intelligence

There are numerous examples for understanding and engaging these two aspects of natural material systems as 'wild intelligence' when using computation. For example,

common fruit flies, which have survived and thrived for millions of years, used to exist as extremely large insects, and the reason for this is that they existed in a very oxygen-rich environment. Interestingly, scientists have demonstrated that their genetics have not altered, the interactions between their genes remain the same; it is responsiveness to the amount of available oxygen that constrains the growth of their respiratory framework. (DeLanda, 2011) Their respiratory system has a branching morphology. This is key to their relationship with the environment, as it affects the amount of oxygen that can be absorbed, affecting in turn interactive growth patterns. Therefore, there is not only a top-down trigger that compels this system to grow to a certain size but, also, growth size is not a consideration, unless it interacts with its environment. Hence, it is in understanding of processes, internal material logics, and how those internal material logics are influenced by external conditions that creates a performative interactive system based on feedback. (DeLanda, 2011) Growth developments in plants also exemplify the same schema. For instance, Alexander von Humboldt's simple seed theory suggests that seeds develop a certain kind of intelligence relative to their environment; this leads to their variational interactive growth pattern. (Humboldt & Bonpland, 2013)

Modeling Natural Systems

Therefore, ***'the implication here is the idea of learning how to make matter model matter, or how to study natural or 'wild' intelligence in a contained but active, refining domain. In this use the computer becomes metallurgical substance, it extends the exploratory evolutionary process of differentiation and refinement by inventing new levels of order and shape'.*** (Kwinter, 2003) With understanding these methods we might ***'use computation to engage aspects of the natural world whose logic previously remained unattained because they are too great and removed from the modalities of a designer's sense of intuition,'.*** (Kwinter, 2003) Within this scaffold, we may also, through iterative processes, de-

velop a framework which is capable of opening novel possibilities to consider ***material not as a passive predetermined element in design processes but rather as an active generator forming the design processes in current architecture.*** (Menges, 2008)

Chapter Two: System Thinking for Material Computation in Architecture

“...What we call Form is a ratio of magnitudes referred to direction in space...We are dealing with Form in a very concrete way. To Aristotle it was a metaphysical concept; to us it is a quasi-mechanical effect on Matter of the operation of chemico-physical forces. To Aristotle its Form was the essence, the archetype, the very “nature” of a thing, and Matter and Form were an inseparable duality. Even now, when we divide our science into Physiology and Morphology, we are harking back to the old Aristotelian antithesis...”

(Thompson D. W., 1992)

Introduction

For a clear understanding of material formation and its computational logic one must understand initially systematic thinking in current discourse, and secondly, how those systems’ behaviours appear in the dynamics of interactions of their parts: that is, not in a linear manner but rather demonstrating a cyclical causal effect based on scripted feedback. Here, the causality of the levels and the amount of interactions cannot be deciphered directly in an obtained equilibrium. This notion should be studied and investigated in the context of systems thinking and its theoretical advancement, not with deductive reasoning methods but rather within an historical context.

Holistic Science

Historically, *holism as a system of a whole encompassing more than the sum of its parts was introduced by Aristotle*. In *Metaphysics*, he wrote that ***“the whole is more than the sum of its parts”***. Holism secludes system’s parts having no influence in the process. (Aristotle, 2007) This means that the behavior of a holistic system cannot be shaped or defined by only the sum of its component parts alone. Instead, the system as a whole determines in

an important way how the parts behave. (Stanford Encyclopedia of Philosophy, 2008) In his science, holism is defined as an absolute top down ordering system. (Stanford Encyclopedia of Philosophy, 2008) Later, Descartes introduced causality for understanding a process. In his Causal Adequacy Principle, he restated Lucretius' famous quote, "ex nihilo nihil fit" defined as "nothing comes from nothing", and introduced a cause to bring something to an effect. (Descartes, 1999) (Lucretius, 1947) (Philosophy, 2008) Although, his contemporary, Francis Bacon, argued for a systematic investigation of nature where experience becomes a source of knowledge, Descartes detached the existence of matter in order to involve innate knowledge, the consciousness of the human mind. Following Descartes, Spinoza and Locke, backgrounded their systems on his casual duality. (Philosophy, 2008) A linear causality as a mechanical explanation was proposed by *Isaac Newton where he used Descartes' tools and developed Galileo and Bacon's method. Immanuel Kant's masterpieces, in particular Critique of Pure Reason in which he introduced the doctrine of transcendental logics, implemented immeasurable changes into science whereas Goethe had used his transcendental schema to decipher metamorphosis in plants.* (Kant, Critique of Pure Reason, 1922) (Goethe, 2009) *In Kant's description of schema there is no possibility of a Newtonian explanation for life processes; thus, Goethe developed a new systemic science for deciphering natural phenomena.* Although analytical examination of these systems is beyond the scope of this inquiry, Goethe's genetic system has been analytically explained in the following chapter. In this chapter, the author's sense of intuition compelled him to continue with the introduction of General System Theory and its applications in architecture and material computation.

General System Theory (Ludwig von Bertalanffy)

Arguably, in the context of system science, it was not before 1936 that General System Theory (GST Dynamic System), introduced by Ludwig von Bertalanffy as a universal

system, changed holism, as it criticized classical physics and its deductive methods (linear causality). (Bertalanffy, 1968) Bertalanffy stated that linear causalities cannot fit into biology, and he argued that real systems are exposed to work together with their environment to obtain qualitatively new properties through a development which can result in a constant refinement. He suggested that “an open system is defined as a system exchanging matter with its environment, presenting import and export, building-up and breaking- down of its material components.” (Bertalanffy, 1968) Its concept includes elements such as system environment, input, output, process, state, hierarchy, goal directedness, information and above all feedback. Bertalanffy wrote that a system should include ***“non-linear causalities within its parts to cycle information with a functional state encompassing various initial starting conditions that are relied on feedback for recalibration of function or as for a ‘homeostatic state’”***. (Bertalanffy, 1976) What Bertalanffy introduced as an ‘open system’ is a

Figure 4 Simple Feedback Scheme, from General System Theory, Foundation, Development, Application, ©Bertalanffy

Bertalanffy’s system introduces several principals into material computation. According to his definition, a system is always trying to accomplish an equilibrium or ‘homeostatic state’; it is operating to find a certain configuration of an equilibrium; and, for that balance to be found there have to be iterative processes. There should be also a mechanism to provide constant feedback for re-informing entire processes in order to constitute a degree of sharpness and accuracy of flow of information within the system. If

we want to analytically explain this system to illuminate its functional quality, we might conclude after deciphering Bertalanffy's system that there would be several different ways of achieving equilibrium relative to the environment. The first aspect is the 'count' (the number of elements involved in the system), the second is the 'type' (what type of elements are in the system?) (how many different types are there?), the third is the 'association' within those elements which elaborates on the scripted rules, and the fourth aspect is feedback embedded in associations.

Systems in Architecture

The General System Theory encompassing both bottom-up and top-down methods within a system based on feedback from the environment is interjected into various disciplines insuring significant advancements. Parallel to this, system thinking was also interjected into architecture by Christopher Alexander's early writings on design process and physical organization, form and functionality. In the 1960s, Christopher Alexander in his early writings introduced models of natural systems such as General System Theory, forms and the concepts of natural processes as Systems Generating Systems in architecture. (Alexander, 1964)

Alexander's System of Systems

Alexander coined the term Systems Generating Systems in Architectural Design in December 1968.¹ With this concept, he redefined forms not as observed objects but as expressed operating generative systems.² It is clearly understood that Alexander tried to

1. "The process of inventing things which display new physical order, organization, and form in response to function. Every aspect of form, whether piece-like or pattern-like, can be understood as a structure of components. Every Object is a hierarchy of components, the large ones specifying the pattern of distribution of small ones, the small ones themselves, though at first sight more clearly piece-like, in fact again patterns specifying the arrangement of distribution of still smaller components." (Alexander, 1964)

2. "1, There are two ideas hidden in the word system: the idea of a system as a whole and the idea of a generating system. 2, A system as a whole is not an object but a way of looking at an object. It focuses on some holistic property which can only be understood as a product of interaction among parts. 3, A generating system is not a view of a single thing. It is a kit of parts, with rules about the way these parts may be combined. 4, Al-

elucidate the difference between the behaviour ('a kit of parts, with rules-actions'), and the system ('a set of interaction generating that behaviour'), and in what perception such complexity can be comprehended. With this approach he introduced three main effects of a system in architecture: *'global behaviour', 'components' forming such behaviour and the 'type' of local relationship between parts, in another word these are Count, Type and Association previously defined by Bertalanffy and others.* (Alexander, 1968) His system's behaviour like Bertalanffy's system occurs in the dynamics of the interactions of the parts in a cyclical causal effect via feedback. This means that his system cannot be directly deciphered in a linear manner, and it is based on iterative processes reconfiguring its form based on feedback. most every 'system as a whole' is generated by a 'generating system'. If we wish to make things which function as 'wholes' we shall have to invent a generating systems to create them." (Alexander, 1968)

Figure 5 © (Alexander, 'Systems Generating Systems', 1968)

Figure 6 © (Alexander, 'Systems Generating Systems', 1968)

New Material Systems Parallel with Cybernetic

This level of complexity introduced into architecture shifted architectural thinking into a systematic view with various approaches. One of these emphasizes seeing form as a result of a systems' behaviour which interacts with its context in material, physical and personal engagement; consideration is given to how the computation of such complicated behaviour-based systems could be achieved. (Frazer, 1995) Parallel to the General System Theory as applied to architecture, Norbert Wiener coined the term 'cybernetics' as a 'learning machine' based on the same idea of 'goodness of fit' based on feedback. (Frazer, 1995) Gordon Pask, cybernetic theorist in architecture, interjected these theories into design thinking to obtain an architecture which is fully aware of its environment based on feed-

back. (Pask, 1969) The multidisciplinary domain of cybernetics which infused various fields such as engineering, biology, sociology, economics and design into architecture, constituted a new paradigm for architectural thinking which highlighted systematic reasoning, correlating outputs, adaptation and self-organization. Contrary to the traditional manner of understanding a building as simply an inactive material object, where the engagement of the human is mostly lost, Pask established his concept as the foundation of a comprehension of architecture as an assemblage of dynamic systems. (Pask, 1969) His concept was further developed by Frazer in the early 1990s with evolutionary methods opening up new possibilities for adaptive architecture via smart material systems.

Figure 7; Musicolor by Gordon Pask; (Behavior Based Design for Interactive Architecture); <http://i1.wp.com/www.interactivearchitecture.org/wp-content/uploads/2015/11/musicolor.jpg>

Feedback as a Key Point for Systems

The implication here is that the feedback introduced in general system theory enables the entire mechanism of a system to recalibrate its function for accurate prediction depending on environmental agencies. ***The most important key point in material computation in architecture can be expressed in an understanding of systems, its variables, its prediction for reconfiguration of behaviour based on feedback which is scripted within the system based on material dependencies and characteristics.***

Transition Function (John H Holland)

John H Holland, the father of agent-based computational modeling methods with genetic algorithms and the most influential scientist in the field of Complex Adaptive Systems, manifests the computational methods and emergent systems based on ‘association’. He eradicated the vague inexplicit concept of previously understood systems as a whole and established more precise and logical behaviors that emerge in a system based on the definition of ‘association’ within elements as algorithms that have been steadily changing the state of function over time. (Holland, 2000) (Holland, 1995) This is what Kauffman called rates of changes in his system. (Kauffman, 2000) He stated that ‘association’ in

Figure 8 from Emergence: From Chaos to order by © John Holland, redrawn by author

Bertalanffy's system is not just the literal connection of 'elements'; but it is actually how these connections might change or how the form of these performances (behaviour) might transform a system from one state to another. He introduced the concept that these transformations could be captured as algorithms within a system, and he called it 'Transition Function'. (Holland, 2000)

The Key aspect of algorithmic computational methods within a system can be captured in Holland's definition of 'Transition Function' described as "a mapping of the possible states of a system that can arise from a function". (Holland, 2000) He elaborates this notion in the use of Cellular Automata³ that creates various patterns (behaviour) in different time spans. This unveils the capability of each 'agent' (or functions) to foster 'complex emergence behaviours' but only when they are employed in a 'combinatorial network' - where the 'conditions of interaction' are as central as 'the properties of the agents themselves'. (Holland, 1995)

3. Cellular Automata (CA) in a two-dimensional grid, game of life, is invented by John H. Conway. The life cellular automaton is run by placing a number of filled cells on a two-dimensional grid. Each generation then switches cells on or off depending on the state of the cells that surround it. The rules are defined as follows. All eight of the cells surrounding the current one are checked to see if they are on or not. Any cells that are on are counted, and this count is then used to determine what will happen to the current cell.

1. Death: if the count is less than 2 or greater than 3, the current cell is switched off.
2. Survival: if (a) the count is exactly 2, or (b) the count is exactly 3 and the current cell is on, the current cell is left unchanged.
3. Birth: if the current cell is off and the count is exactly 3, the current cell is switched on.

(from <http://mathworld.wolfram.com/GameofLife.html>)

Two Primitives:

New CGP's Formed by Interconnection of Primitives:

New CGP's Formed by Added Feedback:

Basic Mechanism for Conway's Automation:

8 inputs, 2 states {0,1}

Transition Function:

If the state is 0, and exactly three neighbors are in state 1, then the state becomes 1; otherwise it remains 0.

If the state is 1, and either two or three neighbors are in state 1, then the state remains; otherwise it becomes 0.

Basic Mechanism Connected to Its Immediate Neighbors:

Figure 9 Postulating CGPs (Constrained Generating Procedures) from a Set of Primitive Mechanisms by John H Holland, Taken from: *Chaos to Order*; Redrawn by Author

One-step Transitions for Some Simple State Patterns:

Figure 10 ;Postulating CGPs (Constrained Generating Procedures) from a Set of Primitive Mechanisms by John H Holland, Taken from: *Chaos to Order*; Redrawn by Author

Simulation 1 © Author; Conway's Cellular Automata

*Animation's Collective Sources: Scripted in Java (Author); John H. Conway's Cellular Automata;
See*

<http://mathworld.wolfram.com/GameofLife.html>

<http://www.stephenwolfram.com/publications/academic/?cat=cellular-automata>

Chapter Three: Material Morphology

“Researchers have been generally aware for some time that there is a hidden relationship among various external parts of the plant that develop one after the other and, as it were, one out of the other (for example, leaves, calyx, corolla, and stamens); they have even investigated the details. The process by which one and the same organ appears in a variety of forms has been called the metamorphosis of plants. This metamorphosis appears in three ways: regular, irregular and accidental....

...Vegetative growth is successive reproduction ... while flowering and fruiting are simultaneous reproduction.” (Goethe, 2009)

Figure 11© Johann Wolfgang von Goethe, from *The Metamorphosis of Plants*, Introduction and photography by Gordon L. Miller, 2009

“Goethe’s formalism, like all rigorous and interesting ones, actually marks a turning away from the simple structure of end-products and toward the active, ever-changing processes that bring them together.” (Kwinter, 2008)

The consensus of ideas directing themselves into the genetic understanding of material organizations is rooted in the doctrine of morphology introduced by Johann Wolfgang von Goethe. Therefore, this part of the thesis investigates the theoretical development of material morphologies to cultivate and foster a new understanding of technical maturation for material computation driven by theory.

Lineage of the Term Morphology

The word morphology itself, which comes from the Greek, defines the study of shapes. Morph refers to form. The original biological significance of form is found in the harmonious characteristics of living things, their internal interactions and relationships causing multiple forms. Logy, in the latter part of the word morphology, puts emphasis on the ‘word’ itself. It refers to the aspects of form that are in accord with a rational law. However, here it implies ***“mind’s eye” indicating the mental processes that form incorporates through the senses***, resulting in a full understanding of an organism in its context, how it relates to and affects itself and environment. (The Natural Philosophy of Plant Form, 1950)

Figure 12 Proliferous rose. Watercolor commissioned by Goethe in the early 1790s, intended for a sequel to the *Metamorphosis of Plants*, © Johann Wolfgang von Goethe

Goethe's Genetic Morphology

“...if I look at the created object, inquire into its creation, and follow this process back as far as I can, I will find a series of steps. Since these are not actually seen together

before me, I must visualize them in my memory so that they form a certain ideal whole. At first I will tend to think in terms of steps, but nature leaves no gaps, and thus, in the end, I will have to see this progression of uninterrupted activity as a whole. I can do so by dissolving the particular without destroying the impression itself.” (Goethe, 2009)

Arguably, Goethe's scientific writings drove the transition from the generic view to genetic view of organic nature.¹ (Cassirer, 1945) *Generic here refers to the linear method of codification of biological systems, where the classification and arrangement of taxonomy is achieved by subordinating the multiplicities of natural organisms into a rational grid or tables, concepts, divisions of species and genera, orders, classes, families, etc..*²

The linear generic version stresses constancy whereas a genetic view stresses changeability in nonlinear systems. (Kwinter, 2008) In Goethe's vision, ***“to understand nature one must grasp more than just its products, one must grasp process of life, and this must be sought in abstract performative principles.”*** (Cassirer, 1945) (Goethe, 2009) In these abstract concepts and visions, Goethe draws on a famous passage from Kant.³ In Kant's description of

1 Ernst Cassirer in the book *Rousseau Kant Goethe* made a sweeping and brilliant condensation of a huge set of intellectual processes originated from Goethe and recapitulated them into a single piece.

2 This refers to Carl Linnaeus' the Generic Classification of Taxonomy System within Newtonian Grid.

3 Kant states that schemata are procedural rules not image or object itself. Because schemata are determinations of objects in general, not specific, individual objects, they are not particular images. Kant asserted that “... a schema must be distinguished from an image.” A schema is a procedural rule. The rule prescribes the

schema, there is no possibility of a Newtonian explanation for life processes. (Kant, 1922)
(Kwinter, 2008)

Arguably, Goethe's vision presents a new concept of how knowledge is created. In 1790, by introducing the concept of morphology, he defined the difference between form and formation, and argued that the relationship between 'gestalt' (form) and its construct is undividable, and that morphologies define the processes that shape form. (Goethe, 2009) Secondly, he nests this new form of science within a dynamic field of transformation that he called ***Metamorphosis of Plants***. He also described 'vertical tendencies' in plants as a set of dependencies in structure. Goethe aimed to link the geometric behavior of natural organisms with their functional logics, maintaining their natural morphologies in a constant state of becoming. This means that he introduced the first example of a dynamical genetic theory using interactive algorithms. (Goethe, 2009) (Kwinter, 2008) Implicit in his interactive algorithms as visionary processes is the fundamental idea that they occur within a relation to hierarchies (steps) of structure and environment.

Goethe's Framework (Leaf, Gradient and Closed Cycle)

"But a leaf is unthinkable without a node, and a node is unthinkable without an eye." (Goethe, 2009)

way to relate a pure concept to an object in general. Schemata are ways of applying pure concepts (categories) to sense impressions. They are prescriptions for graphically illustrating a pure concept. A schema is a method for representing a non-empirical concept in any image as such or any image in general. For Kant a schema is not an image, but a capacity to form images or (perhaps) to construct models. "The schema of a pure concept of the understanding is something which can never be made into an image..." (Kant, The Critique of Judgement, 1914)

Umberto Eco compared a Kantian schema to Peano axioms, Wittgenstein's concept of Bild (a proposition that has the same "form" as the fact that it represents), and a computer programming flowchart. In this way, it is a procedural rule that provides instructions regarding the construction of a sensible intuition from an abstract, general concept. (Eco, 2000)

Goethe's botany introduces the very concept of material computation. Three key elements that he introduces by looking at plants are the foundation for understanding material computational systems. The first process is the idea of the 'leaf'. He states that everything in a plant is a leaf. (Goethe, 2009) This leaf does not exist and does not present anything. He argued that this leaf is a logical matrix of an abstract form. **Therefore, it would not emerge as an ideal state because it is a set of manifested variants.** For instance, a human face can be considered as a leaf because the size of its elements varies in different people. Here, **the leaf is the schema of the face** with its anatomical elements. The second process he considered as **'a condition of an open gradient of progressive refinement'**. (Kwinter, 2008) (Goethe, 2009) (DeLanda, 2002) In this condition, each element instigates a movement from crude to refined. In process number three, a closed cycle is added to the entire system. This cycle occurs in several methods of expansion and contraction in various spans of time that correspond to the different stages of life. (Kwinter, 2008) (Goethe, 2009) (DeLanda, 2002)

These three processes operate on multiple levels. The bases of constraints that establish general parameters, variables and sets of structural information are given in process one. If we consider these elements in a hierarchy, then parameters are dependencies; and variables are information built into the process. Directionality as a state of constant change in the system is added in process two where it causes a break in symmetry; therefore, continuous difference emerges. It becomes unique in each step. Today, it is called the rate of change. (Goethe, 2009) (Kwinter, 2008) Process number two suggests a detachability of events that starts to deform process number one. Process number three adds repeatability to the system to offer a flexible background for structure. (Goethe, 2009) (Kwinter, 2008) This provides a "regular recurrent macro process like an envelope that lands in law-like structure to the perfusion of pure uniqueness generated by process two (directionality)". Repeatability punctuates and gives intelligibility to the system that unfolds in various span of time. This is

what we call feedback. It provides a stable envelop for radical instability emerging in number two. Finally, it produces ***“the multiplicities of simultaneous temporalities”***. (Goethe, 2009) (Kwinter, 1994) (Kwinter, 2008) (DeLanda, 2002)

Kwinter’s Brilliant Condensation of Goethe’s Formation

In Goethe’s schema, organisms are the expressions of the interactions of multiple systems and rules, which are mutually modifiable instructions. Each of these individual entities in the system introduces a different scale of shapes and pressures, and ***“therefore different rates of unfolding create a complexity in a polyphonic structure as a perpetual crosstalk between the strata, possibly the source of stability in organisms”***. (Cassirer, 1945) (Kwinter, 1994) These rules are engines producing deviation within parameters. Here, emergent patterns appear when variations are allowed to interact with other variations. Amazing flexibility arises in various spans of time because of the forces that Gould and Ernst Mayr call ‘Punctuated Equilibriums’. (Hensel, Menges, & Weinstock, 2010) Today, this dynamic innate information can be called as a parameter and the instructions as algorithms in computer programs. (Kwinter, 2008) These various rules and pressures on all scales define form. Indeed, Sanford Kwinter made a sweeping and brilliant condensation of a huge set of intellectual concepts that originated with Goethe and recapitulated them into a single piece to define form:

“... Form [...] is ordering action (here it refers to nonlinear interactive based organizations), a logic deployed, while the object is merely the latter’s distant theme. The great formalists [...] have always been able to peer into the object toward its rules of formation and to see these two strata together as a mobile, open and oscillating system subject to a greater or lesser number of external pressures. The manifest form – that which appears – is the result of a computational interaction between internal rules and external (morphogenetic) pressures that, themselves, originate in other adjacent forms. The (pre-concrete)

internal rules comprise, in their activity, an embedded form, what is today clearly understood and described by the term algorithm.” (Kwinter, 2008)

Gestalt vs Phenomena in Architecture

Arguably, Goethe's formation significantly alters theoretical discourse. In other words, the scientific revolution, which is triggered by Goethe's 'gestalt' switch, has managed to decipher phenomena that previously had obscure features. (DeLanda, 2000) The discourse of phenomenology argues that the scientific revolution has dominated architectural thinking and has transformed architecture into a more purposeful activity where it loses its poetic value and metaphoric meanings and becomes non-representational. (Gómez, 1984) Phenomenologists offer a 'retrograde nature of authority' which systematically and theoretically seeks out essentiality and purity. (Wiscombe, 2006) For the 'phenomenologist everything is just a matter of interpretation in a semantic way; therefore, their metaphors exist in their mind without having reality'. (DeLanda, 2002) Graham emphasizes that because of nonscientific engagement, Martin Heidegger has little to offer us other than an ambiguous drama that features concealing and revealing. (Harman, 2010) Indeed, in his writing *The Question Concerning Technology*, Martin Heidegger argued for essentiality (essence) as giving a reality to what exists in his mind. However, Goethe proved that with proper attention to organic systems and morphologies (which was later developed as morphogenesis), as demonstrated by how scientific advancements have shaped our current technologies, we can illuminate the relationships between formation and materialization.⁴ Indeed science recently has proven that there is no separation between formation (structure) and material logic in organic systems. (DeLanda, 2002) DeLanda compares this to Delueze's interpretation of multiplicities. This means form is not defined by its essence. ***“Unlike essences which***

⁴ This refers to science which its developments assured that dynamics and information in living organisms with nonlinear mechanisms have gained control over the dynamics of energy which in classical terms derives nonliving systems.

assume that matter is a passive receptacle for external forms, multiplicities are immanent to material processes, defining their spontaneous capacity to generate pattern without external intervention.” (DeLanda, 2002) Therefore, current architecture must not seek an essence and search for the retrograde nature of authorities, but rather look for the multiplicities of simultaneous temporalities to script a dynamic feedback introduced in system thinking to move into a space of innovation. (Wiscombe, 2006) What is important here is the theoretical and technical contribution that Goethe’s material formation offers to architectural discourse.

D’Arcy Thompson’s Intermediate Forms

“...Cell and tissue, shell and bone, lead and flower, are so many portions of matter, and in it is obedience to the laws of physics that their particles have been moved, moulded and conformed...

...We pass quickly and easily from the mathematical concept of form in its statical aspect to form in its dynamic relations. We rise from the conception of form to an understanding of the forces which gave rise to it; and in the representation of form and in the comparison kindred forms, we see in the one case a diagram of forces in equilibrium, and in the other case we discern the magnitude and the direction of the forces which have sufficed to convert the one form into other...

...The mathematical definition of a ‘form’ has a quality of precision which was quite lacking in our earlier stage of mere description... We discover homologies or identities, which were not obvious before, and which our descriptions obscured rather than revealed... “ (Thompson D. W., 1992)

Mathematical Constraints for Goethe's Formation

In 1823, the most significant problem in morphology was the application of biological centrifugal and centripetal forces (*vis centrifuga* and *vis centripeta*). (Figure 13) Through imaginative comparison, Goethe pictured parts of plants in order to depict how forces may be integrated into their parts (leaf, petal, pistil, stamen, fruit, seed, etc.). What he noticed was the tendency in plants to contract and expand for opposing forces which lead to the morphological ability to create “lawful” new forms that do not exist in nature. Goethe’s inattention to mathematical expression limited him to diagrams, figures and imaginary processes. Indeed, one of D’Arcy Thompson’s arguments was Goethe’s disinterest in mathematics regarding the shaping of geometrical figures’ material morphologies.

FIGURE 21: Dynamics of leaf formation (a) stemming, (b) spreading, (c) articulating, (d) shooting

Figure 13 © Johann Wolfgang von Goethe

Formation's Mathematical Model

Goethe's vision proved that material logics, processes of formation and form are all parts of the same system. However its abstract mathematical system was solidified by the work of D'Arcy Thompson. Furthermore, Thompson mathematically showed how forces act upon form and formation. (Thompson D. , 1917) Thompson, mathematical biologist, for the very first time delineated a new way to numerically describe the development of form in living organisms. With the use of Polar and Cartesian Coordinates, he aimed to find appropriate mathematical methods to illustrate changes in the shapes of plants and bones in various species (living creatures), which led to his famous predictions about intermediate species in evolution. *Thompson initially superimposed a regular grid on two Pelvises of Archaeopteryxes (flying dinosaurs), then determined certain "land-mark" points (homologies or identities) based on the pelvises' similarities, to find corresponding points. Next, he defined the equation and determined the new grid on the reaction of two sets of landmark points. The result was the deformed coordinate system which showcased the impression of relative forces between two pelvises. Subsequently, he determined intermediate forms which are not created simply by manipulating the same grid and material identities.*

Thompson's Parametric Dependencies for Material Computation's Framework in Architecture

Thompson's vision introduces various parametric dependencies into material computation. Numerical descriptions of form and object in the computational logic of material systems would also allow ***geometrical transformations with mathematical descriptions***. Early in the use of computation in architecture, Greg Lynn had "used intermediate shapes of the tween, along with other computer animation techniques, as the basis for an animate architecture that is defined by co-presence of motion and force at the moment of conception". (Lynn, 1999)

Fig. 500. Curve resembling the outline of a reniform leaf: $r = \sin \theta/2$.

Fig. 501. Violet leaf.

Fig. 499. *Begonia daedalea*.

Fig. 502. Grandi's curves based on $r = \sin \frac{1}{2}\theta$, and illustrating the five petals of a simple flower.

Fig. 503. Diagram illustrating a corolla of five petals, or of five lobes, are based on the equation $r = a + b \cos \theta$.

Fig. 504. Outline of a compound leaf, like a horse-chestnut, based on a composite sine-curve, of the form $r = \sin \theta/2 \cdot \sin n\theta$.

Figure 14; © D'Arcy Thompson from *On Growth and Form: The Complete Revised Edition*

Design-Experiment Number One; Exrimenting with a Dynamic Pattern Language

(Goethe and Thompson's Frameworks)

Inspired by Goethe's framework and Thompson's intermediate forms, the author's intuitive senses were motivated to generate a dynamic pattern that make use of Goethe's computational framework to showcase Thompson's mathematical system and intermediate possible forms. This dynamic pattern discloses elementary rules in its process.

```

float r= Range+noise(R);
Polygon(n,cx,xy,r);
float angle = 360/n;
begin shape();
for (int i=0; i<n; i++){
vertex (cx + r *cos(radians(angle*i)), cy+r*sin(radians(angle*i)));}
endshape();
Then Recursive pattern has applied which corresponds to Noise (F+F+F...)

```

Core Script

Figure 17; © Author; Scricted Leaf; Disclosing Intermediate Forms, [Diagrams illustrate its computational Logic]

Turing's "The Chemical Basis of Morphogenesis"

Although Thomson widely contributed to the understanding of biological forces, morphogenesis was further developed by Alan Turing. In his unpublished paper, "The Chemical Basis of Morphogenesis", Turing elaborated on the Reaction-Diffusion System to explain how forms arise from the chemical activity of a cell. He postulated a system that encapsulates Ring of Cells and morphogens. This nonlinear system as a single organizational mechanism, which makes extensive use of mathematical, biological, and chemical data (the osmotic pressures) and takes on stresses of elasticity and velocity as mechanical inputs, is stable when in a homogenous state. Then, a symmetrical break occurs through morphogens, catalysts that disturb the stable state. This symmetrical break in Homogeneity leads to a new stable state of waves that produces collective forms of patterns in a state of equilibrium, thereby determining the anatomical structure of the resulting organism. (Turing, 1952) The implication here is Turing's argument for the application of certain well-known physical laws to describe the natural behaviour. (Condensed from Turing, 1952)

Turing's Model for Material Computation

Turing fundamentally re-envisaged complex imaginary biological formation. His system postulated new sets of understanding of biology in detail which would illuminate the computational treatment of a particular case. However, he further used this nonlinear equation to analytically explain the morphogen theory of Phyllotaxis. When he applied the reaction-diffusion system as a wave on a sphere, the limitation of mathematical expression circumscribed him so that he speculated on future digital computers. Indeed, he admittedly wrote that "the difficulties are, however, such that one cannot hope to have any very embracing theory of such processes, beyond the statement of the equations; it might be possible, however, to treat a few particular cases in detail with the aid of a digital computer." Today, Turing's reaction-diffusion system, waves, fractals, and other natural procedural

nonlinear equations are widely used in multiple disciplines with the use of computers.

Figure 18; Source: http://www.creationresearches.com/cr5_e.shtml,
(Cylindrical Lattice)

Design-Experiment Number Two

Figure 19; © Author, Re-Envisaging Reaction-Diffusion System

This design experiment is conducted with Turing's nonlinear equation (reaction-diffusion mechanisms) in a combined multilayered format⁵ that showcases not only patterns but also the instability that happens in each step. Here, pixelizations with specific gradients are deployed within each frame in a fractal-like manner to illustrate the amount of variation in each step at multiple scales, highlighting a microscopic vision of the process to visualize anatomical structures. It is worth noting that randomization⁶ also is applied in a manner to emphasize Turing's pattern and wave. This means that hierarchy is applied in a nonlinear manner as well.

Figure 20; © Author, Re-Envisaging Reaction-Diffusion System

5 Collective Sources:

C++ from: <http://pastebin.com/G05X08Mv>,
<https://plus.maths.org/content/os/issue30/features/dartnell/index> https://en.wikipedia.org/wiki/Reaction%E2%80%93diffusion_system

Java from: <http://www.aliensaint.com/uo/java/rd/index.php>

<http://www.wblut.com/2011/07/13/mccabeism-turning-noise-into-a-thing-of-beauty/>

http://www.jonathanmccabe.com/Cyclic_Symmetric_Multi-Scale_Turing_Patterns.pdf

<http://softologyblog.wordpress.com/2011/07/05/multi-scale-turing-patterns/>

<http://www.openprocessing.org/sketch/31195> <http://openprocessing.org/sketch/25845>

<http://www.openprocessing.org/sketch/33444> <http://www.openprocessing.org/visuals/?visualID=31195>

6 Randomization starts from an initial condition of pseudo-random values in the range -1.0 to 1.0.

Figure 21; © Author, Re-Envisaging Reaction-Diffusion System

Figure 22; © Author, Re-Envisaging Reaction-Diffusion System

Figure 23; © Author, Re-Envisaging Reaction-Diffusion System

Figure 24; © Author, Re-Envisaging Reaction-Diffusion System

Figure 25 © Author, Re-Envisaging Reaction-Diffusion System

Figure 26; © Author, Re-Envisaging Reaction-Diffusion System

Figure 27; © Author, Re-Envisaging Reaction-Diffusion System

Figure 28; © Author, Re-Envisaging Reaction-Diffusion System

Figure 29: © Author, Re-Envisaging Reaction-Diffusion System

Figure 30; © Author, Re-Envisaging Reaction-Diffusion System

Figure 31: © Author, Re-Envisaging Reaction-Diffusion System

Figure 32; © Author, Re-Envisaging Reaction-Diffusion System

Figure 33; © Author, Re-Envisaging Reaction-Diffusion System

Figure 34; © Author, Re-Envisaging Reaction-Diffusion System

Figure 35; © Author, Re-Envisaging Reaction-Diffusion System

Figure 36; © Author, Re-Envisaging Reaction-Diffusion System

Experiment Number Three (Matter and Time)

The following design experiments as a purposive purposelessness showcases architectural objectiles (Cache). Here, technical computational approaches for generating these objectiles⁷ have been ***theoretically explained in detail***. Further elaboration on computer language (codified script written in python Gh) is provided on page 81. The author has re-envisioned their design processes from de-cognized natural materialization schemata comprehended through senses-based intuition. He has re-arranged their materials of cognitions within higher faculties of mind which use pure intuition of time and space. Here, materials of cognitions are not substances; and cognition itself has a series of strata that the author will delineate. Objectiles' logic has been deployed without having an external compelling force. They showcase pure paradoxes of the pure becoming of matter. (Deleuze , 2004)

Considering the genealogy which has been argued in this inquiry, knowledge of natural materialization might have begun with experience but surely has not arisen from it. (Whitehead, 1971) Here, experience applies to observing a natural object as a phenomenon and to gathering sense data. By this definition, even the simple linear cause and effect process of deducible logic of mathematics (Aristotle's Syllogism) that Kant calls A Priori is not part of this experience. In this manner, time is perceived in a linear manner to develop initial causes and effects. This means that our mental faculties develop in infancy a kind of hierarchy in a linear parallel manner that uses compartmentalization to make sense of a logic in a one-dimensional time frame that is created by our intuition. Kant in his Critique of Pure Reason introduced a different kind of approach that he analytically explained as transcendental schema. This has been delineated in previous chapters. (Kant, 1922) Indeed, Goethe in his text began his argument with transcendental schema in nonlinear material formations. This transcendental schema for the very first time deciphered a linear Linnean taxonomy (Carl

⁷ *Following objects are calculated with different methods. Various forces are applied with pseudo-randomization method both for the location of vertexes and also subdivisional variations. They are written in python Gh which is a graph based scripting language for Rhino.*

Linnaeus's codification of natural material systems). His dynamic genetic schema introduced complex emergences that may have arisen from simple rules and processes. (Goethe, 2009)

In deciphering the mental faculties of natural objects for re-cogitating objectiles, there must also be several intuitional compartments such as empirical, pure, and heterogeneous. Empirical intuition develops through senses-based knowledge which observes a phenomenon and gathers data. At this stage, concepts are developed and ascend from multiplicities of interactions in various domains to cogitate the natural object. This faculty is what the author calls conception. This developed empirical intuition and conception happens in the strata of cognition. The faculty of cognition has a wide application for generating thoughts about objects. Above this faculty of cognition there is a pure intuition which assumes time as a form with which it cohabits in a linear dimension. This pure intuition is multiplied in its own domain in order to correlate multiplicities of time frames related to each other in a spatial intuition. Theoretically, pure intuition is also used for re-stratifying differential mathematical equations. This is also called pure intuition by Kant. In a different domain, which is also connected to pure and empirical intuition, there is heterogeneous intuition: it re-codifies materials of cognitions that correlate with mapping possibilities, and applies their rates of temporal change in the object. This process also would be used to deploy the faculty of intellect [intelligence for correlating differential behaviour with feedback] into the object in final prototypes (not objectiles).

Natural materialization processes also suggest that complex biological phenomena emerge from very simple rules and interactions that materials develop through evolution in order to adapt to their ecology. It is considered that these internal interactions and rules must have a relation to environmental forces (external). Objectiles in this part of this inquiry only showcase internal rules and interactions which have no relation to external forces. They showcase how variation emerges from those interactions. These interactions are compre-

hended in the faculty of conception and empirical intuition, and their intellect is incarnated into the object without relating any external relation. This also incorporates Thompson's theory of intermediate forms: he argued they may develop through evolution. Design processes of these objectiles decentralizes the gestalt portion, and re-contextualizes that portion in order to exclude certain external forces and properties; it finally re-cogitates and infuses the rest into objectiles in a one-dimensional time frame. These are called objectiles as they partially re-contextualize material objects. It is worth noting that the author borrows the term from Bernard Cache.

Beyond its design process and logic, the objectile undermines traditional solid permanent objects in an event ontology. In other words, it showcases pure paradoxes of pure becoming. Theoretically, it can be argued that there are two ontic principles of thought for event ontology. The first one is the limited becoming of a limited realm of measure in which some substances with specific attributes are deployed with the principles of contradiction. In this sense, in an Aristotelian vision, an object has to possess stable identities, and its progressive development has to proceed step-by-step in a linear one-dimensional time frame. In the second one, called pure becoming, the time frame gets scrambled because the event itself simultaneously happens in the past, future, and present. This pure becoming undermines the substantiality of an object and its self-identity. This pure becoming is illustrated in Lewis Carroll's *Alice in Wonderland* and Gilles Deleuze's *The Logic of Sense*. In the first narrative, what had happened to Alice when she grew large and small in the same time was pure becoming. Here, three dimensional perspectival space has been de-stabilized, undermined and scrambled, and the object is disconnected from his own space and subjectivity. Implicit here is the realization that in pure becoming or pure event, waking consciousness is reconfigured by just one single object. The object re-arranges itself, laws, logics of spaces, causalities and effects, in this process the author calls the object an objectile. In other words,

Figure 37; © Author; Computed Objects Showcasing Materialization Processes

objectile rearranges itself by breaking down laws of space and of the linear time-frame, harmoniously infuses itself with them in a deep paradox. The generated multiplicities are carved into their time frames and spaces. Deleuze in 'Difference and Repetition' reflected on this concept as he referred to a third synthesis of the event whereby novelty and singularity destroys the subject's sense.

It is worthwhile to re-emphasize that objectiles do not have a specific property and that their design schema does not correlate any external forces or any material properties.

Like the purposive purposelessness of nature, they decentralize and destabilize the subject, while they simultaneously break down time and space to carve their multiplicities in a paradoxical manner.

Figure 38; © Author; Computed Objects Showcasing Materialization Processes

Figure 39; © Author; Computed Objects Showcasing Materialization Processes

Simulation 2; © Author; Computed Object

Figure 40; © Author; Computed Objects Showcasing Materialization Processes

Figure 41; © Author; Computed Objects Showcasing Materialization Processes

Figure 42; © Author; Computed Objects Showcasing Materialization Processes

Figure 43; © Author; Computed Objects Showcasing Materialization Processes

Figure 44; © Author; Computed Objects Showcasing Materialization Processes

Figure 45; © Author; Computed Objects Showcasing Materialization Processes

Figure 46; © Author; Computed Objects Showcasing Materialization Processes

Figure 47; © Author; 3DPrintd Object

Figure 48; © Author; 3DPrintd Object

Figure 49; © Author; Computed Object

Figure 50; © Author; Computed Object

Figure 51; © Author; Computed Object

Figure 52; © Author; Computed Object

Figure 53; © Author; Computed Object

Figure 54; © Author; Computed Object

Figure 55; © Author; Computed Object

Figure 56; © Author; Computed Object

Figure 57; © Author; Computed Object

Figure 58; © Author; Computed Object

Figure 59; © Author; Computed Object

Figure 60; © Author; Computed Object

Figure 61; © Author; Computed Object

Figure 62; © Author; Computed Object

Figure 64; © Author; Computed Object

Figure 63; © Author; Computed Object

Simulation 3; © Author; Computed Object

Figure 65; © Author; Computed Object

Figure 66, © Author, Computed Object

Figure 67; © Author

Figure 68; © Author; Computed Object

Figure 69; © Author; Computed Object

Figure 70; © Author; Computed Object

Figure 71; © Author; Computed Object

Figure 72; © Author; Computed Object

Figure 73; © Author; Computed Object

Figure 74; © Author; Computed Object

Figure 75, © Author; Computed Object

Figure 76; © Author; 3DPrintd Object

Figure 77 © Author; 3DPrintd Object

Chapter Four: Evolution

“...I think I have found out (here’s presumption!) the simple way by which species become exquisitely adapted to various ends....” — Charles Darwin¹

“...I think it would be a most extraordinary fact if no variation ever had occurred useful to each being’s own welfare; in the same way as so many variations have occurred useful to man. But if variations useful to any organic being do occur, assuredly individuals thus characterized will have the best chance of being preserved in the struggle for life; and from the strong principle of inheritance they will tend to produce offspring similarly characterized.” (Darwin, 1859)

“The fact that life evolved out of nearly nothing, some 10 billion years after the universe evolved out of literally nothing, is a fact so staggering that I would be mad to attempt words to do it justice.” — Richard Dawkins

Introduction

Although Goethe’s vision in morphology, Thompson’s mathematical work for intermediate species, and Turing’s morphogenesis largely contributed to comprehension of form and formation, a full understanding of natural material formations came into existence with Darwin’s theory of evolution. Morphogenesis and evolution provide a full understanding of biological formation. Therefore, this part of the thesis elaborates on evolution to foster another aspect of material computation which will be infused in the final project.

Darwinian Theory

“I have called this principal, by which each slight variation, if useful, is preserved by the term Natural Selection”. (Darwin, 1859)

¹ Letter to Sir Joseph Hooker (11 Jan 1844). In Charles Darwin and Francis Darwin (ed.), *Charles Darwin: His Life Told in an Autobiographical Chapter, and in a Selected Series of His Published Letters* (1892), 173-174.

Within Darwin's theory, natural selection suggests that the living form of natural organisms today is the result of millions of years of adaptation to various conditions of the environment. This means that at any time, a number of different organisms compete for the same resources in an ecosystem. The organisms most capable of obtaining resources and thus breeding are the ones whose offspring will tend to survive in the future. On the other hand, organisms that are less capable and thus not procreating will have no offspring in the future. ***The distinctive characteristics*** that caused the superior fitness of the more capable organisms ***were selected over the characteristics of the less fit***. Over time, the entire population evolved to create organisms that were more fit as they exhibited more of those ***characteristics that tend to promote survival***. (Mayr, 2001) (Bentley, 1999) (Kumar & Bentley, 2003)

Darwinian Computational Model

Evolutionary computational techniques are abstract models of evolutionary processes in the format of algorithms used to create intelligent search engines for optimal solutions to a specific problem. (Fogel & Michalewicz, 2004) In any programming language, variables, made from custom types (as abstractions) including both data and functionality, are the fundamental concepts that enable us to save data and reuse it while a program is performing. The idea here is that instead of assigning the property and characteristic of an object to our variable through concise considerations, we can let the process search 'in nature' and let the evolution decide the selection of the fittest. For instance, by implying the characteristics of variables (usually mass) of an object (usually particle) as its DNA, objects can make other objects pass down their DNA to a new generation. In this way, simulations can evolve and be intelligently akin to natural systems. However, the concept here is not to study protein synthesis and RNA, but rather to study the core principles in Darwin's evolutionary theory to

foster genetic algorithmic methods. (Fogel & Michalewicz, 2004) (Holland, 1995)

Lineage of Evolutionary Computation

Today evolutionary algorithms are widely used in various disciplines with four main approaches. The first one is Genetic Algorithms (GA) which were devised by John H Holland in 1973 and developed by David Goldberg in 1989. The second is Evolutionary Programming (EP) devised by Lawrence Fogel in 1963. It led to the third development for Evolutionary Strategies (ES) by Ingo Rechenberg and Thomas Back. The forth and most important approach is Genetic Programming (GP) by John Koza which is used by Peter J Bentley. (Fogel & Fogel, *An Introduction to Evolutionary Programming.*, 1995) (Bentley, 1999)

De-pathologized Evolutionary Process

If in architecture one considers a new explanation of a material system which is intelligently aware of its functionality relative to a space that it defines, depathologized evolutionary processes as evolutionary algorithms, they should be interjected into the computing strands of its material organization. Similar to Darwin's evolutionary approach, an "Evolutionary Algorithm" indicates a specific procedure used in a certain way to search and find the most appropriate solution for a set of problems with specific intelligence. (Fogel & Michalewicz, 2004) Therefore, there are three primary core principles of evolution to be studied in order to develop a basic algorithm that follows Darwin's method. The first process is **Heredity** in which powerful creatures live long enough to reproduce and pass down their characteristics to their offspring. (Fogel & Fogel, 1995)² The second process is called Variation. If variation does not occur within the next generation, children will look like their parents, and a new mixture of characteristics can never happen and a population cannot evolve. Therefore, in each population every single entity is different. (Mayr, 2001)³ The pro-

² Fogel postulate on learning by heredity to formulate his masterpiece.

³ He delineates this concept in chapter five, where he argues for variational evolution. Its necessity is emphasized on the conclusion page 114.

cess by which members from populations are selected for mutating and passing down their genetic information is called **Selection**. (Holland, 1995)⁴

Figure 78;© Author; De-Pathologized Evolutionary Logic for Material Computation

4

One part of Holland's masterpiece in argument for complex adaptive systems includes selections.

Population Thinker vs Typologist (DeLanda)

Beyond technical advancements, evolution offers a set of new understandings for the discourse, where population thinking simultaneously replaces the simplest concept of a linear none-intensive fixed archetype in the discourse. This is not to say that the concept of population thinking ignores the type; rather, it conceives the type as an abstract concept in a layering process which does not have an embedded relation to matter. DeLanda writes that for Typologists and Essentialists, who assume matter to argue for a genesis of a form as an expression of a single type with identical properties, variation occurs as an accident of history with ordering systems. (DeLanda, *Intensive Science and Virtual Philosophy*, 2002)⁵ But, consideration of open-ended characteristics of variational-population thinking offered by evolution suggests another approach. The multiplicity of spontaneous characteristics of both heterogeneity and variation under most circumstances in multiple levels of strata for a populationist offers ***a form*** that is continuously evolving within collective communities. Selectively advantageous traits with different origins are propagated through populations. (DeLanda, 2002) Therefore, the notion of type becomes one in a layer of interchangeable concepts within different circumstances. It can be called an ideal norm (types as norms of reactions) as DeLanda puts it.

Ernst Mayr on Variation, Population and Matter

“[For the typologist there] are a limited number of fixed, unchangeable ‘ideas’ underlying the observed variability [in nature], with the eidos (ideas) being the only thing that is fixed and real, while the observed variability has no more reality than the shadows of an object on a cave wall... [In Contrast] the populationist stresses the uniqueness of everything in the organic world... All organisms and organic phenomena are composed of unique features and can be described collectively only in statistical terms. Individuals, or

5 This concept has been scrutinized on page 47.

any kind of organic entities, form populations of which we determine the arithmetic mean and the statistics of variation. Averages are merely statistical abstractions, only the individuals of which the populations are composed have reality. The ultimate conclusions of the population thinker and the typologist are precisely the opposite. For the typologist the type (eidos) is real and the variation an illusion, while for the populationist, the type (the average) is an abstraction and only the variation is real. No two ways of looking at nature could be more different.” (DeLanda, 2002)⁶

Deleuze on Populations for Types

Deleuze on the dynamics of thoughts, equated to populational thinking, as opposed to essentialism writes that:

“First... the forms do not pre-exist the population; they are more like statistical results. The more a population assumes divergent forms, the more its multiplicity is divided into multiplicities of a different nature... the more efficiently it distributes itself in the milieu, or divides up the milieu... Second, simultaneously and under the same conditions... degrees are no longer measured in terms of increasing perfection... but in terms of differential relations and coefficients such as selection pressure, catalytic action, speed of propagation, rate of growth, evolution and mutation... Darwinism’s two fundamental contributions move in the direction of a science of multiplicities: the substitution of populations for types, and the substitution of rates or differential relations for degrees.” (DeLanda, 2002)

⁶ This quote is by the creator of the Modern Synthesis of Evolution and Genetic, Ernst Mayr; which is rewritten by Manuel DeLanda in his book *Intensive science and virtual philosophy*, page 48.

Chapter Five: Design as Knowledge

Introduction

These biological landscapes⁷, which are Goethe's gestalt, Thompson's intermediate species, Darwin's genetic evolution and Turing's morphogenesis, illustrate how embedded rules between form and formation happen. Although they depict how life processes occur, the task that presents itself is that how one can derive knowledge from these cogitated schemata as one single organizational entity for architecture as a material practice. Therefore, the main question is how one can gain knowledge from these multidisciplinary domains. Hence, this chapter investigates various methods in which scientific explorations are conducted to garner knowledge. This domain would constitute a paradigmatic shift not only in material understanding but also in architectural thinking, where architecture would move away from deducible logics into more a more dynamic field where each case is envisaged as a schema and prototype.⁸

Philosophy of Science

The process designers use to generate architectural forms is similar to the process by which theories are generated to produce scientific knowledge. This means that, ***for envisaging a process as knowledge***, it should be studied in the context of the philosophy of science. Therefore, the emphasis here is on the study of philosophy of science in which

7 Inspired by Conrad Hal Waddington's definition of a biological landscape. Waddington, neo Darwinist and theoretical biologist, who laid the foundations for systems biology as well, showed how unfathomably complex but rich material typologies are in epigenetic landscape. He argued and illustrated how forms emerge gradually from homogeneous (formless) environments and substrates. Epigenesis, which in generic terms is defined as "extra growth", describes biological development and emergence of form in an embryo. The critical point here is that Waddington's nonlinear diagram deciphered nonlinear systems in biology and displaced a classical atomist or mechanistic theory of development.

8 This chapter includes notes and intellectual concepts which the author has developed through his intensive interest in philosophy of science to argue for a new understanding of design as science. These notes are mostly taken from Stanford University's publications, Thomas Kuhn's 'The Structure of Scientific Revolutions', and conducive discussions the author had with Prof. Cirka.

knowledge is produced, in order to declare ***that a science of design might be possible, if not yet realized.*** Therefore, initially a philosophy of science is chronologically explained, and then the relationship between science and design is analytically reflected upon in this chapter's conclusion.

Although there is not a solidified definition of what constitutes a science, there are several schools of thought about how theories are shaped. Indeed, the question for science is how it arrives at theories in the first place. The tension is between the philosophers' descriptive method and scientists' normative way of producing knowledge. Even Immanuel Kant argued for a distinction between experience (empirical data), and mental faculties.

Goals of Science

For a clear understanding of the philosophy of science, one must have a clear conception of the goals of science. There are two different goals in science. The first school of thought is called scientific realism. It puts emphasis on a science that produces knowledge for understanding the truth about the world and is comparable to the classical definition of knowledge as a justified true belief. It proposes that, truth (knowledge) is valuable for its own sake and has intrinsic value. Another approach called instrumentalism argues that science needs practical values in order to solve specific problems. The distinction in this method is knowledge that has only instrumental values rather than intrinsic ones.

Bacon on the Scientific Method

In 1620, Sir Francis Bacon laid the foundation of the scientific method in his book *Novum Organum Scientiarum* ('new instrument of science'). At a time when societies were recovering from religious wars, Bacon advocated a very empirical, observational, reasoning method that did away with metaphysical conjecture. He argued for an objective scientific. Bacon proposed that when theories are created, they should be iteratively tested

and ***refined with evidence provided by observation***. This empirical approach aims to ***arrive at a general truth from initial observation***. Bacon admittedly wrote that one might initially objectively collect the ***“first vintage data”*** without prior explanation in mind. This method also considers questions that are raised by observing phenomena. In this method, hypothesis refers to observational science; it follows that it is necessary to initially collect information to generate hypotheses. This method also avoids any cognitive bias of “idols of the mind”. In the empirical model that argues that knowledge comes only or primarily from sensory experience, scientists observe phenomena. With enough observation from that phenomenon, they declare a theory.

Deductive Logic and Inductive Logic

The logical method of empirical science is based on induction and is divided into two parts: Deductive Logic and Inductive Logic. Deductive Logic’s lineage, which is an oversimplified version of inductive logic, can be traced back to Aristotle’s Syllogism. It is an argument for assurance which depends on verification; and is formalized to state the essential character of reasoning. For instance, if statement ‘A’ argues that ‘this is a house’ and statement ‘B’ indicates that ‘all houses are buildings’, then deductive logic concludes that ‘C’ is a format of a house as a building. In this method, if ‘A’ is a fact, and ‘B’ is the rule as knowledge, then ‘C’ is referred as a deduced inferred fact. Inductive Logic is a process by which theories are derived from observation of phenomena. It uses sufficient mappings between the components of scientific investigations borrowed from Bacon. In this method, theories are generalized and observable phenomena are precisely described. If statement ‘A’ is the observation of a phenomena, and ‘B’ represents a theory, then a Prediction occurs in statement C. The traditional example for inductive logic gives this example: if all coppers have been tested and determined to conduct electricity and ‘X’ is a piece of copper yet to be tested, ‘X’ will conduct electricity.

Critics of Instrumentalism (Isaac Newton, David Hume)

There have been multiple criticisms of an inductive methodology. Interestingly, Isaac Newton stated that with the use of instrumentalism he could explain the laws of motion, and that equations could be used to describe gravity. However, he couldn't hypothesize what an actual distance really was. He wrote that *"I have not as yet been able to discover the reason for these properties of gravity from phenomena, and I do not feign hypotheses. For whatever is not deduced from the phenomena must be called a hypothesis; and hypotheses, whether metaphysical or physical, or based on occult qualities, or mechanical, have no place in experimental philosophy. In this philosophy, particular propositions are inferred from the phenomena, and afterwards rendered general through induction."* David Hume argued that ***the problem with Inductive logic is that it is unsafe to generalize about properties of a class in an object based on observations of particular instances of that class***. This alludes to presupposing sequences of events in the future as though they would happen as they had always happened in the past. It is what Hume described in the Principle of Uniformity of Nature. ***This means that induction does not have to actually work just because it did in the past. Hume suggested that we just have to accept induction as an instinct.***

Abduction (William of Occam, John Keats, Einstein, Dawkin's Arguments) (Concilience)

There is another approach toward scientific rationalization which is called abduction; and there have been various statements about it. Abduction is another version of Induction with explanation added to it. The main problem with Induction is that there might be many explanations for a phenomenon. If one wants to choose the best hypothesis among many, one would look at the one that explains the causality of the events or in other words explains most with least. Dawkin on Induction suggests that "never were so many facts explained by so few assumptions". This refers to the role of ***elegance in science***. William of Occam stated that among competing hypotheses, the one with the fewest assumptions should

be selected, and he referred to the elegance of selection as “*entia non sunt multiplicanda praeter necessitatem*” which translates as “entities of explanations must not be multiplied beyond necessity.” On the development of the ode form, ***John Keats declared that beauty is truth, truth beauty. Alfred Whitehead within the associative approach stated that we should seek simplicity and yet distrust it.*** Finally, Einstein concluded that “*raffiniert ist der Herrgott, aber boshaft ist er nicht,*” which means “***God is subtle, but He is not malicious***”. These quotes have in common that they refer to an effort for seeking causal explanations simultaneously as we use induction. Therefore, these theories for abduction suggest verifications with causal explanations alongside the inductive method. Even a recent form of the scientific method called Concilience recommends that different kinds of evidence from different sources should come together to provide causality (verification) and explanation of a phenomenon.

Sir Karl Popper’s Falsification

Although explanations provide verification for logical arguments, scientific theories can never be truly verified, and many have eventually been disproven. A very traditional example of inductive logic is the black swan fallacy which states that “all swans which we have seen are white and therefore all swans are white, and there is not a black swan”. However, in reality, there are black swans in the world. The lesson here is that one cannot look at all swans to prove the first statement, but there should be a symmetry to disprove and falsify it. Therefore, ***an accumulation of confirming instances is not sufficient to verify a universal generalization; even one disconfirming instance is sufficient to refute a universal generalization. Karl Popper stated that all scientific theories should be falsifiable, and this divided science from pseudo-science as Thomas Kuhn puts it.*** Popper compares falsification to the Darwinian process of survival of fittest. It tries from many different approaches to falsify a theory and makes strong arguments in this regard. This method emphasizes a provisional

nature of scientific truth. ***If a hypothesis is battle-tested in many ways and directions and explanatory frameworks are added to it, it becomes a theory.*** The famous modern model of the atom (quantum physical models of the atom) which was postulated in by the theoretical physicist Werner Heisenberg in 1927, is an outcome of this method.

Popper's Problem Statements and the Maze Model (Search Space) in Architecture

Popper's falsification method is incorporated into various disciplines with multiple interpretations. His objection to the empirical method declared that there is no clear logical link from a set of observations to a theory, and hence empirical method presupposes unprejudiced observation. ***The empirical method has been replaced by Popper's Problem Solving Model. In his method, hypotheses are replaced by problem statements, and observation of phenomena are replaced by precise explanations of problem statements. Therefore, refutable hypotheses are falsified recursively to make a strong argument. In support of this method in architecture, Alexander wrote that "There is no legitimate sense in which deductive logic can prescribe physical form for us."***⁹ Herbert Simon interpreted Popper's model as a search space for a set of problem statements with predefined goals as ideal-focused decided solutions. ***Simon compared this search space to a maze model which has a start point and a goal state, and to reach the goal statement each intersection has to be tested.*** This means that ***Popper's problem-solving model***, which accompanies a search space, ***tests possible solutions, and it needs a clear goal statement to have an explicit direction defined as the mapping of the behaviours into various possible states.*** (Simon, 1969) Christopher Alexander described this system for architecture in three phases. In phase one, ***"Analysis", a problem is diagnosed and a set of goals are stated. In phase two, "Synthesis", plausible solutions are given and selected alternatively, and in phase three, "Evaluation", an entire system is shaped, organized and evaluated.*** (Alexander, 1964) Later,

9 (C.Alexander P8 synthesis of form)

Alexander defined this process as goal decomposition in which goals are divided into sub-goals. He also suggested that problems should be broken down into pieces, and boundaries should be defined for search spaces.

Kuhn's Paradigm

There is another version of scientific logic which constituted a paradigmatic shift in the discourse. Thomas Kuhn in his controversial 1962 book, 'The Structure of Scientific Revolutions', pointed out that science does not progress in a linear manner through the accumulation of new knowledge, but rather undergoes periodic revolutions. In science, this is called "paradigm shifts" and describes a condition in which the nature of scientific investigation within a particular field is suddenly altered and mutated. A paradigm shift occurs when scientists need to choose between competing theories that have irregular results. At these moments of crisis, science must integrate old results along with atypical results into one single framework. This means that when normal science keeps moving forward with incremental advances and cumulative information, it refines theories and hypotheses; but every now and then those theories start to strain under the weight of challenging data with multiple outcomes; a sudden shift occurs within a new explanatory directional framework and an ***"abductive earthquake"*** manifests itself. At this point, the conceptual view shifts and a new framework is generated. Examples of this shift in science are Heliocentrism, Evolution, Plate Tectonics and Quantum Mechanics. Another example of this in biology is the Chemiosmotic theory introduced by the biochemist Peter Mitchell. This theory describes ATP synthesis that involves a proton's electrochemical coupling. ***The genesis of Kuhn's argument is that a science must pass through several phases before formalizing a discipline.***

Kuhn divides science into three distinct stages which are discussed in this chapter. Initially there is the prescience stage that uses deductive and inductive logic and does not include a central paradigm. The next stage is "normal science" in which scientists attempt to

enlarge the central paradigm by “puzzle-solving” introduced in Popper’s falsification theory; it replaces descriptive phenomena with problem statements and search spaces. The third stage, which uses normal science with a paradigm in an explanatory framework, is enormously productive. It is called revolutionary science. Kuhn wrote that ***“when the paradigm is successful, the profession will have solved problems that its members could scarcely have imagined and would never have undertaken without commitment to the paradigm”***. (Kuhn, 1996,p24-5)

Generating Processes as Knowledge for Architecture

The genealogy argued in this chapter introduces various domains in which knowledge is generated in order to establish a new science of design that envisages processes and information in architecture as knowledge. *For declaring science of design in architecture as a potential possibility that has not yet been realized, architecture as a material practice should be analytically re-explained. If architecture as material practice is analytically explained to affect the well-being of human lives, then design of the process and information in it is a purposeful activity fulfilling the objectives. On the other hand, design is a contingent activity dependent on circumstances. Design involves norms of reactions and degrees of perfection. Therefore, objectives in design cannot be stated as linear and concrete end goals. This means that end goals might be captured as the final artifacts but not in linear, predictive performance-based processes. Performance belongs to predictions, and thus involves the deductive method. (Aristotle’s top down approach). Goals sometimes are outcomes of processes that had been previously little understood. They should interact to be part of what is possible in the domain of the processes. This means that goals cannot be realized independently in isolation and they have to be obtained simultaneously in “top down” and “bottom up” approaches or in a combination of several approaches. Therefore, design can be understood as a response to some invisible systems of conventions as much as to*

stated objectives like a contingent activity. Hence, formulating these invisible systems as processes in architecture should be understood as knowledge. Indeed, the implication here is to think about the process itself as knowledge.

Generating Schematic Context in Architecture from Cumulating Knowledge (Process) and Results

The critical point in capturing processes as knowledge can be illustrated when types of reasoning styles are compared to design in three stages. The logic of deduction was introduced earlier in this chapter. If architecture has a case that involves facts and formulated rules and considers information as knowledge and process, *it deduces results as an inferred fact. In the second stage called induction, science observes a natural phenomenon to decipher its principles. Here, theories are generalized and observable phenomena are precisely described. This can be compared to the case-based approach in architecture that analyzes the phenomenon of a particular building or structure in order to extract interpretations and general principles. Induction, in combination with the observation process, predicts the rules. In other words, it uses the results of various cases to deduce generalized formulas and rules. But if architecture adopts the “abductive earthquake”, it might be able to treat each case as a schema to study. In this method, we know the rules and results in interactive domains and our statement produces the case. Indeed, this case is the schema introduced by Kant. It becomes a model for thoughts and a model to study: a tool for organizing perceptions into a concept. This case is not an image but rather a conceptual structure organizing the concepts. Indeed, this architectonic system showcases a transcendental schema as Kant puts it.*

Chapter Six: Material Theories and Techniques in Art and Architecture

Theories in Materiality within Practice (DeLanda, Gilles Deleuze, and Guattari)

For a clear understanding of material computation, one must comprehend it within an architectural context, along with its theoretical and technical development. There are still two different philosophies of materiality in current discourse. One imposes pre-conceptual forms on material systems and the other aims to rediscover materialization processes based on material behavior through iterative processes. DeLanda delineates that “in one philosophy one thinks of form or design as primarily conceptual or cerebral, something to be generated as a pure thought in isolation from the messy world of matter and energy. The opposite stance may be represented by a philosophy of design in which materials are not inert receptacles for a cerebral form imposed from the outside, but active participants in the genesis of form.” (DeLanda, 2001) (Menges, 2015)

Deleuze and Guattari on Material Culture

Deleuze and Guattari succinctly defined this concept. ***“On the one hand, to the formed or formable matter we must add an entire energetic materiality in movement, carrying singularities or haecceities that are already like implicit forms that are topological, rather than geometrical, and that combine with processes of deformation: for example, the variable undulations and torsions of the fibers guiding the operation of splitting wood. On the other hand, to the essential properties of the matter deriving from the formal essence we must add variable intensive affects, now resulting from the operation, now on the contrary making it possible: for example, wood that is more or less porous, more or less elastic and resistant. At any rate, it is a question of surrendering to the wood, then following where it leads by connecting operations to a materiality, instead of imposing a form upon a matter”.*** (Deleuze & Guattari, 1987) (Menges, 2015)

By understanding natural material systems and associated theoretical and technical advancements, we might position ourselves to ***‘think about the origin of forms and structure, not as something imposed from the outside on an inert matter, not as a hierarchical command from above, but as something that may come from within the materials, a form that we tease out of those materials as we allow them to have their say in the structures we create.’*** (DeLanda, 2001) (Menges, 2015)

Material Culture (Josef Albers and Frei Otto)

The history of architecture has witnessed architects aiming to engage various aspects of materiality. Josef Albers at the Bauhaus tried to identify material behaviour as a creative domain for developing new models of construction and innovation. Another example of material experimentation was conducted by Frei Otto at the University of Stuttgart. Otto, through what he called form finding methods, investigated a vast number of different material systems in order to study the capacity to physically compute form as an integral process in design. He stated that ***“the characteristic form results from the organization of matter in space, the arrangement of elements according to a number of embedded rules.”*** (Otto, 2004) (Menges, 2015)

Frei Otto’s Virtual Experiment

Throughout modern history we observed several approaches of material investigations. The first one was Albers’s material experimentation, an experimental approach that conceived material as a driving force in design in open-ended creative processes. The second was Otto’s scientific approach to conducting design research. If the architectural discipline cogitates these approaches alongside system theories and genetic computational frameworks, perhaps its design process could reveal novelties within the discourse of an architecture as a material practice. Thereby, discourse engages with capacities to foster an architecture akin to natural systems. (Otto, 2004) (Menges, 2015)

Frei Otto's Brilliant Biographical Interpretation in Architecture

The most brilliant biographical interpretation of architecture as a material practice is found in the work of Frei Otto. His work proposes an intelligent structural system that requires a minimum amount of materials. Through his investigation, which he called form-finding experimentation, he reduced the volume of materials by defining tension and focused compression into a series of anchor points to extend material attributes and correlate environmental factors. ***A dominant misconception about Otto's work has only been emphasized by his exclusive interest in pre-stressed structures.*** His genuine innovation with soap bubbles differs from traditional solutions for common engineering practices in architecture. ***The point is that he used structural systems to deploy his sense-perception from natural systems. Inspired by unlimited natural organizational systems, Otto used lightweight structures as vehicles to investigate and explore strategies for devising pure tension and compression material systems in the deployment process of bio-extended cogitated schemata. His novel material synthesis of structural-organizational ideas is evidence for his parallel deep personal unity with biological space structures.*** His work also connected architecture with the complex and sublime correlation of environmental and micro-climate control factors. ***In this domain, he bridged the realm of science and architecture.***

Comparing Otto's Mental Faculties with Different Schools of Thoughts

Theoretically, there are various criticisms in architectural discourse that require enhanced elucidations and clarifications in order to investigate Otto's concepts, ingenuity, and intuition. This can also be done by comparing Otto's concepts with the theoretical work of Le Corbusier, Gaudi, Fuller, Mies, and Alexander.

There is a deep intimate connection between Le Corbusier's theorization and Otto's ingenuity and indeed both make use of "Universal Natural Law". Le Corbusier on Darwinian law wrote: "this establishes that objects tend toward a type that is determined by the

evolution of forms between the ideal of maximum utility, and satisfaction of the necessities of economical manufacture.” Le Corbusier’s vision and Otto’s brilliant bio-extended schema totally showcase an architectural culture that ***conforms inevitably to the law of nature.***

The early mechanistic form deployment of Antonio Gaudi which makes use of graphic statics and funicular models is also inextricably connected with the natural organizational schema that had motivated Otto. ***Gaudi’s deterministic manifestation of configured diagrams of forces and complex mathematical shapes such as parabolic surfaces (three dimensional catenary networks) also showcases a novel bio-extended architectural culture which enormously utilizes natural materials’ organizational systems, later developed and advanced by Otto.***

The brilliant work of North American super-architect, ***Buckminster Fuller***, also demonstrates a deep relationship between cogitated natural systems and architecture. Fuller with his beautiful plain regimes of signs (language) compared architecture with life; and ***he truly stated that life is anti-entropic. This means that architecture similar to life moves toward greater complexity and organizational capacity. His techno-sphere discloses self-organizing sublime complexity, a schema akin to natural organizational systems.***

Within the systematic approach, Otto’s organizational schema can also be compared with Christopher Alexander’s system. Alexander analytically explains that “a system as an abstraction is not a special kind of thing, but a special way of looking at a thing, it is a way of focusing attention on some holistic behaviour in a thing, which can only be understood as an interaction among the parts.” ***The critical divergent point here is that Otto’s abstraction goes beyond Alexander’s simple linear kits of parts or pattern language, and he defines a recursive system which not only generates a different system but also moves toward a simultaneous refinement and a degree of perfection. This is illustrated when Otto re-classi-***

fies structures according to a number of criteria.

In terms of using a quantitatively minimal amount of material, inclusively with different approaches but parallel mind-sets (themes), Otto's work aligns with brilliant minimalist Miesian Architecture. Their approaches refer to their design objectives, and themes allude to problem solving method. In comparisons, they emphasize minimal problem solving methodologies on which they agree. *The early dominant theme of Otto and*

Mies van der Rohe's work is their minimal qualita-

tive material selections. Within these comparisons, it can be seen that biology had provided a rich inspiration for Otto's intuition and scrutinising process in architecture.

Frei Otto

“The characteristic form results from the organization of matter in space, the arrangement of elements according to a number of embedded rules.”

Otto through what he called form finding methods investigated a vast number of different material systems in order to study the capacity to physically compute form as a integral process in the design.

Material Culture

Figure 79; © ICD/ITKE University of Stuttgart, Source: <http://icd.uni-stuttgart.de>

Current Precedents (AchimMenges, Sean Ahlquist)

Sean Ahlquist and AchimMenges's research and cutting-edge pavilions built at the ICD/ITKE Universität Stuttgart manifest a morphogenetic approach to design. They unveil the morphological complexity and performative potential of a material construct without separating formation from materialization processes. Their projects unfold a novel understanding of material, form, structure and environment in a complex conjunction with integral computational processes. (Hensel, Menges, & Weinstock, 2010) This enables an understanding of material systems as a collaborative outcome of a recalibration of multiple influencing variables and divergent design criteria. This process includes the interaction of external environmental systems. **"The resultant environmental modulations can be understood as highly specific patterns in direct relation to the material interventions from which they originate."** (Menges, 2008)

ICD/ITKE Research Pavilion 2010

ICD and ITKE's temporary research pavilion built in 2010 illustrates the latest advancements in material-oriented computational design, simulation, and production processes in architecture. This pavilion is made entirely with highly elastically-bent thin plywood where wood's natural performance capacity was computed for form-finding criteria. (Menges, 2010) Here, material behavior is the main element driving design. This means that the computational generation of form is directly driven by physical behavior and material characteristics. These dependencies (characteristics) were physically experimented with, and the assessment of deflections of elastically bent thin plywood strips were interjected into computational models. Then, the strips were robotically manufactured as planar elements, and connected so that elastically bent and tensioned regions alternate along their length. FEM simulation with evolutionary systems were used for structural analysis.

Figure 80© ICD/ITKE University of Stuttgart, Source:
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Figure 81; © ICD/ITKE University of Stuttgart, Source:
<http://icd.uni-stuttgart.de/?p=4458>

Figure 82; © ICD/ITKE University of Stuttgart, Source: <http://icd.uni-stuttgart.de/?p=4458>

The significance of this project is that the computational framework argued in this paper has a focus on ***material behavior to augment and disclose performative capacity of material systems in architecture*** to unfold new architectural possibilities previously unexplored. (Menges , 2010) The material form and formation in this performance-based design unfolded a complex structure from one uncomplicated material system. (Menges , 2010) Augmented equilibrium within this system manifested a unique occupiable architectural space with efficiency in terms of material resources; this project also unfolded a reciprocal maturation of both techniques and theory with architectural discourse. (Menges , 2010)

Figure 83; © ICD/ITKE University of Stuttgart, Source: <http://icd.uni-stuttgart.de/?p=4458>

ICD/ITKE Research Pavilion 2012

This pavilion, entirely robotically fabricated from carbon and glass-fiber composites, manifests the possible interrelation between bio-mimetic design strategies expounded in this inquiry and the novel processes of robotic production. (Menges, 2015) ***'The research focused on the material and morphological principles of arthropod exoskeletons as a source of exploration for a new composite construction paradigm in architecture.'*** (Menges, 2015) Although the robotic fabrication of this pavilion demonstrates nobility in terms of construction, its computational model illustrates a new framework derived from direct understand-

Figure 84; © ICD/ITKE University of Stuttgart, Source:
<http://icd.uni-stuttgart.de/?p=4458>

ing of a biological model. (Menges, 2015)

Material Equilibria Installation, ICD , By S. Ahlquist and Prof. A. Menges

The specific focus of this thesis is tension-active systems. The installation, entitled MATERIAL EQUILIBRIA, showcases computational designs of textile micro-architectures and material behavior in forming complex force-active structures. (Ahlquist & Menges, October 2013) With computer-controlled manufacturing, the micro-structure of the knitted textile is differentiated to predict tensile behaviors across its surface. (Ahlquist & Menges, October 2013) A spring-based modeling environment, programmed in Processing with evolutionary methods, is utilized to predict and design the behaviors and equilibria between tensile surface and a bending-active boundary. (Ahlquist & Menges, October 2013) This means that defining ranges and regions of knit density, as well as the stiffness of bounding glass-fiber rods, are augmented by scripted feedback for various forces. (Ahlquist & Menges, October 2013) This prototype manifests various systems and organizational processes that act upon multiple forces from both spatial and material factors. (Ahlquist & Menges, October 2013)

Figure 85; © Source: <http://icd.uni-stuttgart.de/?p=7636>

Figure 86; © ICD/ITKE University of Stuttgart, Source:
<http://icd.uni-stuttgart.de/?p=4458>

Figure 87; © ICD/ITKE University of Stuttgart, Source: <http://icd.uni-stuttgart.de>

Figure 88; © ICD/ITKE University of Stuttgart, Source:
<http://icd.uni-stuttgart.de>

Chapter Seven: Proposal and Projects

Figure 89; © Author; PureTension, Studio, Fall 2015

Form-active Structure, Spring-Summer Studio 2015

Material Testing

Scripting Behaviour

Final Prototype

Figure 90; © Author

Project Introduction

It has been stated that in offering the most condensed and radical statements, pavilions often represent the leading edge of architectural discourse; pavilions of the twentieth century were sites for the incubation of new forms of architecture that were sometimes shockingly original. In fact, they were so new that they were not even recognized as architecture at all. (Menges, 2015) (Sheil, 2008) This thesis' project presents the format of the pavilion as a vehicle for investigating new territories and alignments between the fields of design, engineering and natural science. It will showcase how it may actually lead the author's architectural mindset into the novel, multidisciplinary and multifaceted territory of design culture. The main concept and idea here is to showcase a set of intelligent frameworks for the computation of material characteristics and behaviors through the calculation of physical behaviors which are argued in this thesis. These pavilions and prototypes would echo cross-disciplinary investigations from computation, system qualities, biology, philosophy, and material science. Eventually, the framework would reveal strategies and tactics for computational frameworks as transcendental schemata.

Although evolutionary processes and natural material formations are argued to adapt to environmental conditions, frameworks in this thesis looked at transcendental schemata behind gestalt's logic. As illustrated in the biological dynamo of this thesis, *'structures of living organisms are not distinct from the function that they support; they are themselves the function. There is no difference in their physiological principles; they adapt to the forces exerted upon them and to environmental conditions.'* (Menges, 2015) However, adaption only occurs in turns and twists of embryological development through a feedback loop in which its 'state apparatus' develops. ***The framework for material computation*** within the design of pavilions and prototypes would resonate with ***natural systems. It would consider architecture as a system of systems for unveiling, analyzing, elucidating, and evaluating***

the complex integrated capacities driven from natural intelligence, as Alexander puts it.

Therefore, they are designed through the framework to augment, adapt, and be adapted to the environment and contexts, individuals, societies, deficiencies and disabilities as they engage the architecture.. The upshot of all this is that ***architectural systems would be akin to natural systems and share their intelligence.***

The fact that they are akin to natural systems does not mean that their entire framework is not part of natural intelligence. The framework is not about the classification and naming (labeling) processes of artificial intelligence; rather, it is about substrate independence which is not separated from bio-scaffolding and nonorganic life. Interestingly, man has learned that the tools he has developed and used, have eventually reconfigured consciousness and way of his living through a recursive feedback loop. Tools, evolutionary computational methods, intelligent frameworks, and finally learning machines in this inquiry just continue to extend their capacities into an infinite horizon. But the point is that all of this is us, one inextricable entity from nature and tools that we make. Therefore, the vehicles here are tension-active prototypes and a final pavilion. ***The real idea is to design models of thought or transcendental schemata in the learning machine that will act as a bridge between finite and infinite possibilities and connect architecture with the sublime. This opens up greater possibilities of complexity and forms of beauty. It designs the whole with multiple positive self-reinforcing recursive feedback-loops as it teaches the whole to make a natural emergence.***

In the design of pavilions and prototypes, there is also another theoretical question that needs to be elucidated relating to simulation probabilities. The theoretical development of the philosophy of science also investigates whether simulation can be an experiment that generates a new sort of knowledge or not. Some schools of thought argue that simulation can never truly produce knowledge. They argue that simulation is solely an act of predict-

ing what is possible in the domain of actions. Furthermore, it is intrinsically based on and connected to an axiom and theorem of ingrained (deeply established) preconceived knowledge. It may show new phenomena, but it fundamentally does not question underlying theories. The argument here is not to find a response to search spaces that some simulation provides and that is intimately connected with Popper's maze model. Nor is it about its in-depth spectrum which computes probabilities beyond human understanding. The divergent point here is the truly inquiring and cogent explorative quality that simulation has, and that excludes certain aspects to have an investigative moment. This exploratory investigative moment which excludes certain aspects to achieve a degree of perfection indeed moves away from speculative deducible logics. This thesis consciously eliminates any totalizing preconceptions to engage aspects of materiality that are far from designers' intuitions. Here, the argument is not about virtual reality which casts so many preconceptions about space into a piece of software which doubly refines opacity or transparency but which does not escape in-depth entrenched preconceptions. This thesis operates by stepping out of the traditional mode of design thinking as regards the concept of pavilion construction.

Computing Form-Active Structures' Behaviours

It is argued that architecture as material practice replaces the traditional static plan with dynamic sets of rules and forces. These rules and forces can be referred to as nonlinear behaviours. Form-active hybrid structures include multiple structural systems and components such as glass-fibre reinforced polymer (GFRP rods), textiles, slender beams, cables and membranes that display various nonlinear behaviours such as low or high stiffness and elasticity. When these elements are combined into one single organizational entity, into one analytic assembly that forms a cogent equilibrium, they bring a high degree of complexity into the system in terms of computation. This complexity is relative to their determinate and indeterminate design parameters, and spatial factors' forces (external and internal) in terms

of their nonlinear physical behaviors. Therefore, the consequence here is to ***compute the nonlinear behaviors of these non-homogeneous material systems with a heterogeneous organizational method (depathologized Gestalt and Evolutionary Method).***

Nonhomogeneous Material Systems

These non-homogeneous material systems are used not only because of their initial formless state but also because of their specific characteristics and properties. This means that there is a specific definition for these materials' characteristics and behaviours. For instance, Force-Active describes curved beams or surface structures that base their geometry on the elastic deformation of initially straight or planar formless elements. (Knippers, 2011) These materials' indeterminate design parameters, which are deeply embedded in their structure and architecture, can be computed to obtain an equilibrium state. For example, in one system, the elasticity of several elements can be computed to provide a certain amount of rigidity, firmness, robustness, and resistance to another surface in which simultaneously, a surface or another element's behavioral properties can be manipulated to counter-balance, uphold, form and deform an entire system. It is notable to mention that these interactions between material characteristics result in a system that offers a high load-bearing capacity at a fraction of the weight of traditional building elements. In addition, they aesthetically express force flow and equilibrium. This system also facilitates the efficiency, degree of perfection, and geometric flexibility of materials.

Organizational Systems in Thesis's Project (Macro, Micro and Anatomical Scale)

For computing these material systems, this thesis uses multiple organizational systems in micro and macro domains. Initially, if designing the behaviour is an act of prediction, then predicting the physical behavior belongs to linear processes of deductive logic. However, Ludwig von Bertalanffy's GSD illustrated how classical physics with its deductive

methods cannot fit into a dynamic feedback-based system. Hence, for qualitatively organizing systems, which provide constant exchange of information with their environments and elements with feedback, macro-level processes would be designed based on Bertalanffy's open systems' principles for a 'homeostatic state'. This system would include 'the count' (the number of elements involved in the system), 'the type' (what type of elements are in the system?) (how many different types are there?), 'the association' within those elements that elaborates on scripted rules, and the fourth aspect, 'feedback', which is embedded in the organization. At the micro level, predictions and norms of reactions are replaced simultaneously by rates of change, in the same way that simulation is changed by mapping possible states of transitions. This concept was introduced in Holland's complex adaptive systems to achieve a degree of perfection. But the critical interactions occur on the super-micro level at which the entire system appears to be akin to natural systems. At this level, depathologized evolutionary logic is used as a heterogeneous organizational method to analytically explain and intensively deploy the singularities and computational interactive-based properties of materials to manifest forms similar to fundamental processes of natural formation discussed in this thesis.

Prototype Number One

The re-stratification of material systems argued in thesis is comprehensively interpenetrated and illuminated in an installation constructed at the Gallery in Copenhagen by Sean Ahlquist. It resolves a highly integrative form-finding method for woven textiles and meshes and an unfixed elastic membrane. Prototype number one uses a particle-spring based system for re-envisioning the computational schemata of this installation. Here, the position of mass defined by an array of particles in space, and elastic springs, which have an initial length and a damping value, connects particles. This system has several modifiable attributes such as gravity in all three coordinate directions, as well as strong springs. (Note: evolutionary logic applied to mesh typology responds to bending behaviour)

Figure 91: Primary methods for simulating bending stiffness: (a) cross-over, (b) vector position, (c) vector normal. From (Ahlquist & Menges, *Frameworks for Computational Design of Textile Micro-architectures and Material Behaviour in Forming Complex Force-Active Structures*, October 2013)

Simulating Bending Stiffness with Vector Normal

Simulating Bending Stiffness with Vector Position

-Super Anatomical Level and De-Pathologized Evolutionary Logic, Re-envisaging Elements (Substrate-Independence)

Simulating Mesh Element with Evolutionary Methpd

Simulation 6; © Author; Mesh Element

Prototype Number One

Figure 92; © Author

Figure 93; © Author

Figure94; © Author

Figure 95; © Author

Prototype Number Two

Figure 96, © Author

Figure 97; © Author

Figure 98; © Author

Pavilion

Figure 99; © Author

Pavilion

Site: Located in downtown Toronto, HTO park, an urban beach site, presents a focal point where a transitional condition is played out between the dense urban fabric and the waterfront.

Site

Figure 100; © Author

Pavilion

Current Condition

Figure 101; © Author, Current Condition

Figure 102; © Author, Current Condition

Site Analysis

Instances of elucidations for site analysis initially require a chronological re-explanation of the parameters that define the ecological self-organized system. For the very first time, Alexander von Humboldt in his 'Essay on the Geography of Plants and also Botanical Drawings' depicted how a single seed varies in multiple forms which it develops through feedback-loops within different ecological conditions. Furthermore, Goethe and Darwin's theories, elaborated in this thesis, also illuminated self-organizational systems' possibilities and probabilities within constraints and specific rules (manifestation of the infinite horizon of morphogenetic processes).¹ In this site analysis, rules and parameters are translated into particles and agents for ***re-envisioning spontaneous self-organizational probabilities***.

The transcendental schema for site analysis is similar to the fundamental processes of a natural materialization's schema. It evaluates the accumulated empirical data of environmental conditions in order to inter-penetrate the complex and sublime materialized intelligence that emanates from the interactive feedback-loop. Furthermore, it combines individual elements and substrate-independents into its process. Thereby, critical environmental conditions are gathered as parameters in the first substrate of the self-organizational system. The system then evolves to facilitate intelligent behavior. This stage analyses and indeed simulates an integrative parallel computational schema with many processing elements. ***Parallel computational schema*** relates to ***evolutionary neural systems***, and a ***processing element*** refers to ***an autonomous Agent***. An Autonomous Agent acts as a system that is able to reproduce and also able to carry out at least one thermodynamic work cycle. (Kauffman, 2000) Meanwhile, the evolution of the system is constrained based on the system's criteria. This constraint on the system as a whole implies a form of mutual dependency or coordination between its constituent components or "subsystems". (Ross Ashby)

¹ Morphogenesis the process of development of a system's form or structure. (Embryological Growth, Biological Evolution)

The system does not perform with a deterministic dynamic design parameter in which it might have one state of equilibrium. Instead, it evolves to also calculate what it is to become specifically. In this experiment of autonomous, self-generated architectural analysis, which the author has developed as a design exercise, environmental conditions and restraints are employed, and systems' components and their subsystems respond to it within a recursive evolutionary logic that renders opportunities of studying the emergent aspects of analytical explorations and chances for examining complex interactions within ecology. This analysis is not about opacity or the anticipation of movement in space. Rather, it is a qualitative assemblage of self-organized individuals (with determinate and indeterminate characteristics of design parameters) populated through evolving processes. Here, adaptation and prediction of the system for a degree of perfection is not an exercise, *but it is about its schema which has parallels to the logic of Gestalt.*

Figure 103; © Author, Toronto Weather Condition, from LadyBug

Simulation 9; © Author, Site Analysis, Step One, Scripted Comfort-Zone for Agents

Simulation 10; © Author, Site Analysis, Step Two, Scripted Comfort-Zone for Agents

Pavilion

Here, architecture is defined as material practice. Materiality here does not simply mean substance, and therefore computing its behavior does not only involve computing the substance's behaviour. ***Here, materiality also refers to heterogeneous thought about nature.*** (Whitehead, 1971)

In this sense, its computational frameworks make use of computational models of natural systems. Its organizational capacity is analytically envisaged by infusing morphogenetic and evolutionary schemata. Its transcendental schemata develop through an extension which correlates several agencies (factors). These extensions are integrated with the attributes of materials (substances). These attributes carry the characteristics of matter, and they correlate with embedded inner-connected rules and elements. These formulations of attributes merge reciprocal inner-connected interactions within the material construct, which has both determinate and indeterminate parameters, with spatial factors' forces (external and internal). This process itself, which has a high degree of complexity in its computational strata, is interpenetrated in a manner similar to morphogenetic processes. In this way, the framework for designing the pavilion also deploys a qualitative organizational system including 'Count' (the number of elements), 'Type' (Characteristics of Elements), 'Association' within those elements, and finally 'feedback' in which the system uses to reconfigure and re-stratify its function. At the micro level for 'Association', a parallel evolutionary logic with an integrative undetermined rate of change is used. This is what Holland called 'Transition Function' described as "a mapping of the possible states of a system that can arise from a function". The critical point here is not what can emerge from 'Transition Function'(state), but rather that after the system starts, this state responds to the feedback-loop that is defined at the macro level. In the super-anatomical scale that presents the entire system as akin to natural systems, a de-pathologized recursive evolutionary logic is used as a heterogeneous organizational method to analytically define and intensively deploy the intellectual presence of the singularity of materials and their computational interactive-based properties. The result is a manifestation of forms similar to those arising from the fundamental processes of natural formations discussed in this thesis.

De-Pathologizing Count, Type, Association, Feedback

Simulation 11; © Author, Cell Typology

Simulation 12; © Author; Assembled Cell

Final Simulations and Animation

Figure 105, © Author

Figure 106, © Author

Figure 107, © Author

Figure 108, © Author

Figure 109; © Author

Figure 110; © Author

Augmented Theoretical and Technical Amelioration as a Single Organizational Entity

The projects within this inquiry accordingly augmented a mutual understanding of theories and techniques where they simultaneously constituted an interactive bio-architectural domain. In classical science, it has not yet been verified whether solvable differential equations are purely linear or if they correlate with the real material world. Therefore, this thesis' scientific theoretical dynamo moved into a nonlinear biological domain as it defined architecture as a material practice that correlates bio-extended frameworks for computing those objects. The ramification of this argument was not to oblige one's entire intellect to think about a purely nonlinear world, which would be mentally unhygienic in the author's humble opinion. Therefore, this thesis only de-pathologizes nonlinear dynamic systems in order to study their behavioral patterns. This means that this inquiry by research and intuition aimed to understand and decipher characteristics of diverse qualities of these nonlinear dynamic systems, a barely realizable goal. It fostered increasingly subtle and exact methods of investigations of behavioral patterns within computed models (frameworks). Hence, computers are used to model the behavior in various domains for comprehension of the processes. It referred 'model' to 'program', with 'program' indicating the abstract machine that is a set of numbers, interactions, and relationships. Therefore, abstraction and theory are interrelated, and intimately connected with each other. This means that these all connect theories with practices. In several situations, the abstract sometimes took several paths and relations to the theory and vice versa. However, this thesis constituted and indeed moved into a domain where there is no longer a significant distinction between them. This means that techniques of knowing and doing and making are inseparable within the context of this thesis and its intuition.

In Closing

The open-ended nature of this inquiry compelled the author, through his sense of

Intuition, to only refer to intellectual concepts in the closing part. Just as a gestalt switch deciphered and decoded the invisible character of phenomena, just as 'Lucretius hydraulic hypothesis freed humans from the capriciousness and prejudices of the gods', material computation may free us from deterministic deductive nature of a linear way of phenomenological thinking in architecture. (Kwinter, 2003) ***In this new horizon of systematic alteration in current thinking in architecture, from type to ecology (evolutionary adaptable intelligent design) as Sanford puts it, we should position ourselves to not assume this new emergence as a trivial matter, nor as an abstract conceptual one, but rather develop an intuition for understating and generating a mutual maturation of both theoretical and technical amelioration.*** Within this scaffold, forming the unfolded chaotic properties in capturing code both from organic and inorganic systems as Deleuze puts it, would enable us to be involved as unlimited finite beings. ***In this way, architecture is defined as the work of genius (Schopenhauer's definition) that contemplates multiplicities of simultaneous temporalities in order to bridge the finite with a sublime anti-entropic bio-extended infinite horizon. This means that these transcendental schemata enable us to illuminate our capacities in the universe and see the noblest faculty of man as Aristotle put it.***

Figure 111;© Author

Figure 112; © Author

Figure 113;© Author

Figure 114;© Author

Figure 115;© Author

Figure 116; © Author

Figure 117;© Author

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