5 Defining a Novel Meaning of the New Organic Architecture

"Machines are becoming biological and the biological is becoming engineered."

Kevin R. Kelly

§ 5.0 Current Developments and Trends of Bio-inspired/Organic Architecture.

Starting an overall investigation by categorizing current bio-inspired architectural design developments into "Material", "Morphological", and "Behavioral" to explore a novel definition of the "New Generation Organic Architecture".

At present, people are confronting the unprecedented unification of machine and biology which has been revealed by the means of advancing industrial processes towards the organic model. In his remarkable publication, "***Out of Control: The New Biology of Machines, Social Systems, and the Economic World***" (Kelly, 1995), Kevin Kelly makes an interesting observation that "***Machines are becoming biological and the biological is becoming engineered***". In other words, the clear boundary of machine vs biology is blurring through current technological developments. In "***Out of Control***", Kevin Kelly has further made several explicit points to support his views, that Industry will inevitably adopt bio-inspired methods:

- It takes less material to do the same job better.
- The complexity of built things now reaches biological complexity.
- Nature will not move, so it must be accommodated.
- The natural world itself—genes and life forms—can be engineered (and patented) just like industrial systems.

All the crucial points described above can be easily observed in the architectural industry as well. Each statement corresponds with material optimization, multi-disciplinary technologies, evolutionary processes, and genetic engineering which are all involved in current digital architectural design developments. After years of evolution, the developments of "Organic Architecture" have been now separated into various research focuses which are distant from the original idea coined by the well-known American architect, Frank Lloyd Wright. A group of followers still insist on maintaining Wright's original idea to develop buildings which are green and sustainable, they fit or even blend into the surrounding environment as a whole. But since the power of personal computers and sophisticated modeling software has become relatively easy to access and is employed in all aspects of architectural design, various experiments have been conducted in the last decade, which try to outline a number of new definitions pertaining to "**what are the essential ideas/principles of 'Organic Architecture'?**". Nature has undoubtedly always been the greatest inspiration for the manmade industry, technology, and architecture. This development has only escalated with the assistance from computational technology over the last few decades. The thesis will preview the pros and cons of current design developments under the big umbrella of digital organic/bio-inspired architecture. This discussion will be categorized into three major divisions: "**Morphological**", "**Material**", and "**Behavioral**" owing to the different focus of computational applications within each one of them.

§ 5.1 Morphological

§ 5.1.1 Morphological Development 0

Development pre and post computational assistance.

Instead of digging deeper into the level of thinking how natural objects, such as animal, plants, and landscapes, are formed, architects and artists begin with imitating the appearance of their shapes and analogously re-interpret and re-create them in the design industry. Early architecture examples depict natural forms on engraved layers of columns or rooftop as ornaments on facades. But things started to changes in the 19th century, as people started looking towards mimicking the shape of natural entities and became curios about how these forms were made. For example, Ernst Haeckel as far back as 1866 (Haeckel, 1998), illustrated living creatures including animals and plants to study the morphology of natural entities, wherein he concluded that the morphological development is not only influenced by internal factors but is also impacted by the natural environment. Or consider one of the famous references in the domain of parametric architecture, "***On Growth and Form***" (Thompson, 1992), by D'Arcy Thompson, who focused on analyzing natural forms and studying how to generate them back in 1917. Through time, several newcomers, such as Antonio Gaudi, Buckminster Fuller, and Frei Otto all tried to re-generate natural shapes/forms and apply them into architectural designs from different aspects in terms of their material properties, geometry, and structure. At the time, there was no assistance from computational technologies yet, which made their dedication and contribution all the more admirable. Since the application of computational technologies in architectural design, architects have benefited heavily. However, during the initial phase of computer aided design (CAD), architects still fell into the trap of merely mimicking natural shapes by using the 3D modeling software. Nonetheless, interesting buildings were designed with this mentality of geometric modeling skill by architects during the "deconstructivist" movement. Some of the most prominent ones were designed by the Architects Coop Himm(l)blau, Zaha Hadid, and especially the projects of British architecture firm, "Future Systems". Almost all the projects of Future Systems take inspiration from the nature to design organically shaped architectures over many years. These have been published in two books: "***For Inspiration Only***" (Future System, 1996) and "***More for Inspiration Only***" (Future System, 1999). The skin of the Selfridges Department Stores in Birmingham[51] designed by Future Systems is one such example. The project is inspired by the eyes of a fly, which, is also the inspiration for their visionary project "The Earth Centre" (http://www.earch.cz/cs/future-systems).

§ 5.1.2 Morphological Development I

= Chaos Theory_ the initial phase of computer aided bio-architecture design.

After years of exploration in the field of 3D modeling, Greg Lynn, an architect who has both an Architecture and Philosophy background, developed a parametric thinking approach by using computational techniques based on D'arcy Thompson's analytical logic stated in "***On Growth and Form***" (Thompson, 1992). Lynn used this to generate

51 Please check the Wiki page for more details about the Selfridges Department Store by Future System: https://en.wikipedia.org/wiki/Selfridges_Building,_Birmingham

a parametric model of a house, called the "**Embryological House**". As a metaphor of DNA, 12 control points were able to flexibly manipulate to generate various curvilinear shapes (**Blob**) using different combinations of control point positions. After this, an inevitable wave in both digital and bio-inspired architecture realms to push this parametric thinking to new heights began. Not only in architectural design, but all other sciences are working hard on discovering benefits by following the principles of nature: for deciphering the hidden code behind structures in nature, such as the ways a plant grows, or the generation of a panther's fur patterns...etc. People intent on implementing algorithms discovered from nature to efficiently complete their tasks developed genetic algorithms. The same holds true for architectural design, as architects now attempt to introduce various technological tools like parametric modeling and applied algorithms to architectural design, especially after the development of "**Chaos Theory**" and its implications on computational design. Since Chaos Theory was discovered, multiple useful algorithms have been applied in architectural designs for generating 2d and 3d patterns with the assistance of computational techniques which could hardly be down with manual 3D modeling skills. Alan Turing who had been seen as the inventor of the contemporary computer had a lifetime interest in biological morphogenesis. Although Turing could not witness it himself, but years later, his ultimate dream seems to have come true since the relationship between computation and biology has been tightly bound. Fractals, cellular automation, multi-agent systems...etc., which all work through complicated mathematics algorithms, are able to be easily re-invented using current computational technology. So, pioneering architects have taken these computational techniques as an inspiration and are implementing them into their design projects.

§ 5.1.3 Morphological development II

= flourish developments amongst the young generation of architects implementing computational techniques within algorithms extracted from nature as a new organic Bio-architectural design.

Biothing, founded by Alisa Andrasek, with her colleague, Jose Sanchez, has been heavily experimenting with fractal algorithms, multi-agent systems and embodying them in their design projects (Figure 5.1). These biological principles give the architects chances to design generative rules from a bottom-up perspective similar to how natural objects grow. "**Code sequences generate 'immaterial forms of intelligence... coalescence between the organic and the inorganic**" (Andrasek, 2012). In accordance with Alisa Andrasek's thought, computational technology bridges not only the material and immaterial but also helps with blurring the boundary between biology and the artificial which is again akin to Kevin Kelly's statement that "**Machines (Architecture) are becoming biological**". **THEVERYMANY** can be seen as another pioneering group established by Marc Fornes using computational simulations with recursive logic to generate coral-like, vaporous membranes as a form-finding process. Incorporating the use of CNC machines, laser cutters, **THEVERYMANY** mostly built 1:1 pavilions using sheet-like materials with bending or folding techniques to reinforce the structural supports with simple plug-in/out assembly methods. Like a living plant, the structure was built up through materials as structure without any redundancy making the pavilion have a sense of being an organism. **Michael Hansmeyer** mainly uses recursive computation as well as subdivision methods to not only create several large-scale organic but also slightly Baroque-like architectural elements, such as columns and grottos, and stated that "**we are not seeking to imitate forms of nature in a figurative manner, but instead we reference the processes of their evolution**" (Brayer, Marie-Ange, 2013). Michael's point actually emphasized the major advantages in this phase of morphological development that even when the logic was once taken from nature, it is not simply a matter of reproducing exactly the same what already exists in nature, on the contrary, the logic with the assistance of computational techniques should be able to assist people to generate unexpected, optimized, but also beautiful forms and shapes akin to natural objects. In other words, designers should shift their focus to designing the principles of growth in architecture rather than sculpting the external form. **Nervous System**, another young design group was formed in 2007 by Jessica Rosenkrantz with both architecture and biology degrees and Jesse Louis-Rosenberg whose major is Mathematics. Their biology and mathematics backgrounds make them a relatively strong team of researchers working on the design of natural patterns. They focus heavily on the topic of "**Pattern**"; not only patterns seen in natural organisms but also patterns of growth. Coupling with their professions, they executed digital fabrication techniques, such as 3D printing to realize their industrial design projects from jewelry, lamps, the midsoles of sneakers, and even to a series of 3D printed necklaces and dresses called kinematics, which are all based on the natural growth patterns they researched.

The aforementioned groups are heavily experimenting with digital computational techniques in architectural design. More groups can be listed here under this digital form-finding umbrella with utilizing natural algorithms in architectural design, such as Andrew Kudless' **MATSYS**, Matias del Campo's **SPAN**, Iain Maxwell and David Pigram's **Supermanoeuvre**, who are making numerous fascinating contributions in this field of design exploration.

FIGURE 5.1 Turing Pavilion by Biothing (Alisa Andrasek + Jose Sanche) cooperating with Dshape Italy based on the Reaction-Diffusion algorithms (source: Biothing, https://vimeo.com/20873694).

One of the common points between the above pioneers in computational design is that they use their knowledge to develop/modify the algorithms to fit their designs, and most of them consider materialization as a post-design process, which is totally opposed to how natural organisms develop. Although they have heavily employed digital fabrication to realize their prototypes and mock-ups, this process is unintentionally akin to finding a materialization solution after generating the code in a non-physical simulated universe. In other words, the approach of utilizing algorithms in architectural design in this case is without considering material applications from the very beginning. The positive aspect of this is that there is more freedom for architects to visualize their designs via form-finding techniques and to focus on spatial quality rather than worry too much about construction problems in the early design stage. But, on the other hand, this is exactly the point where there has always been challenges and doubts with their designs because they look more like visionary projects than practical ones which can be actually built. It is not an easy task for architects to solve these practical construction tasks in the early stage of design, but it is potentially feasible to start putting the material or environmental factors as input values like information of a biological embryo to build or even grow with the material properties from the beginning as initial constraints. It is understandable that the above-listed architects are confronting so many different difficult design questions and so they pick their own focus on form-finding process with computational techniques without worrying about applied materials and solving practical issues cleverly with their later design stages. However, young architectural students might take their methods as a given and misuse them with their designs only for generating theatricality, monstrous, complicated forms and claim their projects are organic in nature. "Algorithm" seems to be the magic term to convince people their projects were based on logical translations from organisms to architecture, but as a term of art or nomenclature algorithms in current architectural parlance are totally abusing the essence of mathematics derived from living creatures. If one is not acknowledging the essential idea before applying a specific algorithm, then it is relatively risky in architectural design and fears of reducing the process to a sophisticated method for merely generating "Good Looking" appearance for outer aesthetic purposes become very high. "Algorithms" must be seen as a growing pattern/principle of any organism to be respected and also intensively included in the "design process", not just some random formulas for making organic shapes. In this case, the morphology is truly a process of morphogenesis instead of morphological mimicry. "Genetic algorithm", as another almost magical term, has always been seen as another ultimate solution to all the above doubts when utilizing them in architectural design. Since a "Genetic algorithm" is a relatively special topic closely related to this research's design methodology, it will be intensively considered after the discussions of three divisions of organic/bio-inspired architectural design along with the major inspiration of this research as regards biological aspects.

§ 5.2 Material

§ 5.2.1 Materialization with Algorithms

From the material aspect, several directions are inclusive to this special realm with different focuses but highly related to the material system and also to digital fabrication technology used here. Several experiments can be seen as an extension of the **Morphological** approach which takes materials as a factor along with the development of its unique generative algorithms. Take **EZCT** for example, in their project of "Chair Model", 25 prototypes were generated by the evolutionary algorithm as a biological formation process with natural selection concerning both the material and functional aspects. Later on, with the "Studies in Recursive Lattices" project, they kept exploring the combination of developing the unique generative algorithm. In their study, the recursive algorithm, collaborated with fiber-reinforced concrete as a material system to reduce the redundancy of the useless volume of the materials. A similar idea came across with **Joris Laarman** Lab's project, "Bone Furniture", collaborating with Adam Opel's International Technical Development Center is based on the inspiration of Claus Mattheck's research on the growth of plants and bones.

A series of 3D optimization algorithms in charge of both constructing the main structure lines and conducting the form optimization were employed in the design process which is way beyond the mere imitation of the natural form in the Art Nouveau period (Brayer, Marie-Ange, 2013). By considering the qualities of the applied materials, the algorithms here aren't merely used as a form-finding tool without physical constraints but rather become a relatively reliable process engulfing fabrication and construction.

FIGURE 5.2 Bone chair by Joris Laarman (source: Joris Laarman LAB, http://www.jorislaarman.com/work/bone-chair/, the optimization process can be observed in the same webpage.).

§ 5.2.2 Materialization with Real Organs

FIGURE 5.3 Image on top is the design project "Syncretic Transplants" of Tobias Klein under the guidance of Marcos Cruz. The bottom image is the "gaming console" derived from the film, the "eXistenZ" (source from top to bottom: UCL Bartlett, https://www.bartlett.ucl.ac.uk/architecture/research/projects/neoplasmatic-design, and http://acidemic.blogspot.nl/2015/01/death-to-realism-existenz-oculus-rift.html.

The title of "materialization with real organs" applied in architectural design might sound awkward or even too much science fiction, but it is somehow the simple interpretation of "Neoplasms" (Cruz, 2008) as claimed by **Marcos Cruz**, professor of Innovative Environment in UCL. Also known as the Director of the BiotA LAB in UCL, **Marcos Cruz** revealed his idea of utilizing "Synthetic Biology" technology to transplant real organs/flesh onto architecture bodies to make architecture eventually become a semi-living object. In other words, the real flesh/tissue of an organ is the new innovative material for building up purposeful bio-architecture. It is obvious that "Neoplasms" (Cruz, 2008) is a cross-disciplinary research involving diverse experts, such as biologists, physicians, and engineers to realize his visionary idea. He implied his “Neoplasms” (Cruz, 2008) idea by taking the movie “eXistenZ”[52] as a reference where the organic virtual reality game consoles called game pods have replaced the electronic ones and have to be attached to “bio-ports” inserted in the player’s spine. These game pods have a flesh-like appearance which can be seen as the new material which would be connected to the building through Marcos’s perspective. In the movie, with the bio-port inserted to the player’s spine, the organic game pods gradually become parts of the player, which have three different phases which can be seen as an evolving process also for the buildings of “Neoplasms” (Cruz, 2008). Within the steps of “having flesh”, “being flesh”, and “becoming flesh”, the biologic transplanted flesh emerges as a new material which will gradually blend into each other from both biological and architectural angles to generate a so-called “semi-living” architecture which actually responds as a living body instead of utilizing electric mechanisms to imitate the makeup of living organs. Hypothetically speaking, taking animals lungs for examples, through advanced synthetic biology, numerous lungs can be implemented onto the building’s façade to filter the air penetrating the façade and literally turn the whole building into a semi-living space. This is the philosophical and advanced vision of “organic architecture” from Marcos Cruz’s point of view.

“***Protocell Architecture***” can be seen as an alternative branch of the “Neoplasms” but is relatively more practical in terms of its research approach. A series of experimental projects entitled “Protocell Architecture” in the Architecture Design journal guest-edited by Racheal Armstrong and Neil Spiller explicitly showed several different interpretations of the design idea of “what is Protocell Architecture?”. “**Protocell do not operate within the realms of biological processes that are associated with living systems, but are driven by primordial organizing forces—the laws of physics and chemistry**” (Spiller, Neil & Amstrong, Rachel, 2011). Some try to culture artificial cells to implement the sustainability of the space, for example, synthetic cells generating energy for cultivating the electricity or heat of an interior space in a relatively natural way (applied in Philips Beesley’s ‘the Hylozoic Series’ and his later series of projects); some look into natural principles of physics and chemistry for the solutions from the material world, such as development of inventing self-healing concrete (for example, self-healing concrete by bacterial mineral precipitation of TU Delft’s Micro Lab)[53]. “**The ‘protocell architecture’ can be thought of as an alternative arrangement of terrestrial chemistry that ultimately results in a new living system that has been ‘midwifed’ into existence by human design and technological innovation**” (Spiller, Neil &

52 Please check the webpage for more information about the film, eXistenZ: https://en.wikipedia.org/wiki/Existenz

53 Please check these webpages for more understandings about the “Self-Healing Concrete”: http://www.citg.tudelft.nl/en/research/projects/self-healing-concrete/ and http://www.microlab.citg.tudelft.nl/.

Amstrong, Rachel, 2011). As in Protocell Architecture, they address a lot of the existing technology and attempt to push them to the extreme with the material, or to discover new ways of scientific marriage generating a living system, unlike what Marcos Cruz with his "Neoplasms" (Cruz, 2008) idea was trying to do with an uncertain cyborg-kind of surgery between human and buildings. In the end of the introduction article by Neil Spiller and Rachel Armstrong for the ***Protocell Architecture*** issue of the AD (Architectural Design) journal, they even wrote a manifesto for Protocell Architecture to fight against biological formalism. Rachel Armstrong believes that imitating nature is not the ultimate approach, but to reproduce architecture should be akin to the way a plant produces its fruits in nature.

§ 5.2.3 Materialization, Biomimicry, and digital fabrication technologies

FIGURE 5.4 Neri Oxman's Gemini (source: Neri Oxman, http://www.materialecology.com/projects/details/gemini#prettyPhoto).

Two major series of experimental researches described here as examples are those by Professor Neri Oxman and Professor Achim Menges who coincidently both have similar ideas/interests not only on materiality but also on the logic of organisms' growth as well as integration with architectural application by means of digital fabrication technology. In other words, they both look into the ways of growth of natural organisms and apply these principles in architectural design as fundamentally based on reproducing material' properties along with compatible digital fabrication technology. Of course, they both have their own bio-inspired narratives and specific approaches of digital fabrication.

Ms. Neri Oxman, a professor, is known as the director of the **Mediated Matter Group** with the MIT Media Lab, where she started her preliminary transdisciplinary research between biology and technology from 2006. By extracting bottom-up principles of how natural living creatures grow, she utilized computational techniques to simulate growth pattern and employed digital fabrication methods, such as 3D printing and robotic arms based additive fabrication, to experiment with several prototypes of synthetic materials. In the project "Gemini" (Figure 5.4), a semi-anechoic chaise lounge, Neri Oxman translated the geometry of the Ornithogalum dubium's flower's seed which has a star-like cellular shape interlocking with each other to tessellate the overall form of the lounge, and with the distribution weight simulation ensuring ergonomic comfort for a typical person's weight, each of the generative cellular star-shapes reformed constantly to reach the gradient equivalence of the load bearing as an optimization process. Corresponding with the existing 3D printing and CNC milling techniques, each unique and complex generative cellular unit can relatively easily be fabricated in accordance with the distributed loading simulation result. Against the existing architectural industrial production method of staying homogenous by composing items of homogeneously defined forms and parts, Neri Oxman coined the term "**Digital Anisotropy**" to denote the ability of the designer to strategically control the density and directionality of material substance in the generation of form as nature normally does (Oxman, Neri, Firstenberg, Michal, & Tsai, Elizabeth,, 2012). Based on the above notion cooperating with rapid prototyping methods such as 3D printing technology of Object Ltd., Neri Oxman with her team developed several intimate wearable art pieces corresponding with growth principles of related body parts. For example, by simulating the approach of how hard tissue (skull) and the soft tissue (skin and muscle) interact with each other to construct the head part of a figure, an anisotropy helmet was generated with different thickness and density of material composition to resemble a human organ. The thought of linking the material and the production with the goal of functionality is somehow relatively common but brilliant in nature. While the growth of an organism in nature, the material is always considered in association with its' functionality to adjust the density it will inherit and how this would accommodate the method of producing it. This is core to what Neri Oxman would like

TOC

to deliver to not only architects but also the general public in order for us to re-think the means of design concerning the choice of materials, the suitable fabrication methods of construction in terms of material properties, and the ultimate applied function by fully utilizing the existing digital techniques.

Achim Menges, Professor and the head of ICD (Institute of Computational Design, Faculty of Architecture and Urban Planning, University of Stuttgart), also a pioneer in the bio-inspired design field has looked into both biology and material science with the integration of digital fabrication technology for years. Since 2011, Achim Menges with his research team began to deliver a research pavilion each year within the bio-inspired notion of morphology which has intended to transfer the idea from a theoretical paradigm to real construction practice. The morphogenesis idea of Menges is the linkage between the ecological capacities of material systems and environmental modulations. "**Contemporary architectural design is still characterized by a clear separation and hierarchical conception of the creation of form, space and structure and its subsequent preparation for materialization. In contrast, the approach presented here seeks to employ computational processes for a higher level of integration of form generation and materialization**" (Menges, 2013). It is akin to Neri Oxman's notion of integration concerning space, structure, and material as a whole while designing a building like a natural organism. With the knowledge of morphogenesis and the skills of computational technology, Achim Menges took advantage of material properties and the constraints of Robotic fabrication techniques to experiment profoundly with the combination of biology and design. Every annual research pavilion has a unique biologic/morphological principle and is translated into actual construction by utilizing specific application methods of robotic arms as a unique fabrication process. For example, with the research pavilion in 2011, Achim Menges and his team, took the morphological principles of a sea urchin's structure, and with numerous pressure bending testing of plywood strips as the applied materials, and the computed calculations of the structural stability, eventually, the research pavilion was merged into an integrated design. Examining the exoskeleton of a lobster, instead of normal hot-wire cutting, or 3D printing techniques, in 2012, their team developed a customized tool/head for robotic fabrication to weave the carbon and glass fiber onto a temporary steel frame to build up the pavilion. In 2015, the latest version of research pavilion, Achim Menges and his team investigated the natural segmented plate structure of a sand dollar as a shell structure. Taking timber plates as an essential material, the challenge is to have a further understanding of its bending limitations both theoretically and practically, and the applied linkage to the research of shell structure. The other profound challenge is from the manufacturing point of view. For this, the team invented novel robotic fabrication methods of sewing in order to connect each bending plywood component to eventually compose the resulting timber shell pavilion. Wood and the fibers are the two major materials Achim Menges and his team mostly addressed with their current robotic manufacturing experiments. Moreover, with his essential focus on material, Achim Menges also stepped into the exploration of adaptive architecture. In his other two worlds, renowned projects of Hygroscope and Hygroskin (discussed in Chapter 4), by implementing the properties that the wooden film can absorb and release the moisture in the air to morph its shape (inspired by the pinecone), they developed moisture-driven openings, which, automatically adapt to the surrounding environment without any electricity and mechanics.

"**Nature as model. Biomimicry is a new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems**" (Benyus, 1997). Broadly speaking, most of the bio-inspired designs can be viewed as "Biomimicry". This is especially true of Neri Oxman or Achim Menges who attempt to take their inspiration and learn from natural materiality and digital fabrication perspectives to reveal the potential of implementing them into their designs. Their approach not only imitates the natural logic but also translate them in accordance to natural materials selected. This, doubles the layers of complexity but simultaneously increases the depth of their biomimicry based approach unlike those who just literally use such approaches to mimic the appearance of natural organisms. Regardless of whether we consider Neri Oxman, or Achim Menges, and their followers, they all seem to walk on a path searching for a perfect architecture body optimally composed of natural materials with properties selected with the assistance of simulations and digital manufacturing. This, is already a huge step in bio-inspired architecture with one conflict as compared with living entities in nature. First, let's rule out the possibilities of self-division, self-replication based production logics which can be found in nature, since, these can hardly be achieved by using current artificial approaches in the physical architectural domain. The real paradox thus lies in neglecting "the embedded dynamics of natural systems"; the external dynamic property of the environment and the internal dynamics of metabolism and circulation which all living creatures possess and confront. From this point of view, Achim Menges has realized some ideas with his engineered wooden film experiments in relation to moisture absorption, but to reach a fully adaptive body, it is still a relatively long process of development. This is the key point to be considered: how do we enhance our buildings to evolve from being statically optimized to dynamically optimized akin to living organisms. So, to explicitly work on reversing this contradiction, some architects have shifted their focus towards an autonomous swarm based thinking in architectural design, intent to be relatively closer to the way in which natural entities operate. Instead of sculpting the natural form or taking certain natural mechanisms applied as artificial technologies, this section has brought the bio-inspiration and its implementation to a whole new level than merely studying the principles of the natural system and re-creating the system with its nature-inspired design principles.

§ 5.3 Behavioral

§ 5.3.1 More Than Form Finding

A swarm behavior should be more than just a trajectory of virtual agents meant for form finding in architectural design.

When talking about "autonomous" applications in architectural design, one important example is that of Swarm behavior based design process of **Kokkugia.** Co-founded by Roland Snooks and Robert Stuart-Smith, Kokkugia mostly use swarm behavior logic as a form-finding tool to generate 3D complex geometric space. By coding the swarm with specific principles, an emergent self-organization process is initiated, which, frequently results in a frozen fibrous tracing patterns. This is a common approach utilized by the young generation of architects experimenting with autonomous behavior logics in architectural design which, opposes theories of Marcos Novak's Liquid Architecture with its attempts to liquidize otherwise frozen architecture. Although swarm behavior as a form-finding process seems to now be mainstream in architectural design, the section here will outline a different approach by literally harnessing architectural elements as the agents of a swarm. This notion of designing an architectural component as an agent of a swarm composing a building from a bottom up perspective is in its initial phase and is not yet embodied completely in practice, but has great potential to do so using the ongoing trends in technological development.

§ 5.3.2 A Swarm of Smart Autonomous Entities

Swarm behavior, in the case of this research implies activation of agents to promote processes of self-organization and self-assembly driven by a set of collective principles followed by numerous smart autonomous entities.

§ 5.3.2.1 Autonomous as Transportation and Assembly

FIGURE 5.5 Flight Assembled Architecture by Gramazio & Kohler (source: ETHZ, Gramazio & Kohler Research and Institute for Dynamic Systems and Control, http://www.idsc.ethz.ch/research-dandrea/research-projects/archive/flying-machine-enabled-construction.html)

One of the pioneering swarm simulation based projects was called "**Flight Assembled Architecture**" by Gramazio & Kohler in 2011. Gramazio & Kohler was founded in 2000, and later in 2005, they found the first robotic laboratory in the renowned Swiss Federal Institute of Technology (ETHZ, Zurich) which started experimenting with transdisciplinary computational design, new material exploration and 1:1 prototyping with digital fabrication. Although they are mostly known recently by their projects of robotic arm manufacturing experiments, the "Flight Assembled Architecture" can be seen as the first autonomous robotic assembly project which took robotic applications to the next level in architectural design. Cooperating with Raffaello D'Andrea, the Professor of Dynamic Systems and Control in ETHZ, also the co-founder of the KIVA system, they developed a hi-end system with a scenario of assembling a non-standard building using hundreds of autonomous drones (Gramazio, F., Kohler, M., & D'Andea, R., 2014)[54]. The flying drones were akin to a flock of birds picking up bricks one by one and putting them precisely on location in 3d space to sequentially construct the building. In the prototyping process, they used 4 flying drones which managed to reach to 6 meters' height with polystyrene modules which in reality should be 100 times larger in scale to afford 30,000 inhabitants homes in the residential tower. This project showed great potentials for mimicking natural group activities as a physical swarm instead of simulating the behavior behind the computer screen for generating static/frozen building bodies. The drones were used as transportation and assembly robots/tools but it implied near-term development of making each architectural component as a drone-like module. In other words, each of these drones should be treated as smart entities and as architectural components rather than just a device for transportation and assembly. Simply speaking, here the flying drones should "BE" the architectural components, like a bird in a flock to form a collective living form.

§ 5.3.2.2 Autonomous as Mobile/Transformable Components in Architectural Design

Spending years in developing programmable material, Skylar Tibbits set up his **Self-Assembly LAB** under the MIT Media Lab. The Lab now has a great reputation, and is known for its 4D printing technology worldwide. Skylar Tibbits' ultimate goal is to find a way to merge the physical and digital as one that you can simulate but at the same time program with the existing physical materials so as to match the resulting simulation with the physical outcome. But here, it is interesting to look into his early stage of research, which is relatively more akin to the componential and autonomous modular idea while still using the process of self-assembly. From their Self-Assembly Units of 2008, Macrobot, Decibot, even their Logic Matter, a clear evolutionary process can be observed. Skylar Tibbits at the time attempted to develop a modular component which has automatic transformable mechanisms based connections in between. It is a bottom-up idea to create/generate complexity out of simple geometric transformation occurring in each component's connection parts. Akin to scaling-up a Rubik snake, each triangular shape could twist in any angle on every connection to make different shapes. In other words, all of his projects including the Self-Assembly Unit, Macrobot, Decibot, or Logic Matters, have a regular default shape (the figure of a bird) and with some freedom from the designed transformation mechanism (a function of flying) regardless of whether they are electronic or manual, operating under certain principles (a separation distance in order not to crash into each other), they can self-assemble,

54 Please check the video for the generic idea of "Flight Assembled Architecture" project: https://vimeo.com/33919488

resulting in various expected and unexpected formations (a flock of birds dynamically composing variable forms). Even though Skylar Tibbits has contributed toward the development of programmable materials, but in his C-strain project as a playable reconfigurable sculpture structure or even one of his latest project's, Aerial Assemblies, which are like flying balloons, one can still trace how his autonomous assembly ideas are realized in his projects. His experiments in materials are crucial to him because it is possible for him to develop natural mechanisms/robots without any electronic devices. The morphing effects acquired from programming material properties are however, still relatively fragile to be implemented as supporting structures employed for spatial reconfiguration purposes (the most difficult challenge in Interactive Architectural designs). But if these natural mechanisms were applied to relatively smaller modules as a componential system, then the ultimate form can be potentially more effective in terms of their reconfiguration and self-assembly following a bottom-up logic akin to the proposal of replacing bricks by flying drones in Gramazio & Kohler's Flight Assembled Architecture.

§ 5.3.2.3 A vision of Autonomous Emergent Systems

Theodore Spyropoulos and his brother Stephen founded "**minimaform**" in 2002 and since then have dedicated themselves to researching on computational, parametric, and interactive design exploring intimate relationships amongst things, objects, and people. In 2012, with the "Petting Zoo" project, they intended to mimic an animal-like object formed as an elephant trunk hung from the ceiling as an interactive installation. Owing to the approaching movements of the visitors detected by the camera on top, the microcontroller made decisions based on pre-set code to trigger the movements of the 3 trunks to produce an emotional and ambiguous reaction in the visitors. They are among a few architects who have started to bring the topic of emotion into spatial design. In "Petting Zoo", the atmosphere of interaction between people and life like objects created vivid impressions of the space to enhance the idea of communication between space and people. This innovative notion of creating spaces with emotions will be further discussed in the next chapter. Other than discovering the possibilities of mimicking natural living things and the trend to transform the space into a relatively sensitive and emotional environment, Theodore Spyropoulos as a Director of AADRL (Design Research Lab, Architecture Association) has educated and delivered a notion of bio-inspired modular componential system to his supervised students since then. In recent years, Theodore's studio has several innovative experimental projects akin to Skylar Tibbit's early phase of research that worked with modular systems with mechanisms to build a self-assembly system for architectural design from bottom up.

“ROTO”, “Anti-Bot”, “HyperCell”, “noMad” and “OWO”[55] are all projects conceived with the notion of mobile/transformable architectural components following self-assembly logic to construct “Zero-Occupied Spaces”. Instead of the traditional brick-like architectural components, the essential components of these project either have the ability to be transformable or mobile and can geometrically re-configure to construct immediate response. Zero-occupied implies that when needed, the architectural components can move to the required location to achieve the task but can be dismissed afterwards. All these mobile/transformable components can be once again interpreted as agents of a swarm which have relatively simple intelligence with certain freedom of movement following a set of emergent rules. The only critique of their project is that almost all the projects appear in a pixelated fashion to regenerate a typical shape of an object or building without further geometrical explorations.

When speaking of “Robotic Buildings”, people might directly refer to robotically “**Manufactured**” projects, however, autonomous swarm based robotic componential systems applied to architectural design should be seen aptly as “**Robotic Building**”. With the development of current technologies, such as artificial intelligence, it is to be expected that these small entities can become even smarter and dynamic and a lot more efficient while they act like real living entities. “Bio-inspired” design and its implications can thus be now seen from a very different perspective, wherein, the collective intelligence of physical agents can now truly mimic processes of natural growth, self-organization, and emergence. Kevin Kelly in his publication “***Out of Control***” has already stated that “**these same principles of biologics are now being implanted in computer chips, electronic communication networks, robot modules, pharmaceutical searches, software design, and corporate management, in order that these artificial systems may overcome their own complexity**” (Kelly, 1995). In terms of bio-inspired or organic architecture, there should be more and younger and bold architects ready to contribute their talents in this cross-disciplinary realm of bio-inspired architectural design. “**When the Technology is enlivened by Biology we get artifacts that can adapt, learn, and evolve. When our technology adapts, learns, and evolves then we will have a neo-biological civilization**” (Kelly, 1995). It is this cutting-edge future where there is no clear boundary between biology and mechanisms/ artificial like a cybernetic community that people are heading towards.

55 Please check the AADRL website to have a glance of “ROTO”, “Anti-Bot”, “HyperCell”, “noMad”, and “OWO”: http://drl.aaschool.ac.uk/projects/.

§ 5.4 From Static to Dynamic Optimization

From Static (Genetic Algorithm based form finding approach) to Dynamic (Living creature-like Interactive systems).

Following up from the previous discussion about the application of implementing natural algorithms in architectural design for optimal form-finding, using Genetic Algorithms instead, for mimicking natural evolutionary processes to arrive at an optimal form could be seen as a more convincing approach. However, the research, instead, attempts to illustrate a few critical points concerning the use of Genetic Algorithms especially in the field of interactive architecture.

A Genetic Algorithm[56] is defined as a heuristic search that mimics the process of natural selection using mathematical optimization processes. Since D'arcy Thompson started looking into the relationship between mathematics and morphogenesis, experts like him from diverse research fields have attempted to decipher codes in nature using Math, to see how living things are formed. Ultimately, John H. Holland with his team was able to translate Charles Darwin's ideas on "natural selection & survival of the fittest" in his influential publication "***On the Origin of Species by Means of Natural Selection***" (Darwin, 1859) into a computational algorithm, which is since known as the "Genetic Algorithm". The Genetic Algorithm is the one focusing on the purpose of obtaining the efficient "**optimizing solution**" by learning from nature.

"**Genetic algorithms initiate and maintain a population of computational individuals, each of which has a genotype and phenotype. Sexual reproduction is simulated by random selection of two individuals to produce 'parents' from which 'offspring' are generated. By using crossover (random allocation of genes from the parents' genotype) and mutation, varied off springs are generated until they fill the population. All parents are discarded, and the process is iterated for as many generations as are required to produce a population that has among it a range of suitable individuals to satisfy the fitness criteria**" (Weistock, 2004). Michael Weinstock, one of the pioneers addressing natural morphogenesis has written this explicit description of the Genetic Algorithm. Simply said, the algorithm is running a process that keeps looking for a solution relatively close to the defined "fitness" criteria via iterations through a constant generational production process of selection, crossover, and leaving a small proportion of mutational chance as a disturbance. The searching process terminates either by

56 Please check the webpage for more information about "Genetic Algorithm": https://en.wikipedia.org/wiki/Genetic_algorithm

the pre-set maximum numbers of generations produced (terminating searching), or converge into a certain value (result not close to the optimal fitness), or ultimately a satisfactory fitness level is reached. In terms of architectural applications, the Genetic Algorithm has been broadly utilized in searching the optimal solutions for well-defined form-finding problems, such as sustainability, reducing the materials used, structural analysis, and thermal and lighting performance, which are easier to set up with the required fitness in each of these individual cases. Nonetheless, these problems are pre-embedded in constructing static buildings, which, is not quite relevant, when it comes to designing "Interactive Architecture". Even discussing designing static buildings by using Genetic Algorithms, seems to work the opposite way of how nature operates. It is understandable to take advantage of computational technology to accelerate evolutionary processes. But buildings are like plants and animals which are all highly related to their environment. It is thus not convincing to have a "fitness" criteria which is fixed within a given environmental context. A building is a complex object which has many demanding requirements, and a designer using Genetic Algorithms has to select a certain number of these criteria as fitness values in order to achieve Multiple Optimization. However, the number of fitness parameters which can be assigned has its limitations in order to manage computational speed. If one considers all the demands surrounding the design of a building as fitness criteria, then it might result in the production of a relatively average geometric solution, such as spheres, and thus the outcome loses out on the production of unique architectural qualities.

It thus sounds relatively "objective" to use Genetic Algorithms to do calculations and produce an optimized solution, while, in fact, most of the demands are still designed subjectively following the designers' intentions (such as the maximum population of individuals in the first generation, the number of iterations, and the crucial selections of the fitness parameters). Moreover, the so-called optimized results are relative optimizations, not absolute. Genetic Algorithms here provide a method of creating a relatively optimized body(building) suitable for handling a certain number of fitness requirements, which is perfect for optimizing construction and controlling material usage. However, in terms of interactive architecture, with its inherent need to be dynamic in nature, it is not suitable to use this bio-inspired algorithm, since an interactive construct would need real-time optimization based on the slightest change in its context. In terms of "interactive building design", this is also the reason why this research would rather investigate the role of "genes" as the fundamental building block which regulates morphogenesis. In "***Deleuze and the Use of the Genetic Algorithm in Architecture***" (DeLanda, 2002), Manuel DeLanda pointed out a crucial issue pertaining to the role of an architect in algorithm-driven-design: "**Thus, architects wishing to use this new (computational) tool must not only become hackers (so that they can create the code needed to bring extensive and intensive aspect together) but also be able 'to hack' biology, thermodynamics, mathematics, and other areas of science to tap into**

the necessary resources" (DeLanda, 2002). As interpreted, architects should not only remain fixated to extracting principles from other scientific fields and applying them directly for generating forms. Instead, they should further understand the essential notions of applied sciences and translate them into design strategy. The other issue brought out here is that this research does not oppose the idea of optimization, but suggests that optimization should address the context of the dynamic environment. In other words, rather than running heavy calculations to obtain a singular optimized result, one should seek for dynamic/real time optimization of designs to deal with a constantly changing environment and the diverse individuals which live in it. Real-time interactive architectures, which address issues of sustainability and diverse spatial requirements, can actively sense and adapt to the environment and user's needs. Eventually, dynamic optimization/customization can be potentially achieved with the development of computational and mechanic technologies within architectural design. And this is why architects will eventually "hack" into other related fields.

§ 5.5 EVO-DEVO (Evolutionary Development Biology), the Inspiration of New Organic Bio-Architecture

EVO-DEVO (Evolutionary Development Biology), the hidden secret of morphogenesis and the inspiration of new organic Bio-architecture.

Instead of directly extracting and applying principles from genetic engineering into architectural design without any further interpretations and translations, this research attempts to focus more on extracting hidden secrets behind genes to understand natural Morphogenesis. Genes, shall be studied and decoded **to develop a novel design framework for living creature-like interactive Bio-architectures**. Evolutionary Development Biology (Evo-Devo) is a genre of biology, which, looks into the diverse developmental processes in different organisms and discovers how they evolve according to gene regulation principles, unique to them. By revealing a great deal about the otherwise invisible genes and the simple rules that shape an animal form and its evolution, Evo-Devo introduces the keys to understanding form and its development via a process initiated from a single-cell egg to a complex, multi-billion-celled animal body. There was a long period of time that people could only discover that forms do change, and that natural selection is the driving force, but there was nothing to outline how forms change (Carroll, 2005). After decades of research in embryology and evolutionary biology as two separate sciences, the discovery, that similar structures in animals, such as eyes, limbs, and hearts, were governed by the same genes, made these two disciplines eventually came together to create a new discipline called Evolutionary Development Biology (Evo-Devo). This idea that all animals share the same master gene toolkit is comparable to parametric design thinking which has caught much attention from architects who are eager to learn from biology and nature. This research can be seen as a similar effort, which attempts to extract the most crucial and inspiring principles from Evo-Devo to create a new organic Bio-architecture paradigm.

This research gained a clear insight and numerous interesting inspirations from the publication, the "***Endless Form Most Beautiful***" by Sean B. Carroll, who is at the forefront of evolutionary development biology. The title, "***Endless Form Most Beautiful***" was a quote from Charles Darwin's biological classic, "***The Origin of Species***" (Darwin, 1859), which gave an explicit paradigm of Darwin's pioneering belief back in 1860 that the descent of all forms arise from one (or a few) common ancestor. This, has been further proven and supported by the evidence of the current research from Evolutionary Development Biology. This leads us to the crucial and fundamental idea propagated by Evo-Devo that all animals share the same gene toolkits but have differences in terms of the number of genes and their regulations, which is responsible for the diversity of animals worldwide. Based on this essential fundamental notion, this research is able to extract several useful and logical principles, which are interpreted and listed as three major and interrelated topics: "**From Simple to Complex**", "**Geometric Information Distribution**" and "**On/Off Switch & Trigger**".

§ 5.5.1 Simple to Complex

In terms of results, every complex organic body is composed of numerous amounts of simple and self-similar elements based on information obtained from the gene's regulations (which is the on/off mechanism which will be mentioned later in the section of "On/Off Switch &Trigger"). It is apparent from observation of the spine structure of the vertebrates which can be varied in numbers from a dozen in frogs, thirty-three in humans, to a few hundred in a snake (Figure 5.6, left); and diverse in similar shapes of the cervical, thoracic, lumbar, sacral, and caudal vertebrae. This modular design with repeated assemblages of similar parts, according to Sean Carroll, is the success of evolutionary diversification in biology. This principle can be applied to architectural designs to initiate a radical design revolution. People are easily trapped into believing that complex objects should be composed of complicated elements, but taking a closer look at living objects in nature, it becomes apparent that they are all composed of relatively simple and self-similar elements, a core principle behind: "**from simple to complex**". The "**complicated**" and the "**complex**" have slightly different interpretations here in that the **complicated** leans towards a confusing and puzzling situation where it is hard to find the solution while **complex** is more akin to a logical combination of simple elements. This "**Simple to Complex**" principle relates to Kas Oosterhuis' "**One Building One Detail**" idea in architectural design; "...**any building should have only one single parametric detail mapped on all surface, subject to a range of parameters that render the values of the parametric system unique in each local instance, thus creating a visual richness and a variety that is virtually unmatched by any traditional building technique**" (Oosterhuis, Towards a New Kind of Building, 2011). Here, one can trace a common idea, seen both in nature and Kas's notion of architecture; simplicity is not only applied to the shape of a basic element but also to the logic of the system from how the elements were generated and how the ultimate body was assembled. "**Simplicity is thus intrinsically tied to multiplicity**" (Oosterhuis, Towards a New Kind of Building, 2011). With the differences in the numbers, and diverse but similar morphological elements, there are plenty of geometric outcomes which can be generated within this "**simple to complex**" logic from an architectural design viewpoint. Furthermore, if the Evo-Devo idea of all animals sharing the same gene toolkits is taken as an inspiration, then it is easy to relate to the current parametric world in architectural design. However, it would be a better fit if we consider this from a modular/self-similar componential design perspective. Such a simple systematic approach will be further discussed in the "**On/Off Switch & Trigger**" section, which clarifies how architectural designs can learn from the morphogenesis of an animal gene's intelligent mechanisms.

§ 5.5.2 Geometric Information Distribution

The process of several cleavages, gastrulation, progressing into forming three main layers of the embryo; the innermost(endoderm), middle(mesoderm), and outer layers, eventually leads to the development of establishing regions within these layers to form localized tissues and organs in the embryo's body based on the "**Fate Map**" (Figure 5.6, middle up). Like an instruction, a "**Fate Maps reveals that, at some point in development, cells 'know' where they are in an embryo and to what tissue or structures they belong**" (Carroll, 2005). Like making a geographical map, through a precise dividing process of defining poles, axes, longitudes, latitude as a coordinate system, a **Fate Map** will let the genetic switches make marks on the precise coordinates as a GPS system defining the body segments and divisions of diverse cell types, where different organs and tissues belong. Repeating the subdivision process, each organ and body part will be refined with more details, locally generated via cell interactions besides the global specifications of the **Fate Map**. The formation process of an organism is relatively

TOC

simple than what most people think, in terms of logic, which fits exactly the quotation from the physicist Jean Perrin, "**to explain the complicated visible by some simple invisible**". As mentioned before, to directly extract principles from biology and reuse them in architectural design without translation is not the approach of this research. Besides, it is not the ultimate goal to re-create a new species of animal. Although the geometric formation process is quite fascinating and intriguing, this research rather focuses on how the information process behind formation is assigned and distributed. A **Fate Map** works as a global information protocol for cells as regards the kind of cellular differentiation and specialization tasks they need to undertake by demarcating different functional zones. This can be seen as several power-/guide-lines in an initial stage of design to define certain areas for specific functions either based on internal functional influences or physical external environmental impacts. After this, the local information distribution mostly happens while building up the pattern of the hair, scales, fur or feathers. A quick and simple example from the publication of "***Endless Forms Most Beautiful***" can clearly explain this bottom-up idea: in an initially uniform field of cells (Figure 5.6, mid-down 1), two cells assigned by the **Fate Map** begin to differentiate and inhibit cells in contact with them from doing so (Figure 5.6, mid-down 2). Cells in other regions begin to differentiate and inhibit their nearest neighbors (Figure 5.6, mid-down 3), which eventually establishes a regularly spaced pattern of cells (Figure 5.6, mid-down 4) (Carroll, 2005). Regardless of the self-assembly or self-adaptive applications in designing interactive architectures, this kind of bottom-up information distribution protocol can be perfectly implemented by referring back to the aforementioned logic of simple-complex modular componential idea while designing an intelligent interactive architecture based on a swarm logic.

§ 5.5.3 On/off Switch & Trigger

The gene switch (On/Off Switch & Trigger), plays an important role in regulating the formation of an organism. For example, the switches inside the category of the Hox gene tell an organism where and when to evolve different body parts in time. The Hox gene is a collective term including several different types of genes holding a specific morphological task to turn on the gene switches. For example, the Dll(Distal-less) genes are in charge of limb formation, Pax-6 genes play crucial roles in eyes development, Tinman genes are dedicated to the formation and patterning of the heart, and the UBX genes control the differences of the arthropods' forewings and hindwings. But these Hox genes can also play roles in different development of the formation process and that is the reason why the body becomes complex. Take Dll genes and butterflies for example, the major task of Dll genes are generating the limb formation, but a moment later, while it goes to the development of the fur on the wings, the Dll genes will shift their tasks to regulate the pattern of the wings. In other words, these genes switches hold a major and other additional tasks and precisely switch them on and off to generate different cells and proteins through time to sculpt the ultimate body. Taking a closer look at the switch control, "***Endless Form Most Beautiful***" once again gives a great example of how this gene switch works. The switch is basically controlled by "lactose". When lactose is absent, the gene switch is off, because the lac repressor binds to the switch and represses gene transcription. In contrast, when lactose is present, the gene switch flips on and the repressor falls off the switch to trigger the transcription and translation for the enzyme production. This is the exact process of how DNA transcripts to mRNA and translates it for producing demanded proteins (Carroll, 2005)(Figure 5.6, right). These gene switch turn on and off to trigger the enzyme production process in a highly efficient manner. Surprisingly, only around 3 percent of the DNA regulates an organism's formation process through time to produce the intricate complexity of mature animal bodies. This switch, on and off trigger is on one hand akin to the 0 and 1 calculation logic of computational technology. There is another instance of the on/off switch to exhibit how simple but powerful this intelligent mechanism can be through the expression of the Hox6 gene. The on/off regulations of the Hox6 genes defines the neck length of different animals. For example, the position of Hox6 in a goose is longer than a chicken and a mouse, and there is no space between Hox5 to Hox6 gene in a snake which makes a snake have no neck in its morphogenesis. It is because of the layering of nested combinations of the gene switches that make all animal bodies refined and sophisticated in terms of ultimate shape. "**It is by 'computing' the inputs of multiple proteins that switches transformation complex sets of inputs into the simpler outputs as three dimensional on/off patterns of gene expression...**" (Carroll, 2005), which can be seen as a simple-to-complex expression in terms of an organic generating system. One more crucial morphological idea of this on/off logic is that it takes dynamic movement of the body after they were built into account. In other words, the gene switches are not only taking care of the formations but also considering the functions, which the forms will afford afterwards. Ubx gene is the gene which regulates the difference between the hindwing and forewing of a fruit fly. The Ubx gene turns off during the formation of the forewing making it larger, flat, venated and powerful which is beneficial for flight, while the Ubx gene turns on making the hindwing to balance by sensing and correcting yaw, pitch and roll during flight (Carroll, 2005). This particular principle of taking animating movements of the forms into account makes it even more intriguing and fascinating, when we try applying it to interactive Bio-architectural.

TOC

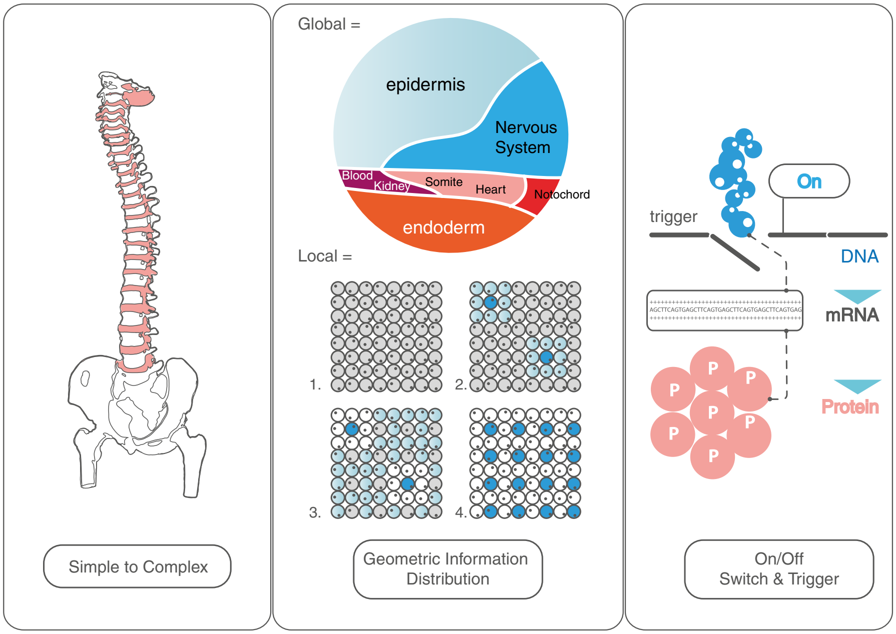

FIGURE 5.6 Diagrams illustrating the fundamental principles extracted from Evo-Devo by this research. "Simple to Complex" referring to the modular elements idea of constructing animal bodies; "Geometric Information Distribution" indicating the internal communication globally as a Fate Map system, or locally as neighboring distribution protocols; "On/Off Switch & Trigger" implying the essential logic of building complex animal bodies by following relatively simple rules as an On/Off (0 and 1) logic to produce proteins as demanded.

§ 5.6 Conclusion

This chapter starts with a discussion of how the gap between the domain of biology and engineering is diminishing and how this helps in addressing the question: "**what is the definition of the organic Bio-architecture**". The chapter further looks into diverse developments in the realm of bio-inspired architecture design, especially the ones utilizing contemporary computational technology, but hold different unique design perspectives. Some of them focus on generating forms with algorithms inspired from nature, some work on material properties with digital fabrication techniques, some want to push swarm robots further as architectural components, and some literally utilize genetic algorithms as an optimized form-finding process. This research takes its' bio-inspiration mostly from a novel biological field, the Evolutionary Development

Biology (Evo-Devo) to see what are the crucial and fundamental principles behind natural morphogenesis of animal bodies. Instead of literally/directly employing the technology from Evo-Devo, it seeks to take the inspiring principles of Evo-Devo and re-creates the useful parts and rules applied to architectural design with the assistance of computational technology. This concept will lead to a summary of all the aforementioned ideas of each chapter by generating the design framework for the bio-inspired interactive architecture entitled "HyperCell" which will be thoroughly illustrated in the next chapter. This research believes that the ultimate goal of Interactive architecture is to become an authentic organic architecture which can pro-actively adapt and react to the environment as well as the users demands. To achieve this goal, it is inevitable to understand the morphological principles of living creature. By learning from Evo-Devo, based on the fundamental idea of all animals sharing the same gene toolkits, this research has extracted three major directions/ principles awaiting to be deployed into new organic and interactive Bio-architectural design: "**Simple to Complex**", "**Geometric Information Distribution**", and "**On/Off Switch and Trigger**". Akin to the parametric idea in today's digital architectural design, it is relatively easier to understand the idea of taking the gene regulations as the combinations of parameters for generating architectural design. Furthermore, "**Simple to Complex**", "**Geometric Information Distribution**", and "**On/Off Switch and Trigger**" can be simplified and interpreted as essential characteristics of modular componential systems, bottom-up information protocols, and 0/1 switches for triggering formation assembly logic. In other words, the design framework developed by this research should lead to an intelligent componential idea compatible with the swarm behavior logic in terms of self-assembly and bottom-up local communication protocols, and its ultimate geometric form should be generated with simple on/off logic considering the movements which need to be animated.

References

Andrasek, A. (2012). Open Synthesis// Toward a Resilient Fabric of Architecture. *Log, 25*, 45-54.

Benyus, J. M. (1997). *Biomimicry: Innovation Inspired by Nature.* New York: HarperCollins Publishers Inc.

Brayer, Marie-Ange. (2013). Natur and artifice: Affects and artifacts in naturalized architecture. In M.-A. &. Brayer, *Naturalizing Architecture* (pp. 14-37). Orléans: Edition HYX.

Carroll, S. B. (2005). *Endless Forms Most Beautiful: the New Science of Evo Devo.* New York: W. W. Norton & Company, Inc.

Cruz, M. (2008). Synthetic Neoplasms. *Architectural Design: Neoplasmatic Design, 78*(6), 36-43.

Darwin, C. (1859). *On the Origin of Species by Means of Natural Selection.* London: J. Murray.

DeLanda, M. (2002). Deleuze and the Use of the Genetic Algorithm in Architecture. In N. Leach (Ed.), *Designing for a Digital World.* New York: Wiley-Academic.

Future System. (1996). *For Inspiration Only.* New York: John Wiley & Sons.

Future System. (1999). *More for Inspiration Only.* New York: John Wiley & Sons.

Gramazio, F., Kohler, M., & D'Andea, R. (2014). Flight Assembled Architecture. In M.-A. &. Brayer, *Naturalizing Architecture* (pp. 136-137). Orléans: Edition HYX.

Haeckel, E. (1998). *Art Forms in Nature: The Prints of Ernst Haeckel* . Munich: Prestel.

Kelly, K. (1995). *Out of Control: The New Biology of Machines, Social Systems, & the Economic World*. New York: Basic Books.

Menges, A. (2013). Morphospaces of Robotic Fabrication. In S. n. Brell-Çokca, & J. Braumann (Eds.), *Rob | Arch 2012: Robotic Fabrication in Architecture, Art, and Design* (pp. 28-47). Berlin: Springer.

Oosterhuis, K. (2011). *Towards* a *New Kind of Building*. Rotterdam: NAi Publisher.

Oxman, Neri, Firstenberg, Michal, & Tsai, Elizabeth,. (2012). Digital Anisotropy: A Variable Elasticity Rapid Prototyping Platform. *Virtual and Physical Prototyping (VPP)*, 261-274.

Spiller, Neil & Amstrong, Rachel. (2011). It's A Brand New Morning. *Architectural Design: Protocell Architecture, 81*(2), 14-25.

Thompson, D. (1992). *On Growth of Form*. London: Cambridge University Press.

Weistock, M. (2004). Morphogenesis and Mathematics of Emergence. In M. Hensel, A. Menges, & M. Weinstock (Eds.), *Architectural Design, Emergence: Morphogenetic Design Strategies, Volume 74, Issue 3* (Vol. 74, pp. 10-17). New York: Wiley.