A MODEL TO INTERPRET BIO-INSPIRED DESIGN AND ITS IMPACT ON DESIGN CURRICULA

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ABSTRACT

A MODEL TO INTERPRET BIO-INSPIRED DESIGN AND ITS IMPACT ON DESIGN CURRICULA

Inspirations from nature is widely used in the field of design. Rising concerns about the irreversible and hazardous effects of humankind, direct the developments in the field of design and technology once again to nature. Biomimicry is a term that connotes the life and imitation of nature and this imitation can be applied also in the context of design as in many areas of life. Nowadays, design has started to use not only the simulation of the shapes of nature but also the structural and systemic features of the nature. In the field of architecture, there is a rising interest towards buildings designed by bio-inspired processes together with the seek for sustainable solutions. Architecture schools which are following the advancements in contemporary built environment and building technologies started to include bio-inspired design courses into their curriculums. Within the scope of this thesis the prominent bio-inspired architectural products are examined in order to; (1) a categorization proposal is developed to read bio-inspired design approaches, (2) the impact and the place of bio-inspired design approaches in leading architectural school's curriculum.

Keywords: *Biomimicry, biomimetic design, bio- inspired design, architectural education, architecture curriculum*

ÖZET

DOĞA ESİNLİ TASARIMI ANLAMAK VE TASARIM MÜFREDATINA ETKİSİNİ YORUMLAMAK ÜZERİNE BİR MODEL

Tasarım alanında doğadan esinlenmeler oldukça yaygın olarak kullanılmaktadır. İnsanoğlunun doğa üzerindeki geri döndürülemez etkileri ve bunların yarattığı endişeler tasarım ve teknoloji alanındaki gelişmelerin yönü doğayı korumaya yönelik üretimlere çevrildi. Biyomimikri köklerine bakıldığında yaşam ve takliti bir arada bünyesinde barındırmaktadır ve bu taklit hayatın pek çok alanında olduğu gibi tasarım bağlamında da uygulanabilmektedir. Günümüzde tasarım, daha önceki doğayı taklit eden yaklaşımların ötesinde doğanın sadece şekillerinin simülasyonunu içermekle kalmayıp aynı zamanda yapısal ve sistemsel özelliklerini de tasarım ilkesi olarak kullanmaya başlamıştır. Mimarlık camiasında doğadan esinlenerek tasarlanmış binalar ve bunlara duyulan ilgi sürdürülebilirlik arayışlarıyla da giderek artmaktadır. Yapılı çevre ve yeni teknolojilerle entegre olan mimarlık okulları müfredatlarına doğayı taklit eden tasarım derslerini dahil etmeye başlamışlardır. Bu tezin amacı kapsamında doğadan esinlenen mimarlık ürünlerinin başlıca örnekleri incelenerek; (1) doğa esinli tasarım yaklaşımlarını okumak için bir sınıflandırma önerisi geliştirilmiştir, (2) doğa esinlin tasarım yaklaşımlarının önde gelen mimarlık okullarının müfredatına ve önde gelen mimarlık okullarının müfredatındaki yeri incelenmiştir.

Anahtar Kelimeler; *Biyomimikri, Biyomimetik tasarım, doğadan esinlenen tasarım, mimarlık eğitimi, mimarlık müfredatı*

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"Whenever we talk about biodesign we should simply bear in mind just how amazingly superior a spider's web is to any load-bearing structure man has made – and then derive from this insight that we should look to the superiority of nature for the solutions. If we want to tackle a new task in the studio, then it's best to go outside first and look at what millenia-old answers there may already be to the problem."

Luigi Colani

CHAPTER 1

INTRODUCTION

Nature has been always an open book to mankind since the beginning of its journey on earth, to discover and to learn from it. With their primitive observational skills, mankind learned how to survive on earth by looking at other creatures and imitate their behaviors and advance the necessary skills. They collect food, covered their thin skin, found or built a shelter as to reach the strongest animals' actions that can survive in nature. These men have already learned *"the survival of the fittest"* by experiencing long before Charles Darwin's (1859) theory and their characteristic features, like the other living creatures, had been adopted throughout the millions of years (Thompson, 1945). The time passed, human achieved to survive, and their needs went beyond from the survival of a single body to the sharing of the food and the shelters as the giant population (Johnson, 2001). These critical problems were not only faced by the human race for the first time, other living creatures, such as plants, animals or micro-organisms, were faced with similar conditions and they figured out the most suitable ways for their survival as well. These brilliant engineers of nature, with their inherent self-organizational skills embedded into their genetic code, overcomes the problems in one way or another via adapting themselves according to the conditions. They always find and proceed with the best solutions which are impressively revealing precedents for us to follow. For instance, bird nests; inspired the first additive built structures, and spiderwebs set an example for bridging across the large spans caused by water or other dangers (Benyus, 2007).

More than being an open source library for learning and imitating, nature has always been an inspiration concerning humankind's unique ability to design. It has been a common practice for designers to observe Nature and imitate its aesthetically appealing, well-functioning and economic designs. Leonardo Da Vinci was one of the first to openly document the processes of imitation through his proposals including flying machine ornithopter, considered as one of the prime examples of design mimicking a living organism. The interest in nature increased afterward and with the 19^{th} century discoveries in the science of biology, the categorization of the species by Georges Cuvier, and life forms illustrations of Ernst von Haeckel led to morphological studies and interpretations of life forms into the field of design in Guiseppe Arcimboldo's paintings, Jean-Marie Le Briss's *"artificial albatross"* (1857) first designed and built flying machine, Louis Sullivan and his successor Frank Lloyd Wright's architectural works which were considered as the first examples of organic architecture (Mazzoleni, 2013).

The interest in biology directs designers' and engineers' attention and investigation on nature more and brought the idea of biological organisms to be viewed as embodied technologies that are equivalent to human inventions. The only difference is that they are more advanced in solving problems and with greater economy. While looking at the extraordinary adaptations that have evolved in natural organisms, humankind senses inferiority of its achievements in comparison to nature's and draws conclusions as there is a lot more to learn from nature (Pawlyn, 2011).

Janine Benyus's introduction of "biomimicry" as a new science in 1998, concentrated many researchers' attention onto this field. From most of the disciplines of the natural and applied sciences, researchers have started to look back to nature and conduct many studies by using analogies to develop models between these distant domains. Biological analogies had been used in architecture for a long time relatively with a superficial understanding. In the wake of technological developments and findings, also with the rising interest to the more sustainable solutions, architecture deflects its direction towards biomimetics, this time in the search of deeper connections (Collins, 1978a).

Architecture's search in nature tries to surpass formal relationships via numerous studies conducted in the field of research and practice. The advancements in the computation led architects to create virtual environments in order to imitate nature in virtual platforms that helped them to understand functional and systematic relations found in nature and to apply or integrate these relations into architectural solutions. Architects developed new approaches named "bio-" like; bio-inspired architecture, biomorphic[1]

[1] The concept of biomorphism is coined by Alferd H. Barr in1936 MOMA catalogue to describe the trend of "curvilinear", "decorative" and "romantic" **forms in abstract art drawn upon organic shapes of plants and animals**. Mostly in favor of free flow (https://www.artsy.net/gene/biomorphic accessed on 04.05.2018 21:15).

(Barr, 1936) architecture, bioconsructivist[2] (Mertins, 2004) architecture, biophilic[3] architecture (Wilson, 1984), bionic and biomimetic[4] architecture (Neumann, 1993).These formulations offers a series of approaches concerning formal, logical, performative and materialistic aspects of architectural design.

These new "bio" frameworks are now getting increasingly incorporated into the design processes through the use of findings of biomimetic research. The developing body of research can lead to insights either as design methods or as design tools. With these new methods and tools brought by biomimetics, the horizon is broadened in the level of abstraction for the use of natural precedents (Pohl & Nachtigall, 2015), and new solutions are developed for design and engineering problems. By its interdisciplinary nature, biomimetics is not only affecting or leading physiologic and morphologic inventions in Biology and affecting only Architecture and Building Engineering disciplines but also other major disciples like Chemistry, Mechanical Engineering, Industrial and Systems Engineering (Helms, Vattam, & Goel, 2009), whose solutions are also beneficial for the creative design processes of architects and building engineers.

The new materials, technologies and virtual environments are the results of multiple interactions with biomimicry at different levels. The set of unacquainted new tools, technologies and materials are now getting familiar for designers (Frazer, 2001). The pioneering architects, such as Antoni Gaudi, Buckminster Fuller and Frei Otto's works and experiments where they used more of naturalistic principles both formally and strategically set precedents for following generations (Pawlyn, 2011). Like many other disciplines, architecture has the master-apprentice tradition which is also visible in academic environments. These pioneering master architects and engineers –mostly teaching in prestigious universities in the U.S. and Europe- spread their inventive ideas to the academy and with their successors deepened the research and experiments upon the relationship of the biomimetics as a part of architectural design processes. Institute for Lightweight Structures (IL) in Stuttgart, led by Frei Otto, was one of the first schools

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[2] Detlef Mertins introduced the term "bioconstructivism" in an article with the same title in 2004, where he overviews **the form-finding principles derived from nature by the architects and used as design ideas** in last 250 years.

[3] The term biophilic is coined by Edward Osborne Wilson in *Biophlia*, 1984 to describe the instinctive bond between human beings and other living organisms as: ***"the innate tendency to focus on lifelike processes"***.

[4] Göran Pohl and Werner Nachtigall (2015) quoted from John von Neuman (1993): *"Bionics/Biomimetics as scientific a discipline is concerned with the technological implementation and application of structural, procedural, and developmental principles of biological systems."*

observing nature and using its formal, materialistic and structural principles as building properties (Nerdinger, 2005). The achievements and worldwide successes take attention, become new mainstream approaches, and their tools and methods have started to be included in architectural curricula. This research intends to identify how these tools and methods are implied and integrated into the leading architecture schools undergraduate and graduate level curriculums, then tries to open a discussion on how and where it is leading to.

1.1. Aims and Objectives of the Study

This study explores the integration of biomimicry into the architectural design processes by providing a closer look at architectural education, and architectural practice and research. The study consists of two parts. In the first part, a categorization of bio-inspired paradigms will be drawn out with the analysis of most prominent examples to detect if there are any major trends, and in the second one there will be an investigation of the integration of bio-inspired design at the undergraduate and graduate level architectural education over the leading architecture schools.

In this context, the research questions are:

1. Are there any noticeable clusters within biomimetic approaches in architecture that share common principles?

2. How research and practice in biomimetic approaches infiltrates into architectural education?

1.2. Method

The research carried out in this thesis consists of two main methods. Exploratory research is conducted in the initial stages to examine how architectural practice, research and education intertwined on the basis of emerging bio-inspired concepts, and to present an overview of the literature and to state different biomimetic approaches by following the emerging cases in literature to provide example for each major category.

The study has started with the investigation of the most known projects held in the field of practice and continued with the bio-inspired design approaches in academy both in the architectural curricula and the advanced researches. Both parts were studied by using sampling method, with different sampling criteria. First part which is about the field of practice sampling is conducted according to the most striking built examples in the public eye and discussed in the academic discourses. The second part of the research is upon the analysis of the academic contributions into the field and sampling was held by looking at the most successful architecture schools according to the QS Top 50 Architecture Schools ranking. Entire investigation was held as an internet-based research since the built examples design teams and leading architecture schools are physically distant.

The outcomes of the study were presented in two main clusters, "projects including bio-inspired design approaches in design process", and "bio-inspired design courses in architectural curriculum". "Bio-inspired design approaches in design process" consisted of three parts which are investigating on "inspirations from the physical properties of Nature", "building performance concepts inspired by Nature", and "inspirations from the logics of Nature". The second cluster is "bio-inspired design courses in architectural curriculum", contains "research groups or projects working on biomimicry, biomimetics and biologically inspired design", "graduate level courses", and "undergraduate level courses". These clusters were critically analyzed as to understand their permeable and impermeable organizations, likeliness and differentiation by looking at their impact on both research and practice and architectural education.

1.3. Overview

Chapter 2 presents a literature review under three main topics: biomimicry beyond inspiration, bio-inspired design terminology, and bio inspired design approaches in the field of architecture. Biomimicry beyond inspiration is a subchapter that is projecting the different point of views of imitating nature, learning from nature and designing with nature. Through the bio-inspired design terminology, the words commonly used in biologically referenced designs and named after "bio" are explained. In bio inspired design approaches in the field of architecture, an overview from a larger perspective is presented.

Chapter 3 is an explanation of the research design methodology. It details how qualitative-exploratory research is conducted for the data collection in a meaningful frame drawn by the thesis and presents the critical approach of the categorizations to detect whether there are major trends in architectural research and practice.

Chapter 4 provides a classification of architectural approaches concerning their formulation of bio-inspired design. The first category is the buildings that have design inspirations from the physical qualities found in nature. This has three sub chapters explaining the formal, structural and material properties of natural organisms used as source of design, each property is explained through three built examples. The second class includes buildings designed with a focus on performances inspired from the natural systems. The third and comprises of buildings designed following logical principals extracted from nature and used as design strategy.

Chapter 5 presents the bio-inspired trends in architectural education in three sub-chapters: graduate and undergraduate programs. The three sub-chapters that are research programs, graduate level courses, and undergraduate level courses. Comparative analysis of this classification is given together with a projection about the possible trends for the future of bio-inspired courses integration to the architectural curriculum.

Chapter 6 is the conclusion. It provides a summary of the thesis. Analyses and research findings are synthesized within the frame of architectural education and possible implications and significance of the study is explained.

1.4. Contributions of the thesis

The present study aims to explore whether there are any major trends in bio-inspired architectural design, how research and practice in this field infiltrates into architectural education, and accordingly to map out how bio-inspired conceptions are implemented in in architectural design curriculums. The purpose of this study is to present an overview of the integration of biomimetics into architectural design and education. Making suggestions upon the directions for curricular adjustments are far beyond the scope of this thesis research however readers may initiate starting points to develop models by looking at the current conditions presented in this thesis study.

CHAPTER 2

LITERATURE REVIEW

This chapter presents an account of the literature on three main subjects, namely "biomimicry beyond inspiration from nature", "bio-inspired design terminology", and "bio-inspired design in the field of architecture".

2.1. Biomimicry beyond inspiration from nature

Starting from ancient Greece, natural organisms were being studied due to their harmonious balance, proportion, and continuity between the parts of a design as the ideal of beauty (Steadman, 2008). Internal relationship between the parts of natural opuses are fluid, both formally and functionally, so their fitness in the ecosystem level. Looking at both plants and animals, their impressive qualities in means of structure and contribution of the parts as an integrated whole were described by Aristotle as the best works of art. Ettore Sottass defines design as "*a way of building up possible figurative utopia or metaphor about life*" (Dormer, 1993) and design carries the formal aspects of the relationship between life and design to an intellectual level. Being the environment we are designing in, also being the environment for finding the solutions from makes nature the main source of analogy for basic source-target relationships (Lakoff & Johnson, 1980). The metaphorical paradigms are generally definitive and leading insights via a high-level understanding of specific properties of the parts of nature that can be carried to manmade objects.

In line with the ideas mentioned above, Janine Benyus puts forward a new term "biomimicry", based upon her longtime investigations. She claims that the ideal connection with nature would only be possible by shifting from "learning about nature" to "learning from nature" (Benyus, 1998). The difference between these two are as follows. The first one sees nature as an unfamiliar domain that is needed to be familiarized in order to defeat and conquer it; the second one accepts Nature's wisdom and is ready to be an apprentice of it. Throughout the ages humans learned about nature, they caused irreversible damages to nature. Benyus (2007) states that "there is no other environment for humankind to continue their life than the one which is devastated by their hand". She continues her arguments by drawing attention to the importance of working towards sustainable solutions to protect nature and live under the same roof and steer into biomimicry which has started to be seen as a way to achieve this (Benyus, 2007).

Biomimicry[5] is a synthetic term, etymologically originated from Greek bios, means life, and mimesis which means imitation. In the beginning of 1970's Werner Nachitgal defines biomimicry as: *"learning from nature for self-sufficient engineerable design"* which he revises it later on as: *"learning from structural, procedural and developmental principles of nature to form a positive network of man, environment, and technology"*, depending on the progressive understanding of nature surpassing from formal achievements in means of sustainable, organizational, and systematic procedures it follows to operate (Pohl & Nachtigall, 2015).

Benyus (1998) provides a framework for the science of biomimicry in principle by looking at nature as model, measure, and mentor. In consideration to nature as a model, biomimicry could be described as studying nature's models and imitating or inspiring from these processes to solve human problems. One example to use nature as model is the water repellent and self-cleansing properties of lotus leaf. It provides a model for textile industry to achieve waterproof fabrics used in outdoor garments. From the perspective of nature as a measure, biomimicry can be understood as an ecological standard which will evaluate our designs and innovations with its master knowledge and directs questions to designs whether they are the fittest and the most economical and functional solutions for that situation. The optimal material uses in bone structures sets a standard for the economic use of materials in manmade products, which establishes an example for the use of nature as a measure, with their reduced surface area and differentiation of material concentration. Color adaptivity of the insects (dynastes Hercules and cycholichilus beetles) under different humidity and sun exposure conditions investigated in the Bio Skin Project lead by Susanne Gosztonyi of AIT (Austrian Institute of Technology), forms an opinion about heat gain regulation between summer and winter periods with color changing facades. The most different and considered as the most important principle is looking at nature as a mentor. Re-valuing of nature as not just to extract something from it to apply human creations but searching about what we can learn

[5] Biomimicry (noun), Biomimic (verb), Biomimetic (adjective)

from it. Velcro sets a good example with how George de Mestral invents a new material in 1941 by questioning and analyzing how burdock plants stick that well to both his pants and his dogs' fur. Mestral uses two facing layers that have different tactile properties, the one with small hooked layer is adhered to a looped surface without slipping (Chandiramani, 2016).

The interaction between biology and other disciplines, such as design and engineering, can have two different ways of interaction in means of the effects and influences on each other. Each of them defines a path that is more direct or indirect as a method of procedure (Table 1). The path linking design to biology is a more direct approach that requires designers to identify problems and biologists are involved mostly with their research findings in a stage of matching the organisms addressing and solving the similar issues (Panchuk, 2006). In other words, a problem driven approach is conducted during which there is an initial design problem whose solution is searched from nature's library (Helms et al., 2009). For example, Daimler Chrysler Bionic car inspired by box fish for the form abstraction and tree growth for the structural configuration with minimized stress concentration of tree branching (Zari, 2007). The designers were looking for a lightweight container which performs in high stability and spaciousness. That's why they brought different solutions for different aspects of the design problem and figured out a way to combine them in one single design solution. On the other hand, from biology to design is a more indirect approach starts with the biological knowledge, which is more general principles of natural designs and aims to find problematics for these principles to be applied. One of the good examples of this can be found in the sustainable approaches used in the Eastgate Building, Harare, Zimbabwe, designed by Mick Pearce. Mick Pearce analyses the self-cooling ventilation system of termite mounds and applies it to adjust day and nighttime temperature of the office building and reduces energy consumption in comparison to the other mechanically ventilated office complexes. This solution driven approach leads designers to learn about nature with deeper analysis of natural problem-solving processes (Helms, Vattam, Goel, Yen, & Weissburg, 2008) and can support more creative solutions with possibly increased depth of analogies.

All these understanding of nature as model, measure and mentor, together with design to biology and biology to design approaches implemented in different biomimetic levels. These levels are classified according to the depth of biomimicry by Maibrit Pedersen Zari (2007) and categorized under tree main groups, organism level, behavior level and ecosystem level in terms of the context it could affect. The first level is organism refers to mimicking a specified organism entirely or a portion of it. Organism level biomimicry is the form-based biomimicry that is the bio-inspired design for innovation (Zari, 2018). Velcro is an example of it while the designer used the physical properties of the organism and represented it as a product.

Table 1. Method of procedure (a) from design to biology, (b) from biology to design

The second level is behavior which is to mimic a specific type of behavior of an organism that uses it to survive or replicates daily in relation to a larger context. Zari (2018) defines behavior-based mimicry as the type of bio-inspired design that is for human well-being. Mick Pearce's East Gate building is designed in a way that the designer used the behavior of the termites in the mound rather than their own features in order to create comfortable building climate.

In the third level, an ecosystem mimics another ecosystem that functions successfully in terms of components and working principles. It has been seen as the sustainable form of biomimicry by Marshall (2009) and (Zari, 2012, 2018) as ecosystem level mimicry concentrates on the process strategies or the functions in the fauna and flora of a particular place.

2.2. Bio-inspired design terminology

The rising interest towards nature have introduced a new terminology for designers to define and clarify their naturalistic approaches which display variety. Even their common ground is the use of the ideas from nature for further technological attitudes, they are distinguished with the emphasis of different characteristics of biological inspiration (Vincent, 1995).

Biomimicry is included into the scientific literature with the term "bionics" by Jack Steele in 1960 at a forum of US Air Force held in Ohio (Vincent, 2001). Bios meaning life in Greek and -ic for like, combined in the manner of “life like”. Few years later Otto Schmitt introduced the term “biomimetics” derived from two Greek words “bios”, meaning life, and “mimesis”, which means imitation (Bar-Cohen, 2005). The term is easily accepted into language with its noun (biomimicry), verb (biomimic), and adjective (biomimetic) forms enabling multiple uses to define situations.

At the beginning, “biomimetic” and “bionic” words used synonymously. However, bionics is more concentrated on *“the mechanical systems that function like living organisms or parts of living organisms”*[6], this differentiation can be understood from how it combines the prefix “bio” with the “nics” of technics and electronics (Al Muderis & Ridgewell, 2016). In the field of design and engineering, bionics goes towards the kinesthetics, artificial limbs, moving sculptures or structures that imitates physical and mechanical functions of biological life forms and how they relate themselves with the environment. Like in the hypothetical examples from architecture, Archigram’s 1964 “Walking City” which has conceptual contributions for later architects to think and use Nature’s mechanisms to help progressive building design (Rowlings, 2018).

On the other hand, a group of German architects led by Frei Otto uses the term “Bau-Bionik”, for the purpose of building with nature’s principles (Pohl & Nachtigall, 2015), bionic is used as the German equivalent to biomimetic. Similar understanding of bionic and biomimetic is used by John von Neumann (1993), who views to biomimetics/bionics as a scientific discipline that is concerned with the technological implementation and application of structural, procedural, and developmental principles of biological systems. Biomimicry is presented by Janine Benyus in 1998 as a new scientific discipline targeting *“learning from and then emulating natural forms, processes and ecosystems to create more sustainable designs”*. Biomimetic is practiced through learning from nature for the improvement of technology and the wholeness of form and function is achieved through a process synthesized from Nature’s precedents.

Biomimetic approaches are often used in design and architecture mostly for their formal grandiosity. One to one implementation of design principles derived from biology, sometimes even through a literal copy, is called as biomorphic approach by Julian Vincent (2001) and defined as *“the abstraction of good design from nature”*. The concept of biomorphism is coined by Alferd H. Barr in 1936 to describe the *“forms in abstract art drawn upon organic shapes of plants and animals”,* mostly in favor of free flow. As a

[6] Oxford dictionary definition of bionics. https://en.oxforddictionaries.com/definition/bionics accessed on 11.05.2019

word, biomorphism is etymologically composed of two Greek words bios, meaning life or living and morphosis form which will be defined as forms of life or forms looking alike life (nature). In the field of design and architecture biomorphic approaches are frequently used for symbolic associations. These associations can be categorized into three according to their use of nature as source of formal inspiration, source of spatial or typological innovation, and source of relational information for geometrical and structural performance or material innovation (Agkathidis, 2016). From this perspective biomorphic and biomimetic approaches seems alike; however, the main difference is the sustainable analogies that are mostly the biomimetic ones.

The other point of view for the bionic or biomimetic architecture is that implies not only the form-related aspects of mimicry, but the inherent qualities of construction as well (Grüber, 2011). The broader understanding of biomimicry accepts it as the design and production of materials, structures, and systems that are modelled on biological entities and processes. This extensive point of view derived from the integration of biology into design field and this period of "-isms" called after "bio" becomes a rising trend in architecture.

Detlef Mertins, an architectural theoretician whose works concentrated on modernism in architecture, surveys this bio fashion in his article *Bioconstructivism* published in 2004. Mertins overviews the form-finding principles derived from nature by the architects and how these principles were used as design ideas in last 250 years. He introduces and uses the term "bioconstructivism" in reference to constructivism incorporated with biocentrism in 1920's and 1930's, that can be stretched out to contemporary biologic thoughts for experimental form-making (Mertins, 2007).

Biophilia is yet another term coined by Edward Osborne Wilson in his book *Biophlia*, 1984, to describe the instinctive bond between human beings and other living organisms as: *"the innate tendency to focus on lifelike processes"*. Biophilic design focuses on the aspects of natural world and aims to bring them into the modern built environment to create a good habitat for our health and wellbeing (Kellert, 2015). It is different from "bio-utilization" which refers to the direct use of nature for beneficial purposes as in the plantation used in and around buildings for evaporative cooling purposes (Pawlyn, 2011). Bio-utilization is always a literal use of nature while biophilia is generally used in highly abstracted schemas.

Through the integration of digital technologies more into the field of design and architecture, deeper and detailed collaboration with biology becomes dominant. Post millennial approaches to nature inspired designs follows the "biodesign" trend. Biodesign refers specifically to incorporation of living organisms as essential components, enhancing the function of the finished work. It goes beyond mimicry to integration, dissolving boundaries and synthesizing new hybrid typologies (Myers, 2014).

All of the different labelings stating nuanced diversity according to the proximity between designs of nature and how they are implied to manmade designs. Although their primary concentrations have been changing, all of them are trying to come up with well-functioning, less harming solutions in accordance with sustainability.

2.3. Bio-inspired approaches in the field of architecture

Biological inspirations for architects while developing design ideas is a long-lasting approach rooted almost in the very first designs of architecture. Observing nature mostly depending on the visual perception within the limits of human understanding (Beveridge & Perkins, 1987) helps architects find similarities between two distinct domains, i.e., biology and architecture. These analogies[7] brought at least two levels of inspiration; one is the visual appearance and composition and the other is the functional one.

For the first group of inspiration, i.e., visual appearance and composition, Steadman (2008) states that *'organic'* wholeness of the work of art is the source of beauty. This concept was very influential also for our research while it is directly related with the physical properties of the nature carried to design and analyzed deeply in further chapters together with the examples of the architects who are influenced by organic wholeness produced accordingly. Steadman continues by arguing for an equivalence between *'the beautiful'* and *'the usefulness'* leading way to the functional interpretation.

In the beginning of the nineteenth century, there was a big debate in biology about whether to consider natural organisms as mechanisms or not. George Cuvier questioned the mechanical philosophy in his laboratory work and tried *'to grasp the manner in which organic forms might have been invented by comparing and studying living things as if they were machines created by the industry of man'* (Steadman, 2008, p. 45). This helped later on D'Arcy Thompson to draw analogies between anatomy and building

[7] biological analogies/ natural analogies/ organic analogies

construction. The Forth Bridge is a cantilever railway bridge constructed in 1889 in the east of Scotland, an example includes many analogies like similarities between the connection methods of constructive tubes of the bridge and bamboo stems. Mainstone (1975) also drew an analogy by comparing double cantilever system of the bridge with the skeleton of a heavy bison through a visual analogy indicating the integration of bones carrying the bodyweight as structural elements coming together and carrying the building, stating that: '*the legs correspond to the bridge's piers, and the backbone, neck and tail are cantilevered out from these supports'* (Figure 1).

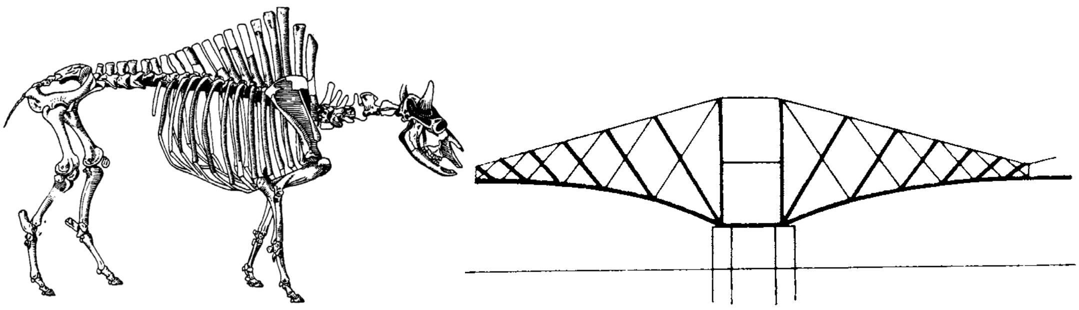

Figure 1. (a) Skeleton of fossil bison, (b) two-armed cantilever of Forth Bridge

It is almost inevitable to escape from the biological analogy in architecture as the first architectural theoretician Vitrivius predicted in ancient times. Three principles of good architecture that are firmitas (durability), utilitas (utility) and venustas (beauty) should be based on the imitation of the nature according to Vitrivius. Looking at the plants and the animals, their self-standing ability, answering to necessary conditions and perfect look, he proposed architecture should have the same properties. Following his analogy, he claimed Greeks invented the architectural orders understanding the proportions of the greatest work of art, the human body (Figure 2a), which would define proportions (Figure 2b).

As Greeks were able to understand and explain the principles of nature, they were able to draw more general rules (Vosniadou & Ortony, 1989) like Vasari describing the qualities of a well-proportioned building should represent the human body both as a whole and in all its parts. Vasari made *face-façade analogy* through which he says: *'the façade should have the symmetry of human face, the door placed like the mouth, the windows like the eyes, and so on'* and suggests using the proportions of human body to define the ratios and apply it to the size of building elements in plan and on façade (Figure 3).

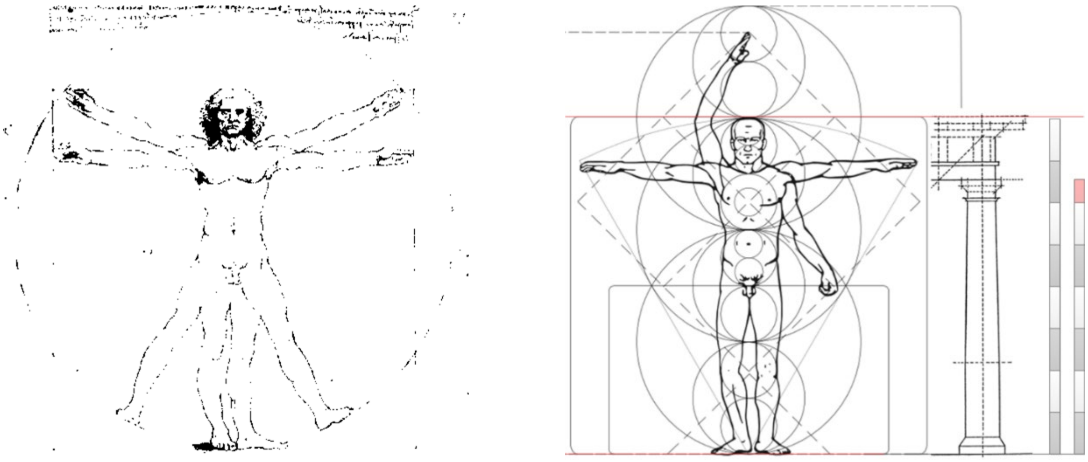

Figure 2. (a) Leonardo da Vinci's representation of Vitruvian men, (b) Doric column in relation to human proportion

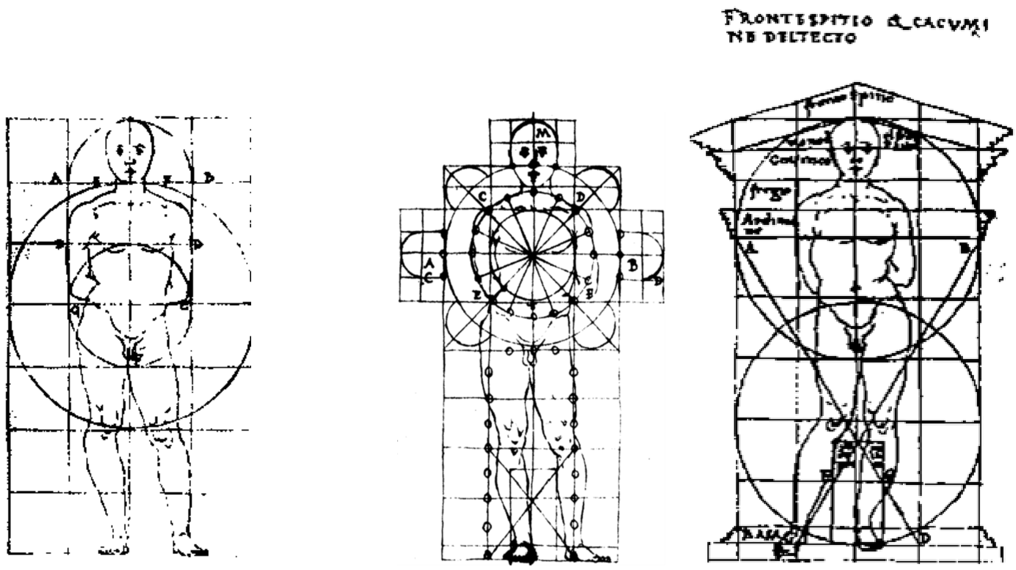

Figure 3. Leonardo da Vinci's representation of Vitruvian men.

This similarity between the beauty of organic and the beauty of the artificial forms were accepted to depend on the fundamental mathematical principle 'golden section' which can be found in both artificial and organic works of art. This mathematical rule enabled builders to process an incremental growth by adding larger units increased proportionally as in spiral forms found in nature like in the cauliflower, the head of sunflower, the skin of the pineapple, the snail and many of the animal horns. With this spiral analogy, mathematicians and biologists thought that they found the order of the growth principle of nature which could be applied to their own creations. At that point architects were only able to use biological references as between domain analogies, in other words they were using superficial properties of plants in ornamental features, because they were not able to construct structural similarities letting them use the entire formal relations of natural forms on the buildings. This brought the conclusion of *"organic forms are fixed and absolute"* (Coleman, 1964), buildings and species may not have any other relation except the visual ones since they belong to two very distant domains.

Biologists in the nineteenth century started classifying species according to their complexity. Rocks and crystals were on the bottom of the imaginary chain of beings, continuing with plants and animals, humans were on the top. Each differentiated group was categorized according to the identification of the size, shape and spatial arrangement according to Cuvier, whose religious beliefs direct him to believe that organic species were fixed, distinct and unchanging for all time. This classification becomes a byword at those days, which also influenced architecture. Durand, for instance, drew an analogy between the methods of classification of natural history and architectural history. Cuvier's impact on architecture was not limited to the classificatory analogies, depending on the specific topics of biology, such as *'correlation of the parts'*, *'coherence'*, and *'unity'*, his works were centered upon the function and relationship with environment, that enables others to draw analogies like anatomical analogies between the skeleton of animal and structural column-beam framework. This was also interpreted by Horatio Greenough as: *"the separation of building's 'skin' from its structural 'bones' is made".* Viollet le Duc considered Gothic buildings in means of structure most complicated and complete organism ever produced by man like those of nature (Figure 4). Steadman (2008) quoted from Cuvier: *"in art as nature an organism is an assemblage of interdependent parts of which the structure is determined by the function and of which the form is an expression of the structure."* (Steadman, 2008, p. 45)

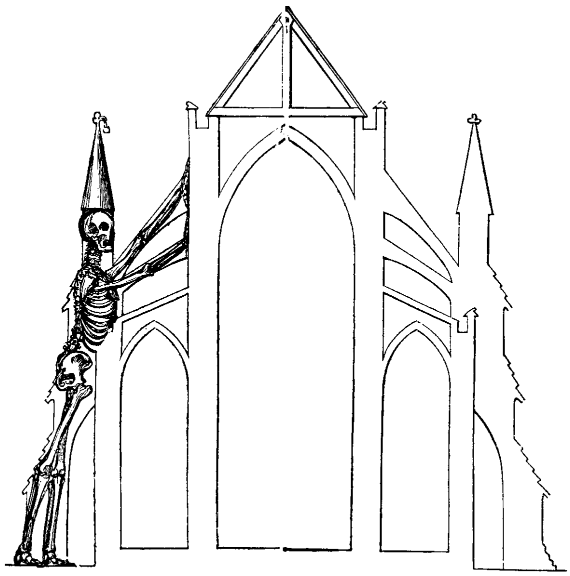

Figure 4. A. Bartholomew, diagram comparing the counter-abutments of Gothic vaulting with the human skeleton. From Specifications for Practical Architecture (London,1840).

By looking at the spatial arrangement of plants, growth strategy, Goethe established a theory with which he claims the through application of one plant's growth strategy to another, it is possible to generate new plants. He took his argument on morphological studies further by stating that this is also applicable to animals. Darwin as a great follower of Goethe's botanical studies, nourished his thoughts with Cuvier's common features for species and also was interested in the continuation of growth. Using the influence of environment and correlation between organs (Collins, 1978a) he suggested a new hybrid model by arguing that continuation of functions which are carried by organs are dependent on environmental factors, through which he explained the variations between species (Figure 5(a)) and why there were some extinct species. Darwin's evolution theory covering adaptation, transformation, mutation and natural selection were used by D'Arcy Thompson's *On Growth and Form* (1945) which explains growth strategies of different species sequentially to their morphologies.

The unequal growth in the parts of natural organisms were problematized by biologists who were dealing with the mathematical explanations of growth of organisms. The *growth analogy* established between plants' variation in size and human baby's changing size of body parts during their lifetime, let to an 'allometry' (Figure 5(b)) which was considered as the consequence of the organic form. This kind of allometries also can be found in architecture. For example, proportions of columns, which are thickened according to loads imposed. Eidlitz (1881) stated as follows:

> In nature forms are the outcome of environment. Environment determines function, and forms are the result of function. Building forms must be adapted in an equivalent way to the 'environment' in which they are situated, through the skill of the architect 'until the functions resulting [from this environment] are fully expressed in the [architectural] organism. (p.358)

Eidlitz is bring us back to the discussion of *'does form follows function, or does function follows form?'*, as in Sullivan's famous motto *form follows function* showing us the understandings of biotechniques amongst architects and artist in the beginning of the twentieth century. These ideas were concentrated in *"form is the necessary result of function – and of optimization"* (Mertins, 2007). The relationship between form and function is considered as a *necessary* condition for *beauty* in functional analogy, mentioned as usefulness analogy above, whereas it is considered as *necessary to life* in biological analogies.

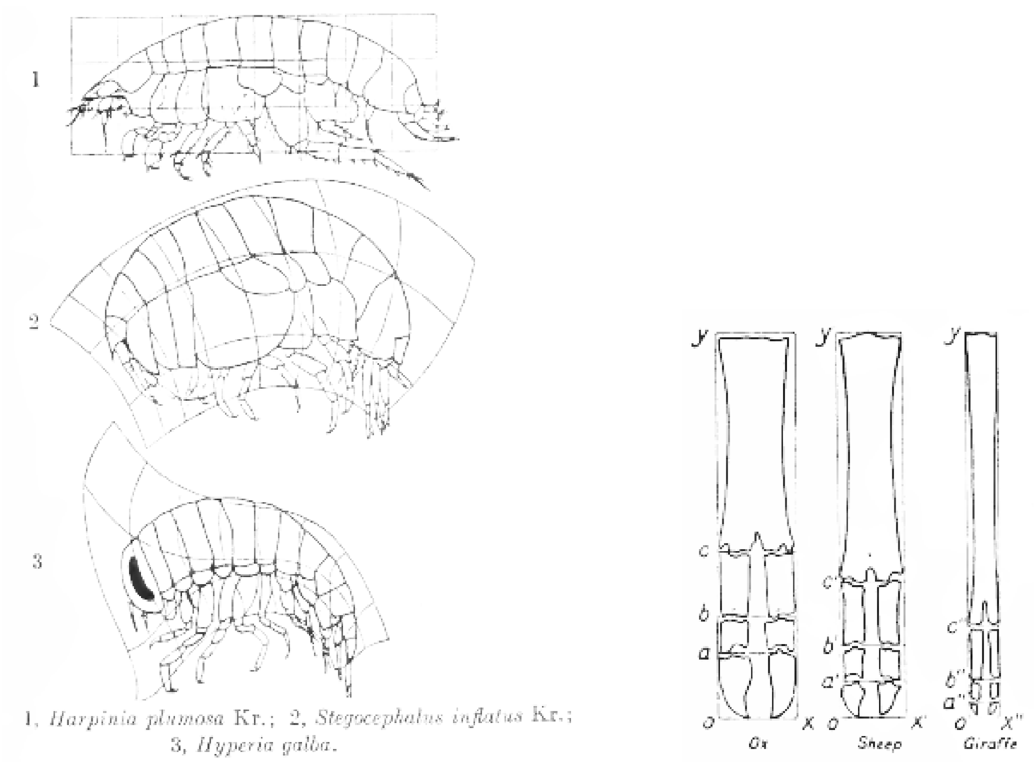

Figure 5. (a) Transformations of testaceans belonging to same kind through distortion as an adaptation occurred under specific environmental conditions resulted as irreversible mutations, (b) Proportional differentiation of closely allied forms of legs according to the principle of similitude.

Sullivan and his successor Frank Lloyd Wright, the followers of *form follows function*, were associating its origins in nature with mechanical metaphors (Steadman, 2008) . Sullivan sees human body as a container of organs to maintain functions necessary for living, like the machine parts which perform in a predetermined sequence. By using human body-machine analogy as a starting point Frank Lloyd Wright synthesized machine representing nature to a relevant model for architecture in his words: *"this thing we call the Machine… is no more or less than the principle of organic growth working irresistibly the Will of Life through the Will of Man"* (Heynen, 2004). Le Corbusier took the machine-nature analogy similarly and he was able to see buildings as performing artificial organisms similar to machines by declaring his *'a house is a machine for living in'* motto. Heynen (2004) states that *"the creations of mechanical engineering are organisms that approach perfection and obey the same evolutionary laws as the creations in nature that arouse our admiration. The harmony [of nature] is present in the works that emerge from the studio or factory"*.

Like his companions Mies van der Rohe also believed that architecture and technology evolve just as life forms evolve. For him, architecture should achieve a new harmony with the changing environment in terms of its history and material (Mertins, 2007). He was looking at the organizational principles of nature through which he established structural analogies between natural and artificial communications. Natural communications are happening within inner organs of the organisms and for outside between other organisms and environment. Artificial communications occur between building as an open construct to the landscape that allows people to move and exchange between inside and outside (Mertins, 2007).

In admiration for Sullivan, Gaudi had peculiar understanding of nature. Rather than learning from nature, Gaudi learned about nature and used it as eternal mirror of his architecture. He tried to repeat beauty created by the innate 'engine'[8] and drived most wonderful arrangement of parts to the whole and of the whole to the parts. Gaudi was expressing his passion to nature with his master tree analogy through which he positioned nature as a teacher that is always knowledgeable when he said:

> I seized the purest and most pleasant images of nature. Nature, which is always my master (...) The great book, always open and which we need to make an effort to read, is the book of nature; Other books are taken from this one and include the errors and interpretations of human beings. Everything comes from the great book of nature (...). This tree near my workshop: This is my master! (Estevez, 2015, p. 246)

Gaudi described the analogy to nature as the '*objective beauty'* (Estevez, 2015). He tried to simulate the real loads the building would have to support as a natural

[8] Innate engine used here as genetic algorithm which didn't exist at his time so we can relate it afterwards

organism. Gaudi was using visual recall cues (Beveridge & Perkins, 1987) in his architectural representations where his main source of inspiration was nature. For Beveridge and Perkins(1987), the use of nature *"may act as a visual recall cue, that is, a visual stimulus within the problem that matches the initial state of the visual stimulus within the analogue solution."*.

When Gaudi was commissioned as the chief architect for the construction of Sagrada Familia, he dedicated himself to express the beauty of God's creation and represent it in his architecture. To do that he tried to build as high as possible and he interrelated each part crucial for the whole. He scientifically analyzed the loadbearing structure, as he understood that the gravitational impact should be reduced as much as possible. Gaudi had followed a gravitational analogy, through which he was experimenting by using reversed catenary chain where he took gravity not as a greater attractive force which collapses building under its own weight but as an impulsive force which sustains building by using its own mass (Figure 6(a)). This helped him also mimic natural systems' physical self-organization in relation to the parts of their body (Figure 6(b)).

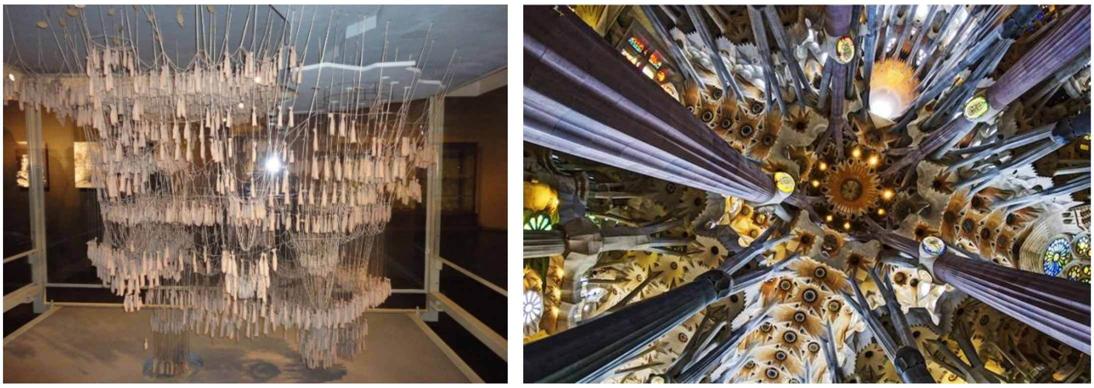

Figure 6. (a) Hanging chain model (inverted catenary arch) of Sagrada Familia used in the design development by Antoni Gaudi, (b) Inner structure of Sagrada Familia inspired by the combination of tree structures and reversed catenary model.

Gaudi's physical experiments were used as the source of the analogies by the architects in the late twentieth century. With the help of advancements in biology, genetics, machine industry and greatly depending on computers, architects dive into the field of nature by looking at its inner logic of its morphological processes (Frazer, 1995).

Frei Otto was one of those designers who was very much inspired by Gaudi's use of natural forms efficiently. He established an *efficiency analogy* between natural forms optimal use of materials to achieve specific structures and use of building materials wisely in means of economy and structure (Figure 7 (a), (b)). Otto was looking at cellular arrangements in the tissue of the leaves and structural tubular veins of them to use in his lightweight structures by which he tries to imitate nature's building principles in different scale and materiality (Mertins, 2007).

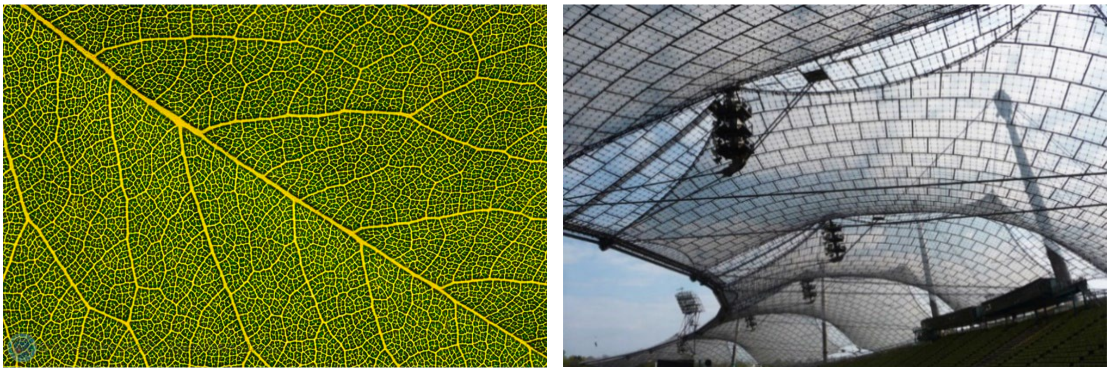

Figure 7. (a) veins and tissue of a leaf, (b) Munich Olympic Stadium roof designed by Frei Otto, 1972.

Like Otto, Buckminster Fuller was also dealing with the optimal structures achieved by nature. But he approached the issue in a more evolutionist way through thinking that the evolution occurring in nature can also happen in architecture. By looking at the natural selection mechanisms in nature, architectural selection should happen for obsolete techniques (Steadman, 2008). He draws analogies looking at the successful patterns[9] found in nature like honeycombs, soap bubbles and he builds a hybrid model of geodesic domes which is a groundbreaking case for architecture. Both Fuller and Frei Otto used an algorithmic understanding of natural patterns for their morphological studies while Otto was going towards the direction of *biomimicry*, which endeavors to improve performance and efficiency by modelling its functional design on natural principles, Fuller was following *biomorphism*; in other words, he was keen on learning to follow the forms found in nature.

Santiago Calatrava is considered as one of the most successful architects in using biological analogies in his designs. In his analogies, he uses the optimized properties of the organisms converting them into building or parts. He uses superficial analogies (Figure 8 (a)) and similarities as well (Figure 8 (b)) (Gentner & Markman, 1997). His

[9] pattern here used as particular organized arrangement of objects in space and time.

designs are considered as complex and simple imitation of nature by representing physical similarities together with sophisticated principles that can be encountered in nature.

Figure 8. (a) L’Hemisfèric in the City of Arts and Sciences in Valencia, Spain, 1998, (b) Oriente Station, Portugal, 1998. Calatrava’s tree-like structures

In the new age, the computer and software systems are becoming the norm in contemporary architectural practice and research. The designers are conducting the design tasks and processes in the virtual environment for the designs that are for the natural environment. Artificial worlds created in software environments direct architects focus on to design/create an uninterrupted system as nature which has the capacity to evolve on its own. The designers working on evolutionary architecture, establish analogies between information extracted from biological environment and employed it in creating the artificial environment. In *An Evolutionary Architecture* (1995), Frazer stated that research focuses on the inspirations of formative process and informative systems of nature (Frazer, 1995, p. 10-11):

> We can say that architecture is literally part of nature in sense that the man-made environment is now a major part of global eco-system, and man and nature share the same resources for building. In turn, our description of an architectural concept in coded for is analogous to the genetic code-script of nature.

Frazer advocates for the “blueprint” in nature, which enables generating forms to be formulated as a coded set of responsive instructions. Evolving products can be linked to naturally evolving[10] organisms where new designs are always based on a previous entity. This new perspective that looks nature as a responsive environment, helped designers to simplify natural responses as to mimic them in manmade environment

[10] Term evolving used/understood as improvements/improving.

synthetically with their designs. They found a chance to develop possible set of solutions for same design problems as coded instructions, which may close the gap between the nature’s designs and man’s designs.

CHAPTER 3

METHODOLOGY

The current research is an exploratory study to examine how architectural practice, research and education are intertwined in reference to emerging bio-inspired design concepts. The topic is considerably new and unexplored; therefore, a qualitative analysis was conducted to better understand the state of the art. The qualitative approaches are broadly used to explore a new phenomenon, the underlying reason of this has been mentioned by Given (2008) as "to capture individuals' thoughts, feelings, or interpretations of meaning and process." The general definition of qualitative research is described by Denzin and Lincoln (2005) as follows:

> Qualitative research is multi-method in focus, involving an interpretive, naturalistic approach to its subject matter. This means that qualitative researchers study things in their natural settings, attempting to make sense of, or interpret phenomena, in terms of the meanings people bring to them. Qualitative research involves the studied use and collection of a variety of empirical materials… that describe routine and problematic moments and meanings in individuals' lives. (p. 3)

The advantage of using qualitative research method throughout this exploratory study lies in its flexibility to lead the research according to the findings emerging from the field. The main goal is not to prove a hypothesis but investigate the idea with open-ended questions to single out salient outcomes, sometimes the unanticipated ones (Mack, Woodsong, MacQueen, Guest, & Namey, 2005).

The thesis is divided into two major sections. The first one is the investigation of architectural projects inspired by natural analogies, with the aim to propose an analytical framework to view bio-inspired design. The second section, then, concerns with the impact of the bio-inspired design on the architectural curricula at design schools. Since it is not possible to analyze all of the architectural projects and entire architectural schools' curricula sampling method is preferred. The sampling was done following Morgan's (2008) formulation. Morgan (2008) views sampling as *"the process of choosing actual data sources from a larger set of possibilities. This overall process actually consists of two related elements: (1) defining the full set of possible data sources—which is generally termed the population, and (2) selecting a specific sample of data sources from that population."* (p. 799-800)

3.1. Categorization of the Bio-Inspired Design Approaches

The first part of the study offers a review and a classification of the most striking built examples from architectural practice. The selected buildings are either the ones to open a totally new path for their successors or they are accepted as the most advanced examples. By looking at the precedents, the appearance of the natural organisms has a giant effect on bio-inspired design. According to Agkathidis (2016) the visual clues inspiring designers are mostly effective on formal inspiration, leading spatial or typological innovation, relational information for geometry and structural performance, and material innovation. On the other hand, when we look in detail, it can be seen that appearance is not the only thing which was used as a design clue, as mentioned by Grüber (2011) designers are also using inherent construction qualities and the processes.

By looking at the prominent authors and practitioners working on this field, it is observed that the mainstream research in this domain is concentrated on specific keywords. For instance, Jan Knippers and Thomas Speck of the Institute of Building Structures and Structural Design (ITKE) concentrated their works on structures with their material and mechanical properties (Knippers & Speck, 2012). Achim Menges in Institute for Computational Design and Construction focuses on more to the innovation of new building principles inspired by nature with its techniques, form and materiality and changeability (Menges, 2013). Michael Weinstock from Architectural Association (AA) works on the geometrical allowance of materials in order to invent new formal relations exist in nature (Weinstock, 2006). Beyond architects and building scientist, mechanical engineers have also contributed by their multi performative systems as they perceive nature's multi performative materiality (Deuschle, Halliday, & McGuire, 2018; Di Salvo, 2018; Maier, 2012; Menges, 2012) with particular focus on the behavioral performances.

While these designers and researchers conduct physical experiments upon their ideas, John Frazer, Greg Lynn, Neil Leach and Karl Chu are working on the representation of nature in virtual environment. Their studies depend on the analysis of nature as a series of complex systems and smaller mechanisms working within it. This line of research aims at synthesizing the nature's working principles into understandable logical principles explained through computable algorithms.

All these different approaches are examined throughout our research and in order to analyze the buildings and the biological inspirations embedded into their designs a categorization is needed. In order to make this categorization John Gero's function-behavior-structure paths (Gero & Kannengiesser, 2013; Qian & Gero, 1996), Mak and Shu's form-behavior-principles (Mak & Shu, 2004) and modified version of it by Basin and McAdams (2018) which divides form into sub categories as "materials and structures" and "mechanisms and processes", Chakrabarti's five levels (Chakrabarti, 2014), Nagel, Schmidt and Born's seven categories (Nagel, Schmidt, & Born, 2018) were examined for their suitability of our exploration.

Gero's function-behavior-structure (FBS) formulation approaches this categorization from a perspective that design influence is inherited from a primitive element, that can be either a physical or a logical entity. This primitive element by grouping with other primitive elements can form up the structure element and tries to behave in some specific way to achieve a specific function (Gero & Kannengiesser, 2013; Qian & Gero, 1996).

Mak and Shu's idea on form, behavior and principles explains the hierarchical relationship between each stage of the pyramid, as shown in Figure 9. Mak and Shu claim that by moving upwards in the hierarchy of the pyramid, above level explains the lower level's reason for existence. On the other hand, by moving downwards, each level below explains how to achieve above one. Moreover, Mak and Shu (2004) advocates the use of the principles extracted from nature uses deeper analogies as strategical influences by nature; however, the use of formal relations uses simple analogies to transfer the features of the biological entity. Basin and McAdams (2018) build on Mak & Shu's arguments by analyzing formal inspiration to materials, structures, mechanisms and processes. Their contribution to Mak & Shu's pyramid involves dividing it into two as "materials and structures" and "mechanisms and processes". Basin and McAdams (2018) claimed the formation process works like a mechanism and structures are depending on the materiality.

Chakrabarthi's SAPPhIRE model of causality explains how an entity using physical phenomena works to achieve its functions and change the state of itself and the surrounding (Chakrabarti, 2014). It is the hierarchical ordering of 'parts', 'physical phenomenon', 'state', 'physical effect', 'organ', 'input', 'action' according to the relationships that can be constructed in between them. He interpreted the relationship as: *"Parts (P) of an entity and its surroundings create organs (R), which are the structural requirements for a physical effect (E). A physical effect is activated by various inputs (I) on the organs and creates a physical phenomenon (Ph), and changes the state (S) of the* *entity. The changes of state are interpreted as actions (A), as new inputs, or as changes that create or activate parts."* (p.207) Chakrabarthi prefers to use the SAPPhIRE model to analyze different biological entities catalog them as stimuli for bio-inspired design of new ideas.

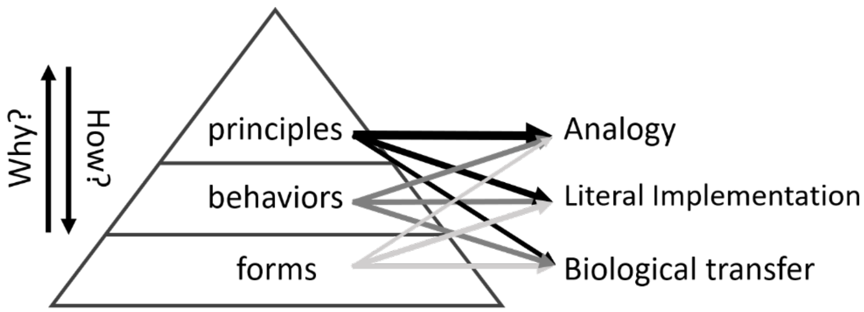

Figure 9. Mak and Shu's abstraction hierarchy and similarity categories[11]

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The most current categorization is presented by Jacquelyn Nagel, Linda Schmidt and Werner Born in their article "Establishing Analogy Categories for Bio-Inspired Design", through which they introduce their perspective of analogy categories together with Mak & Shu and Chakrabarti's (Nagel et al., 2018). Their categorization includes the Biomimicry 3.8 Institute's classification of biological information for inspiration as system process, function, form and architecture (Benyus, 1998), and additional categories

[11] The diagram presented in Figure 9 is the combined version of diagrams presented in Mak and Shu (2004) as Figure 1 and Figure 3.

surface and material mentioned by Bar-Cohen (2006). Nagel et al. (2018) categories and definitions are presented in Table 2 and the table which they compare their proposed model with Mak & Shu and Chakrabarti's categories are presented in Table 3.

Our interpretation to Nagel et al. (2018)'s proposed categorization is to add and combine it with the uncovered or not mentioned approaches that we synthesize from the literature reviewed above. Form is accepted as a preliminary element for researchers. In Gero, Shu and reference to the Chakrabarti's theoretical approaches, it is the initial element that is perceived and related in the firsthand. It's also underlined in the works of Knippers, Menges and Weinstock's works which are achieving some forms with different approaches. Likewise, Lynn, Frazer and Chu's algorithmic approaches are resulting with virtual creation of relations existing in nature in the form of some shapes occurred in software environment and sometimes tested via prototypes that are allowed by the digital manufacturing technology. Since it is inevitable to detach form from the structure and its materiality, our research will hold cover them under the topic of '*inspirations from the physical properties of nature'*. It will have three sub-categories as follows: (1) *form*, (2) *structure*, and (3) *material.*

Table 2. Analogy Category Definitions by (2018, p. 2)

Category	Definition
Form	Visual features including shape, geometry, and aesthetic features; external morphology
Architecture	How objects are interconnected or structured, geometry that supports the form; internal morphology
Surface	Attributes that relate to topological properties; surface morphology
Material	Attributes or substances that relate to material properties
Function	The actions of the system or what the biological system does; physiology
Process	Series of steps that are carried out; behavior
System	High level principle, strategy, or pattern; when multiple categories are present

The second constituent of our categorization is covered as 'process' by Nagel, 'behavior' by Mak & Shu, 'state change' by Chakrabarti's texts, and mentioned as performance in Agkathidis, Hensel, Knippers, Menges and Weinstock's works. Process and the behavior are thought as the two inseperable measures for the part analysing *'the performative aspects of the nature inspiring building designs.'*

Table 3. Analogy Categories Compared to Supporting Work by Nagel et al. (2018, p. 5)

Proposed Model	Mak and Shu	Chakrabarti	Abstraction Level
System Function	Principle	Organ Attribute	High
Process	Behavior	State Change	
Form Surface Architecture Material	Form	Part	Low

The third constituent to analyse bio-inspired design approaches is given as system and function in Nagel's approach, which is also mentioned as function in Gero's paths, Mak & Shu tackle it by looking it as principles which Chakrabarti called the similar problem as organ or attribute. The common ground where all these researchers meet is the systematic understanding of the nature in this last constituent. They are trying to deal with the relations in between the parts of a system which they observed in nature and where they try to apply in their design as a hollistic approach. This hollistic approach can be observed in the works of Deuschle and other researchers coming through the mechanical enginering discipline, as mentioned in the parts concentrated on the nature's multi performative materiality. Inevitably, Frazer, Lynn and Chu's works that are focusing on replicating the natural world on virtual environment handles it as a complex system whose principles are tried to be represented. By looking at the rich literature behind, our research will name the last major constituent of its catalog as *'building design inspirations from the the systematic principles of nature.'*

3.2. Analysis of Bio-Inspired Design Courses and Research Groups

The second part, the thesis presents an analysis of the architectural education with respect to biomimicry. In the beginning, conference proceedings and latest publications were taken as the general pool of the subject matter of the study; however, initial results showed us that there is not enough research presented in conferences surpassing the presentation of studio outcomes. On behalf of our research that aims to understand different theoretical and pedagogical approaches and shifts in architectural education with the integration of bio-inspired design, conference proceedings seem not to be the correct filter for the exemplification of our analysis. The alternative was to look at the architectural schools and investigate their curricula. Since it would not be possible to cover all the architecture schools as a part of this study, top fifty architecture schools in the world was selected to investigate and determine how bio-inspired design is integrated into their programs, as they are defining the trends inspiring the other architecture schools around the globe.

To determine the top 50 architecture schools in the world, two trustworthy ranking lists were used: THE- The Times Higher Education World University Rankings-2018[12] and QS- Quacquarelli Symonds World University Rankings-2018[13]. Two ranking lists use different sets of ranking criteria. THE ranks architecture schools according the general success gradation of the universities, however, QS sorts according to architecture schools' success. For this reason, the QS World University Rankings-2018 was used as the base for our research.

Using the QS World University Rankings-2018, a new table was constituted to have an overall view and a clear understanding of the programs' relation to the bio-inspired or biomimetic approaches[14]. The first four columns of Table 1 come from QS-Top 50 Architecture School Rankings, they are the world ranking of the school, world ranking on architecture, the name of the university, and the country that the school is located in. Different than QS-Top 50 Architecture School Rankings, these schools' rankings amongst the top 100 universities are included in the table. Some of the schools are distinguished with the department of architecture however they are not ranked in the top 100 university rankings.

The following eight columns indicate the specifics of the University's approach to bio-inspired design. The columns display whether the University has a research group conducting one or multiple research projects or whether the University provides a full course containing the topics: biomimetics, biomimicry, bio-inspired, and biologically inspired. Since visiting these schools was not possible within the scope of this thesis, the data was collected through the official web pages for each institution. Another critical step is the language, some of the Universities share data only in their native language which presents an obstacle in terms of access. The identified courses were analyzed to

[12] See appendix 1
[13] See appendix 2
[14] See Appendix 3 for full table

understand their content and questioned whether there are obvious interaction and collaboration between different departments working upon bio-inspired design topics.

From 13th to 20th column, each analyzed course is identified according to related department, program name, program level, course code and name, year(s) and semester(s), the name and title of the instructor/ coordinator, and the eligibility to student groups.

The columns between 21 and 26 include categories related to the depth of the analysis upon specific course; availability of the brief, syllabi, assignments and their details, readings, and lecture notes. The last column gives the source url to reach the related information.

Table 4. Headers and the response methods previewing the table of Bio-Inspired Design Courses and Research Groups in Top 50 Architecture Schools given as Appendix 3

World Ranking	World Ranking on Architecture	Name of the university	Country	Research Group / Project	Course	Courses Available (biomimetics, biomimicry, bio-inspired, biologically inspired)	Published on Web	Language - English (E)/ Native (N)	In Department of Architecture	In other Departments	Interaction with Department of Architecture	Department Name	Program Name	Program Level:(Bachelors (B)/ Masters (MSc/March)/ Doctoral (PhD)/ Research (R)	Course Code	Course Name / Project Name	Year / Semester	Instructor(s)	Availability to Graduate (G) / Undergraduate Students (U)	Brief Available	Syllabi Available	Assignments Available	Assignments in Detail	Readings Available	Lecture Notes Available	How to Access (url)
number	number			x / 0	x / 0	x / 0	x / 0	E / N	x / 0	x / 0	x / 0									x / 0	x / 0	x / 0	x / 0	x / 0	x / 0	

3.2.1. Procedure

After determining the analysis categories, five main criteria played determinant role to compare the data in a meaningful way. First one is the accessibility, since the research has been conducted from distance, online publications are considered as the main data sources. Concerning our keywords and selected institutions, anything published on web is added to our data set. In addition to web publishing, program and course directors contribution were asked via e-mail to share the course briefs of syllabi; however, the replies were insufficient. Some course briefs and syllabi were presented in yearbooks and student portfolios published online which are also included to our data set. If the subject was not published on web with its syllabus or overview, it has to be eliminated from the data set since there is no way to access it.

The second criterion is the validity for architecture field. There exist more courses than the ones overviewed in the scope of this thesis. Underlying reason for this is the subjects' relation to the field of architectural design, if the subject is not touching to architectural research or education it is disregarded. The third one is the classification of subject according to target groups. Three major target groups were found as a result of the tabulation: researchers, graduate students, and undergraduate students. The fourth one is the major method of administration in the course: whether the subject is addressed in theory-based or application-based method. The fifth one relates to whether the activity is compulsory or selection basis.

The target groups enabled to understand the integration of bio-inspired concept into the architectural curriculum at different levels. We have prioritized the research programs over the topic by concerning the transfer of information from experts to novices. In order to educate someone upon a specific topic, one must first make a research, learn the topic, use it to test the accuracy then learn it. According to that we have created a hierarchy; researches, graduate studies, and undergraduate level courses. The researches were put at the first level. Then the graduate level studies were at the second level. The last level should be the undergraduate level, where the validated knowledge will be transferred to the novices.

After the fragmentation into three as research groups/projects, graduate level courses, and undergraduate level courses the data is presented within the order of Bio-Inspired Design Courses and Research Groups in Top 50 Architecture Schools Table.

3.3. Interpretation of data

Bio-inspired design approaches are examined categorization explained in Chapter 3.1. Categorization of Bio-Inspired Design Approaches, these categories are compared and contrasted in Chapter 4.4. Interpretations as to detect whether there are any overlaps between the categories. Moreover, the depth of the analogies used in the projects are traced and also compared with each other in order to come up with an understanding of whether any of the categories can hold the possibility of deeper analogical transfer. Lastly, our initial chart of categorization will be validated or re-interpreted according to findings.

Bio-inspired design approaches in architectural education are examined under three main heading that are the three main target groups of the courses. These courses are analyzed upon the basis of major topics from the literature, each courses method of conduction and the use of bio-inspired analogies. In Chapter 5.4. Results and Discussions the common trends are tried to be presented after the completion of our analysis. The common grounds will be pointed out and similarities at the borders of categorization will be reconsidered.

CHAPTER 4

PROJECTS INCLUDING BIO-INSPIRED DESIGN APPROACHES IN DESIGN PROCESS

In the new age, the architects working mostly in the field of research, frequently used nature as a source of inspiration in their designs not only by its fascinating geometries, but also with the materials and structures performing accordantly without external control (Hensel, 2006a, 2006b). Unconventional forms found in nature, achieving multiple functions simultaneously always with optimal material use is the prime purpose of designers who are trying to reach the inherent logic of nature (Menges, 2013), that informs organisms to morph, process and react (Chu, 2010) as a system. The architects tried to imitate nature's creation processes by using analogies by mapping out from nature's processes to a human designer's processes. Nature is used as a model and the information extracted from the biological environment is mapped to the artificial environment that surround the designer and his thoughts.

There is a group of architects, taking advantage of the developing technologies, and shifting their attention to the life and actions of the living organisms for the inspirations of formative process and informative systems of nature (Estevez, 2005). John Frazer is one of the leading architects who see architecture as a literal part of nature. He asserts the idea of the environment created by humans' hand as part of the global ecosystem in which nature and humans are using materials from the same pot (Frazer, 1995). From this point of view, two entities using the same materiality can share the knowledge of how to deal with them. Through analogies biological processes are used as a source to develop an understanding, learning and imitating. This approach leads to a different formulation of architectural designs that enable certain intelligence by learning from its generations that can be initialized to the ones designed initially by nature, and evolve throuhly.

The common ground of Frazer and Estevez's ideas in the way they are looking at Nature for how it deals with problems, which are both crucial for survival. Their way of using biological inspiration corresponds to the definition of the biomimicry with holistic approach (Benyus, 1998).

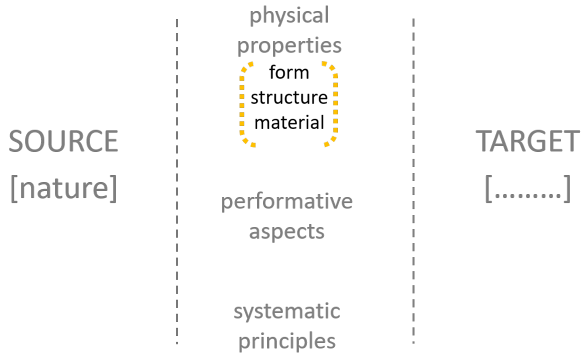
From the perspective of using nature as a model for creative problem solving, Arciszewski and Kicinger (1997) mentioned three different levels of problem solving inspired from nature to solve complicated design problems; visual inspiration, conceptual inspiration, and computational inspiration. Visual inspiration is the commonly used one which consists of matching the pictures of living organisms to create similarly looking engineering systems (Arciszewski & Kicinger, 1997). Visual inspirations are used in architecture and building engineering to develop the skin, structure and the appearance of a building. Conceptual inspirations are coming from the principles found in nature and used in a sophisticated way to determine the working principles of the artifact. Living organism's reaction to heat differentiation is an example for building designers to determine thermal comfort in the building. Computational inspiration is the way natural organisms works like a mechanism both in relation to its inner body and outer surrounding. Natural procedures are abstracted to design protocols which may or may not lead to contain visual and conceptual inspirations too.

Another view is a more specific one focusing on more tangible results discussed by Koelman (2004). According to Koelman (2004), *"biomimicry can be applied to buildings in three fundamental ways: to make stronger, tougher, self-assembling, and self-healing materials; to use natural processes and forces to accomplish basic building functions."* (p.1) The first way is directed towards the structure and building methods. The second one is concentrated on to achieve proper building envelope as a protective shelter that occurs in natural design fluently. The last one is looking from the perspective of sustainability and better use of the raw materials we are borrowing from nature and how to give them back.

These three main branches also exist as key concerns of architectural designs; however, some of them have subcategories which are close to other sections and makes this differentiation blurry and sometimes overlaps. Architecture, with its interdisciplinary nature can have multiple categorizations to conceptualize nature and use that on behalf of its designs. As mentioned by Estevez (2005) for a deeper understanding of biological inspirations in architecture beyond the conceptual approaches; designers are concentrating on physical dimensions including formal systems, structural systems and material systems found in nature performing well, achieving unconventional forms and behaving according to intrinsic logics.

This chapter presents an exemplification of the built examples from the field of architecture that uses biological inspirations. The examples are selected on the basis of emerging bio-inspired concepts and arranged according to the major chunk of studies on: physical properties of nature carried into building designs as form, structure and material, performative aspects of natural entities that inspire building designs by their differentiated behaviors in accordance to the conditions, and the systematic principles extracted from nature inspires building and its relationship with the environment. Each category is presented with different biomimetic approaches by following the emerging cases in literature. There is a table set to use as a basis for the analysis of each example in accordance to the category that it belongs.

Table 5: Base table for understanding the bio-inspired design approaches used in building design



4.1. Inspirations from the physical properties of Nature

Nature's designs and configurations can be copied or adapted to be used as source of inspiration for manmade creations within the capabilities of human production (Bar-Cohen, 2005). These copies or adaptations are tractable mostly in physical properties of within architectural components at various scales, directly or indirectly in an abstracted way. The direct copies-directly looking like a duck, dog or a specific plant are not included into biomimetic, biomorphic or any kind bio-approach; since there is no abstraction but a direct use of external characteristics as a decoration. In order to surpass the use of nature as decoration and to yield more sophisticated design inspirations, external characteristics of natural organisms were used abstractly to come up with unusual building designs. The interaction between architecture and nature is being conducted as the abstraction of what architects see in nature, ranging from construction techniques to materials and aesthetics (Arslan Selçuk, 2009).

This section presents a classificatory overlook to the interaction between cases from nature and architecture on the basis of physicality. According to Estevez (2005), physical properties of nature is used as source of building design inspiration should be classified into three, as the major design decisions that architects need take into account; form, structure and material. So, physical properties of nature used as source of building design can be classified in three major groups according to their relevance; formal inspirations, emulating the appearance or the shape; structural inspirations, imitates the micro or macro scale loadbearing capacities; materialistic inspirations, leading the innovative building materials by looking at the natural precedents (Estevez, 2005).

4.1.1. Buildings inspired from the forms in Nature

The wide range of forms generated with minimum material and maximum performance has always been a source of inspiration for architects (Allison, 2008). The form is different than the shape; while it is not only about the appearance, it is about formation, how things are morphologically coming together to form an object. Architects are using the forms of nature by looking at their performative principles (Leach, 2009).

In this section three examples are presented; Burj Khalifa, The World Trade Center Hub and the Helix Bridge. All three display the characteristics of formal inspirations from nature. Even though their starting point seems simple as looking at a creation of nature and abstracting that, they are all using different strategies that are informed by the morphology of the specie they are imitating.

4.1.1.1. Burj Khalifa

Burj Khalifa is a 162-story tower, the tallest building within the capacities of human building technology with its 828-meter height, in the metropolitan of Dubai, United Arab Emirates. It was designed by SOM (Skidmore, Owings & Merill) and the leading the architect was Adrian Smith. The construction had started in 2004 and it was completed in 2010.

Adrian Smith (2008) explains the design process of Burj Khalifa with his talk on the Council on Tall Buildings and Urban Habitat 2008- 8th World Congress held between March 3-5 in Dubai. The theme of the congress was: *"Tall & Green: Typology for a Sustainable Urban Future"*. Burj Khalifa's sustainable and environmental concerns affecting the design are explained through visual media reflecting the design process.

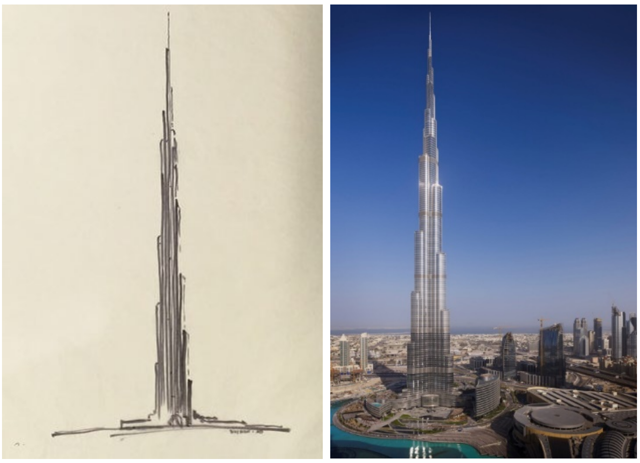


Figure 10. First architectural design sketching of an elevation by Adrian Smith and photo taken by Nick Merrick after completion.

According to Smith (2008) Burj Khalifa's initial design schema depends on architects' previous experiences with a schema he applied for a 72-storey building he designed for Samsung in Seoul, which is a "Y" shaped plan radially organized three chunks around a core. The project in the phase of competition entry looks like a flower from the top and the architect and the design team started to call it as "desert flower", which brought them a stylistic and structural inspiration from a real flower later.

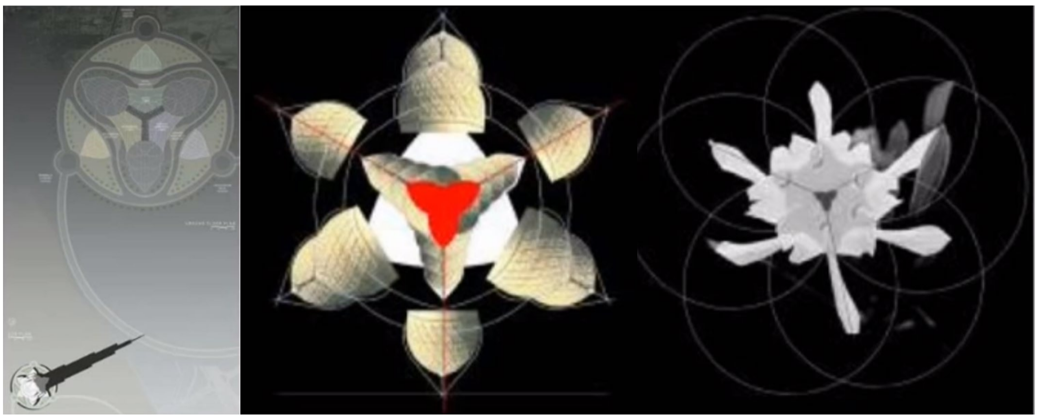


Figure 11. Design proposal for the competition entry of Burj Khalifa

The building concept was derived from the flower “Hymenocallis” known as spider lily (EmaarPJSC, 2018). The Hymenocallis belongs to Amarllidaceae botanical family and mostly planted in moisturized areas close to water. The flowers thin and white petals elegantly tapered outwards from the central core inspires the design of the tower.

Figure 12. Hymennocallis[15]

Formal organization of Hymenocallis’s petals overlapping each other like a helical spiral with scaled down surface area helped architects and structural engineers trying to achieve the stability against the wind.

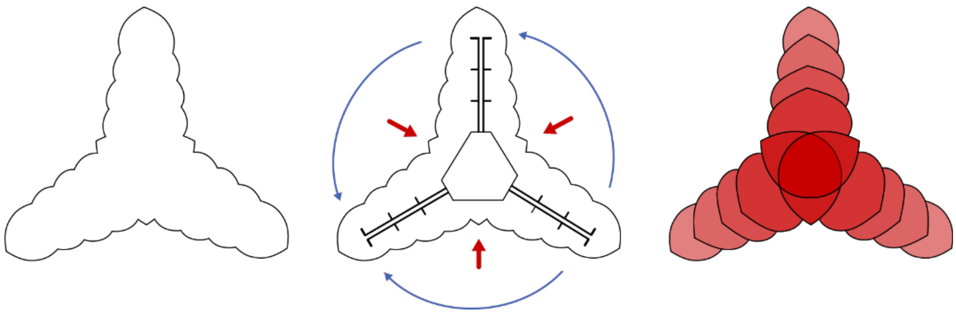


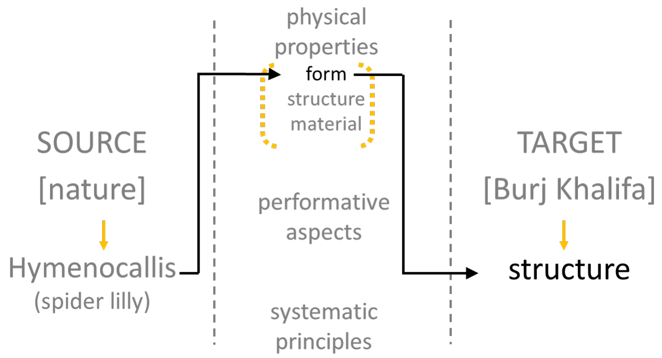
Figure 13. Burj Khalifa's footprint, structural and floor plate diagrams (EmaarPJSC, 2018).

The plants abstracted footprint provides a Y-shaped plan schema allowing the steel reinforced concrete frame to take this shape. The central core provides torsional resistance while y-shaped buttresses providing lateral bending resistance, similar to an I-beam (Fu, 2018). This plan schema also provides an optimal amount of window space

[15] Source: https://florafaunaweb.nparks.gov.sg/Special-Pages/plant-detail.aspx?id=2119 accessed on 12.05.2019

while tower grows the building step back consecutively in each segment from different branches to prevent sloughing (Engineering, 2010).

Table 6. Bio-inspired design approaches used in Burj Khalifa



Although the design has not started with the observation of nature, the architect uses a problem driven approach where he directly searches for the specific problem (y-shaped organization) from the nature's book. Hymenocallis's gradually organized petals arranged around a central core brought the formal inspiration which is used in the structural organization of slabs by lower ones carrying the above ones and the form synthesized from Hymenocallis creates a resistance to twisting effect which may occur by the wind.

In addition to the form related profits to reach the height, Burj Khalifa encapsulates structural and material and energy efficient design with its reduced mass, sky sourced ventilation system and condensate recovery system ("Burj Khalifa / SOM," 2017). This nature inspired architectural approaches, ecological and sustainable solutions integrated into buildings life sets an example for the use of biomimicry in a building which looks like having a conflict with nature.

4.1.1.2. The World Trade Center Hub

The World Trade Center Hub is the third largest transportation center in New York, appear to be free standing monumental building, a connector element for Daniel Liebeskind's masterplan for Ground Zero the area of 9/11. It was designed by Santiago

Calatrava in a form of spectacular "oculus", already considered as an icon of 21st century design before the starting of construction. The project began to arise in 2006 and the construction was completed in 2016.

Calatrava explains his design concept as "looking back first to look forward" and having this idea in his mind he envisioned a form abstracted from "a bird released from a child's hands" (Jodidio, 2006). His approach to the released bird contains both formal and philosophical reflections on the building design. The philosophical reflections can be understood from the oculus, the central space of the hub, is taking the daylight from the spine designed as a skylight spanning 335-foot uninterrupted opening that allows the "Way of Light" to pass through the main transit hub. According to Bernett (2017), dynamic and diffused use of daylight abstractly connecting occupants of the oculus to nature, making WTC Transportation hub as a clear example of biophilia as the oculus splits and opens, daylight washes the hub's floor at the time of North Towers collapse, on each September 11th at 10.28 a.m. and the entire space is filled with the daylight in remembrance of the tragedy (Baldwin, 2018).

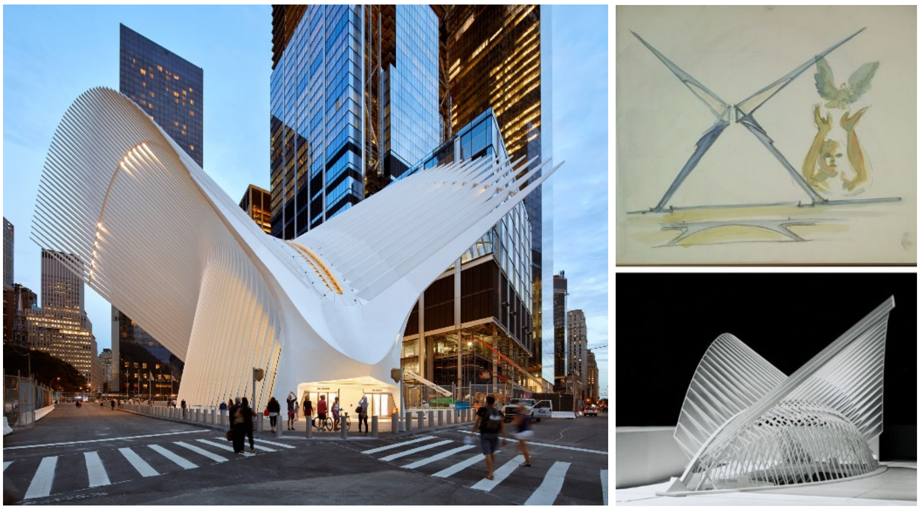


Figure 14. WTC Hub - "oculus" photo taken by Hufton & Crow after completion, and Calatrava's early sketches exhibited with the model in Hermitage Museum in May 2012[16]

The form of the building, the elegant geometry of the bird-like structure, especially the abstraction of flapping movements of the wings achieved by an array of the bilateral structural ribs spanning the large open space (Stevens, 2016). Even though the

[16] Source: https://www.architecturaldigest.com/story/santiago-calatrava-hermitage-museum-architecture

initial design aiming to emulate the movement of the flapping, that can be observed from the kinetic model shown in Figure14, the result was a static version of that with height difference between two rows due to the technological challenges as shown in Figure 15 in detail.

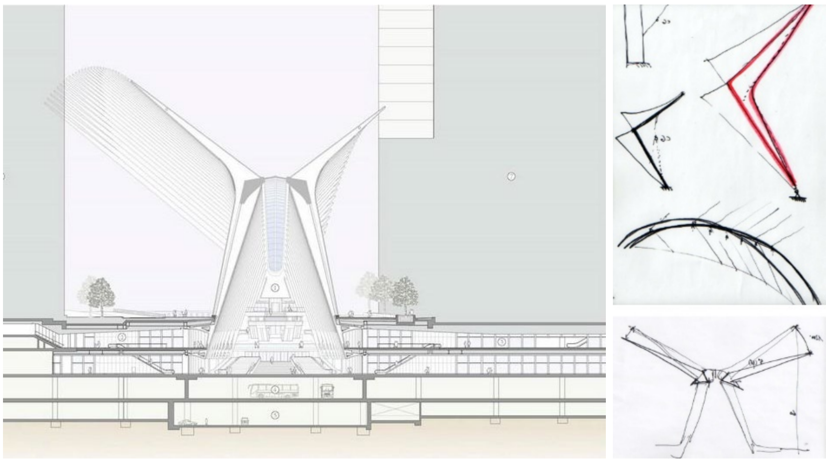


Figure 15. Section[17] and process drawings[18]

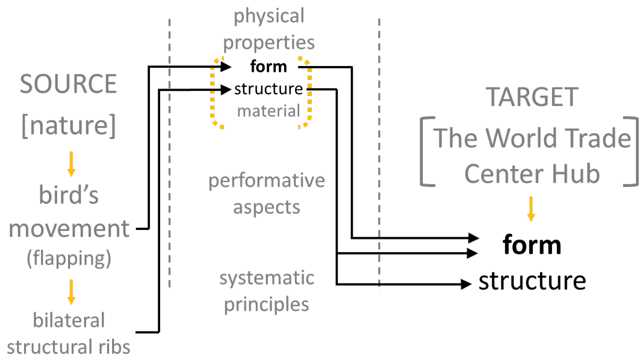
The form of the building, the elegant geometry of the bird-like structure, especially the abstraction of flapping movements of the wings achieved by an array of the bilateral structural ribs spanning the large open space (Stevens, 2016). Even though the initial design aiming to emulate the movement of the flapping, that can be observed from the kinetic model shown in figure14, the result was a static version of that with height difference between two rows due to the technological challenges.

Calatrava's use of biological analogies for the design of this building was consisted of two steps. His design based upon the movement of a bird, where he directly uses the visual scene created by this movement and use it as the form of the building. In addition to achieve this form and the desired scene, he used the bilateral structural ribs through which the flapping effect is added to the form and let the building form to touch the ground on its two asymmetrically positioned wings.

[17] (Source: https://www10.aeccafe.com/blogs/arch-showcase/2016/03/13/world-trade-center-transportation-hub-in-lower-manhattan-new-york-by-santiago-calatrava/)

[18] (Source: https://www.arch2o.com/stress-test-santiago-calatrava-world-trade-center-transportation-hub/)

Table 7. Bio-inspired design approaches used in the World Trade Center Hub



World Trade Center Hub is a spectacular example of biological reflections on a building design by its form abstracted from the motion of a bird which has also a philosophical background connected to freedom. The structure was also inspired from the movement of the wings where it was designed in a way that bilateral structural ribs positioned. This building shown us that physical appearance of a natural organism does not have to be copied directly or as a whole; however, it can be transferred into meaningful design inputs that can help novel design solutions.

4.1.1.3. Helix Bridge

The Helix Bridge provides a vivid example to those approaches where the final form is acquired through a 280 m long lightweight stainless-steel structure in a form of double helix curve. It is a pedestrianized connection across the Singapore River located in Marina Bay area and links city's existing Central Business District to new Bayfront District. The design of the bridge was commissioned to Cox Architecture & Architects 61 after an international design competition held in 2006 ("Helix Bridge / Cox Architecture with Architects 61," 2012). ARUP was involved in the construction that is completed in 2010.

Figure 16. Helix Bridge[19]

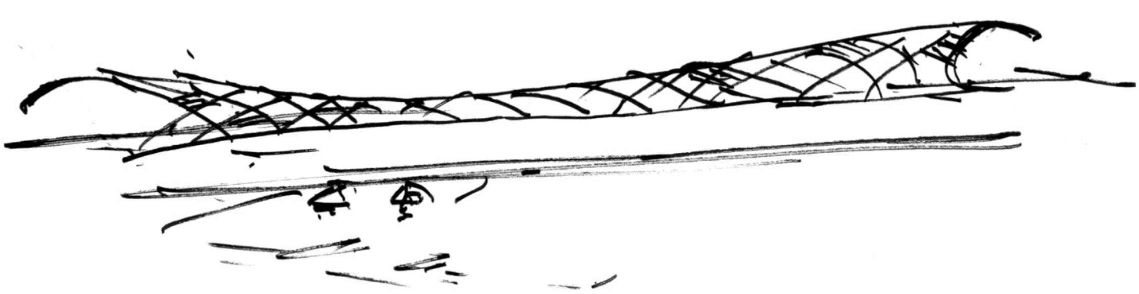


Figure 17. Philip Cox design sketch for Helix Bridge[20]

The architects define the double helix as *"A pair of parallel helices intertwined about a common axis"* (Storer, 2015) and use the shape of DNA chain as a design inspiration symbolizing "life and continuity, renewal and growth" (Zakaria, 2016). The bended stripes helped to eliminate the buckling while passing a span almost 300 meters. Architects and structural engineers used tree helices on this structure, one tighter one runs in the opposite way of other two to have much more open frame (D'Allison, 2016).

Other than the spiral form of the bridge, the structural connection of helices was designed as in the DNA, considering them as phosphate-sugar base backbone relation, this time to connect the other two helices and the slab rather than one other helix. It was achieved via the use of tensegrity. The helix bridge sets an example of micro scale organizational details abstract use in a macro scale structure.

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[19] Source: http://www.archichannel.com/project/helix-bridge-6/

[20] Source: https://www.coxarchitecture.com.au/project/the-helix-bridge/?discipline=architecture#!

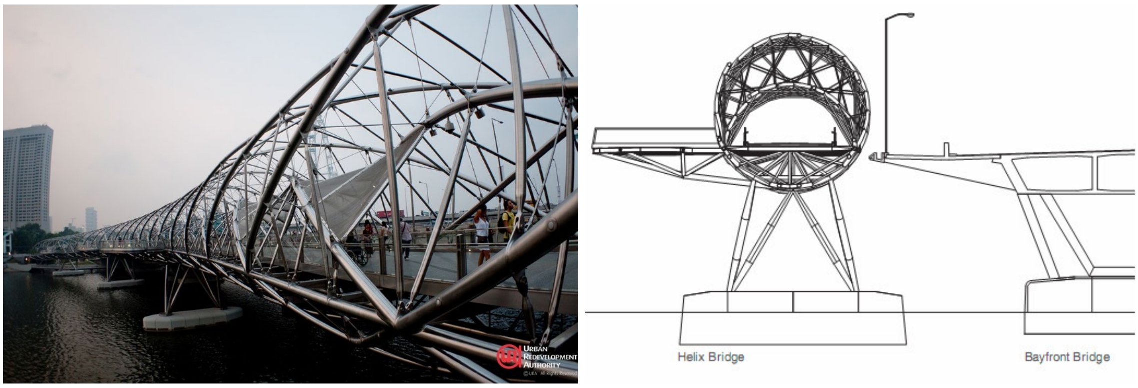
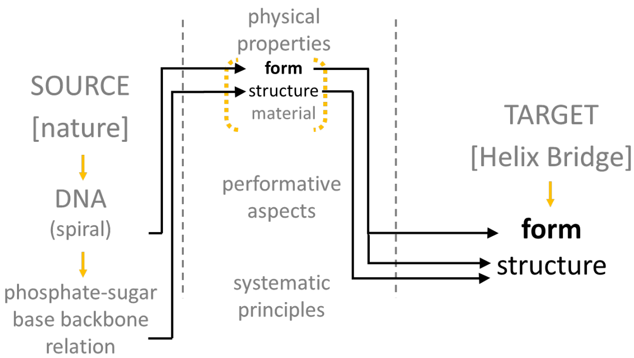


Figure 18. Helix Bridge section drawing[21]

The DNA helix is used as the design initiator with its form; however, the form contains also the information for the primary structural system. Moreover, this single source of inspiration holds a clue for secondary structure with its micro scale organization. Helix Bridge is a very good example by its design which starts with a solution-based approach and improves the design with the problem-driven approach.

Table 8. Bio-inspired design approaches used in the Helix Bridge



These three examples whose designs started with the formal inspirations from nature resulted in different outcomes. Burj Khalifa's design starts with a form which ends up with structural conclusions. The World Trade Center Hub's design starts with a stop motion view of a natural entity which creates a building form is supported by a structural organization found in nature applied in building structure; which informs both the form and structure.

[21] Source: https://archello.com/project/helix-bridge https://www.archdaily.com/185400/helix-bridge-cox-architecture-with-architects-61

4.1.2. Buildings inspired from the structures of Nature

From the perspective of procedural ordering principles of structural design, biology and architecture can be seen as diametrically opposite as stated by Knippers and Speck (2012). Architects, with civil engineers, see structure as a hierarchical system by selecting the load bearing mechanism followed by secondary support systems that mostly demonstrate different material combinations compared to the primary component (Knippers & Speck, 2012). However; in natural constructions structures are evolved from their initial formations, they are varied with the mutations, adaptations and natural selections. In nature the hierarchical order is constructed in a more complex way. These levels are using the same materiality but in a different formation (Dunlop & Fratzl, 2010).

Moreover, in architecture form and structure can be separated from each other which is not visible in nature, since the material organization giving the from is the same thing with the structure that holds species together. In this section the biological references used in structural system design by the architects and civil engineers will be overviewed by looking at the innovative examples Beijing National Stadium, National Aquatics Centre and Airport Stuttgart Terminal 3 buildings. The intention is to show the variety and representational richness in natural inspirations transferred into design inputs.

4.1.2.1. National Aquatics Centre in Beijing - Watercube

The National Aquatics Centre in Beijing famously known as the Watercube, is designed as a landmark building of Beijing 2008 Olympic games. It is a venue for watersports; swimming, diving, synchronized swimming and water-polo with its enormous hosting capacity of 6.000 permanent 11.000 temporary, maximum of 17.000 people ("Water Cube - National Aquatics Centre," 2010). The design was commissioned via an international competition and the winning project was owned by PTW Architects, Chris Bosse and Rob Leslie-Carter, their conceptual approach is to create a water like spirit and their title “Watercube” [H2O] becomes an outstanding title for the building. The construction had started at the end on 2003 and finished in the beginning of 2008 (Baraona, 2008).

Figure 19. National Aquatics Centre in Beijing[22], a look from outside

During the competition period, planning team calculated the needs of the functional program and realized footprint which almost covers the entire site in the form of a square and the building will be looking like a square prism. The design challenge was to achieve the most beautiful and convenient design; by using the maximum buildable area to fit the functions within the limits defined by the site boundary, and by considering the necessary airiness for the halls. The design team decided to have a continuous skin covering the walls and the roof and started to look for possible structural topologies can fill the space as triangulated space frame does, but in a more decent way (Carfae, 2006).

As it was reported in REF, in formulating the structure of the building envelope, the design team was in search for possible solutions informed by biological systems addressing similar problems. They looked at natural patterns, organic arrangements of living cells and mineral crystals and find seemingly the most effective solution from the previous researchers works on foam structures, soap bubbles. The design team figured out how soap bubbles connect each other by distributing load equally and can achieve self-standing structure spanning distances from the works of Professor Weaire and Dr. Phlean (Carfae, 2006).

Because of their nature, bubbles always try to stay in aspherical shape to use less surface area and energy, and when they met they merge and shared their walls in-between and started to have straight edges (Danielson, 2014). In the case of multiple bubbles come together and merge, the ones located in the center started to have the polyhedral shapes. As indicated in the studies by Professor Weaire and Dr. Phelan, 12-14 sided polyhedrons

[22] Source: https://moreaedesign.wordpress.com/2010/09/13/more-about-watercube-%E2%80%93-beijing-china/

can form an equal volume that would distribute the loads equally within a space (Carfae, 2006). This was used by PTW architects and ARUP to achieve a lightweight and porous steel structure starting from ground, cover walls and the roof like a thick skin.

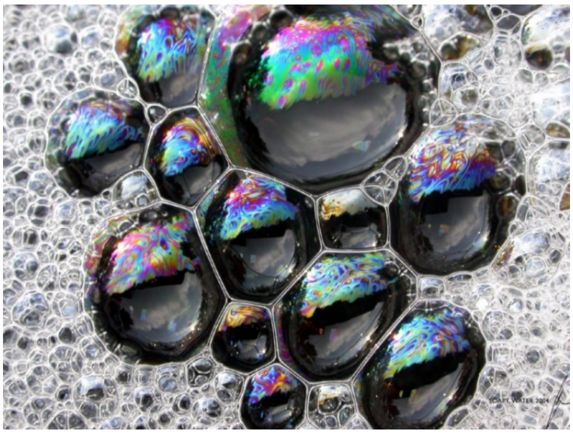
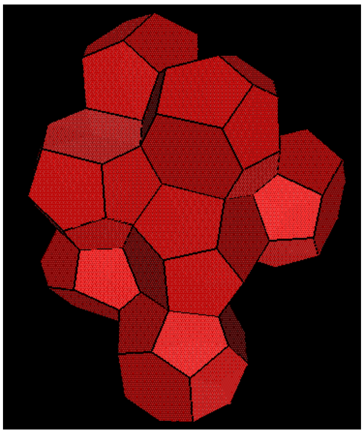
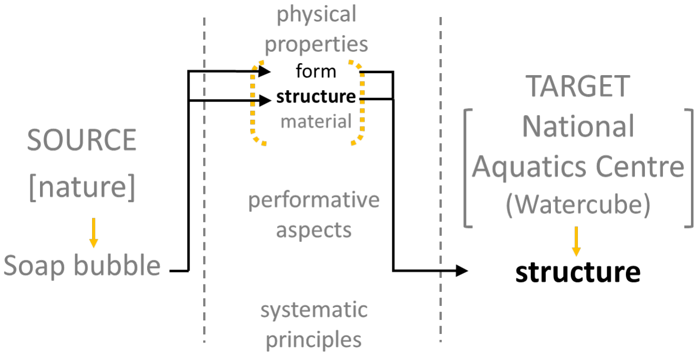



Figure 20. Soap bubble, Phelan-Weaire Polyhedral Array[23] (Batten, et. al.)

The design of the National Aquatics Centre in Beijing used a problem-driven approach which is searching for a structural system that can pass through a large span envelope. The soap bubbles equal load distribution amongst their self-standing structure was used as the initial source of design idea. On the other hand, soap bubbles form helps structure to be rigid enough for the outer bubbles by having one open side always with spherical surface and flat polygonal surfaces arranged on the faces of the polyhedral forms.

Table 9. Bio-inspired design approaches used in the National Aquatics Centre in Beijing



[23] Source: https://moreaedesign.wordpress.com/2010/09/13/more-about-watercube-%E2%80%93-beijing-china/

The interior and exterior faces of this thick skin are covered with spherical sectioned transparent plastic ETFE (ethylenetetrafluoroethylene) bubble panels that are connected to the edges of each polygon. By this way the artificial bubble structure with its cladding lets lighter, higher insulating capacity and cleans itself with rain and imitates bubble's nature in multiple levels (Burridge, 2008).

4.1.2.2. Beijing National Stadium – Bird's Nest

Beijing National Stadium is designed by Swiss architects Jacques Herzog and Piere de Meuron with Ai Weiwei's artistic consultancy for 2008 Summer Olympics and Paralympics held in Beijing. The design process had started in March 2003, construction began at the end of 2003 and finished in early 2008. It is designed to host maximum of 100.000 visitors under the giant structure spanning 333 meters ("Beijing National Stadium," 2017).

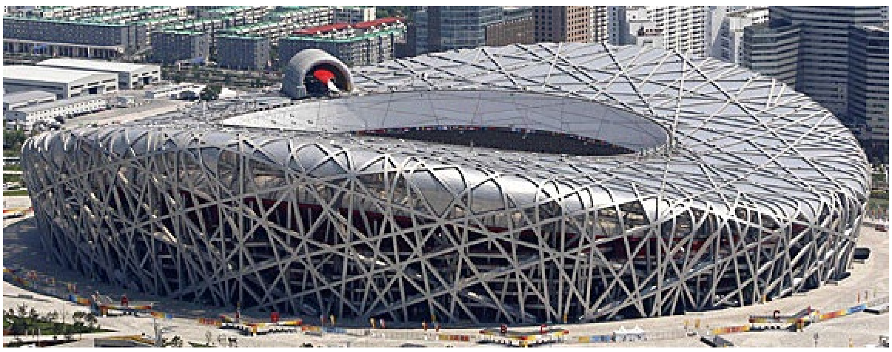


Figure 21. Beijing National Stadium photo taken by Elizabeth Dodge [24]

The design team had started the concept of complete "emptiness" to achieve the large span needed for the fields (Weiwei, 2008). While they knew China wanted to have something new and outstanding for this important stadium, Herzog & de Meuron thought the stadium as "a collective building, a public vessel" by relating the emptiness of core

[24]Source: http://www.bestourism.com/items/di/1077?title=The-Beijing

surrounded by crowd (Gallardo, 2015). This vessel idea directs them to unconventional circular roof design which was removed in the construction stage.

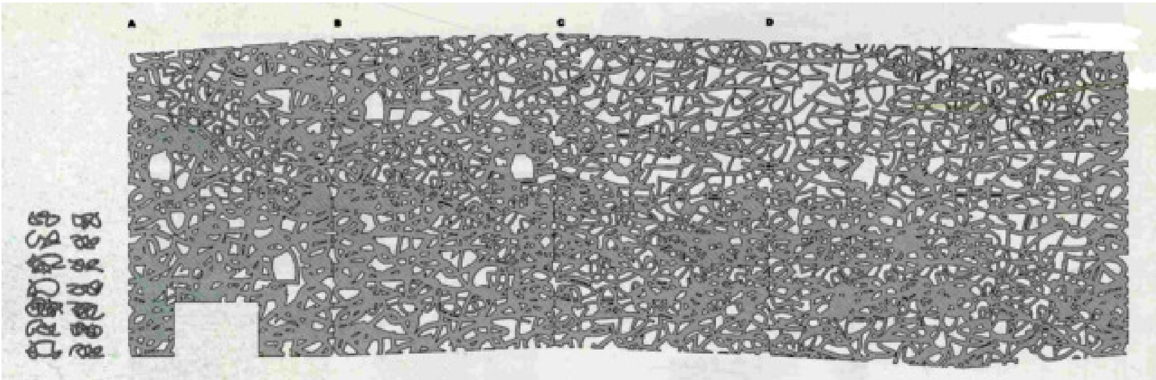
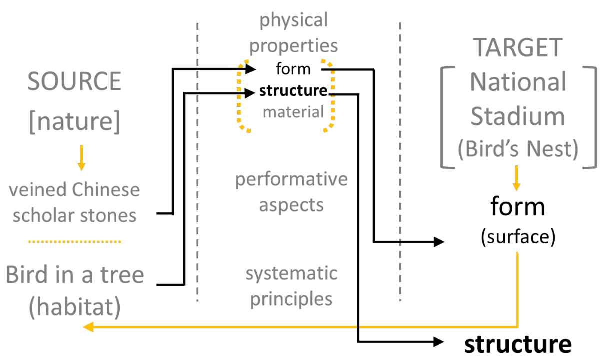


Figure 22. Initial sketch of Herzog & de Meuron to wrap around a circle to create self-standing structure[25]

The original inspiration of Herzog & de Meuron was coming from Beijing's local crackle glazed pottery and heavily veined Chinese scholar stones, used in the facade; Ai Weiwei reinterpreted on their initial design sketch by seeing it as a bird in a tree, then design progressed towards the bird nesting with the panelized approach ("Beijing National Stadium," 2017).

Table 10. Bio-inspired design approaches used in the Beijing National Stadium



[25] Retrieved from: https://beijingbirdsnest.wordpress.com/architecture/

The initial design of Herzog & de Meuron uses the veins of the stone as a pattern applied to a surface that is wrapped around the vessel. This surface attribute extracted from nature is used directly used as a surface pattern for the initial design; however, this pattern lead to an unexpected insight by reminding Ai Wei Wei a bird's nest that is having similar pattern which is three dimensionally organized as a self-standing structure. In addition to the structure, the partial use of mud used in the bird's nest as an adhesive creates a solution to cover the necessary part, interpreted as closing the roof with panels in between the structural system.

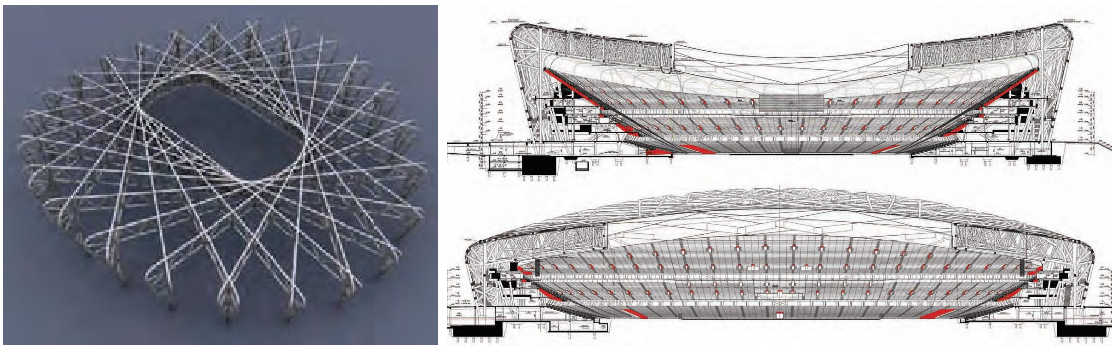


Figure 23. The primary geometry as 3-D partialized space truss[26].

With the help of panelized approach, 24 portal girders aligned very regularly and hidden in the seemingly random arranged secondary structure dividing it. In addition to primary and secondary elements supporting each other, the spaces in between them are filled with a translucent membrane, ETFE, as if the empty spaces stuffed in between the nest materials ("Beijing National Stadium, 'The Bird's Nest'," 2009).

4.1.2.3. Airport Stuttgart Terminal 3

The new terminal of Stuttgart International Airport was designed by GMP - Architekten von Gerkan, Marg und Partner- the planning and construction was held between 1981 and 1991. The terminal was designed to be visited by four million passengers annually. Its unique architectural characteristics with the emphasis on tree like

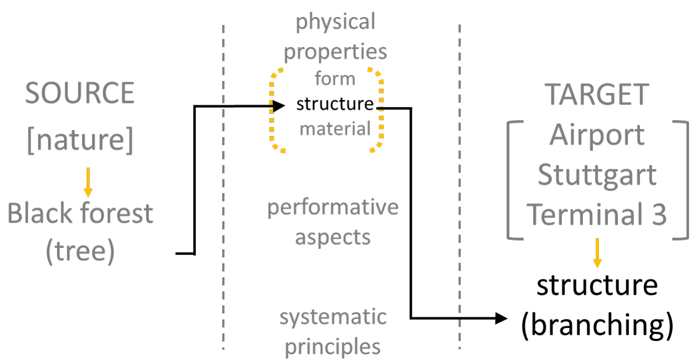
[26] Retrieved from: Arup Journal 1/2009

structure to carry the mono-pitched roof. The open plan schema help passengers to find their way easily ("Airport Stuttgart Terminal 3," 2004).

Figure 24:Airport Stuttgart Terminal 3[27]

Architects inspired from the neighboring Black Forest while designing the tree-like support structures in the entry portion and nourishes his ideas with the contemporary architectural trends (Ahmeti, 2007). The GMP team designed the roof surface in twelve segments each carried by a steel tree. The structural loads are transmitted through the branches and collected in the trunk.

Table 11. Bio-inspired design approaches used in the Airport Stuttgart Terminal 3.



[27] Source: https://www.gmp-architekten.com/projects/stuttgart-airport-terminal-3/

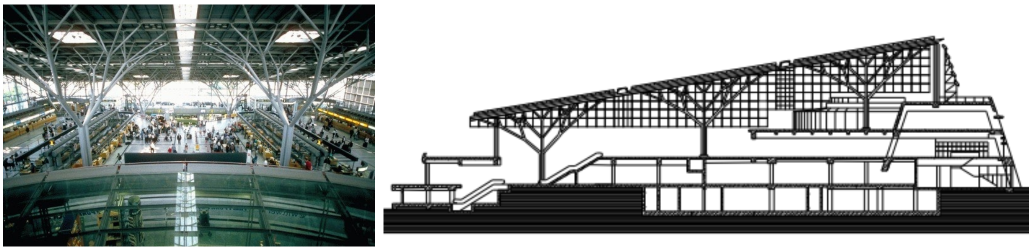


Figure 25. (a) Stuttgart airport- view from the top of the gallery[28], (b)Section B-B of Stuttgart Airport Terminal 3[29]

The building contains both biophilic and biomimetic characteristics, it is considered as a remarkable piece of manmade landscape architecture by Eggen and Sandanker in 1995 with its forest like atmosphere experienced by the users. The tree like structural supports are organized in a way that a thick trunk consisted of four tubular poles, each tube spread to tree branches with four sub branches and carry the roof from 48 nodes in each tree structure (Ahmeti, 2007).

These examples are using the structures exist in nature as a precedent for their structural design. The common ground of the design team's designs lies beneath their solution-based approach which they are looking for the suitable structures that can be applied for their design problem. National Aquatics Building in Beijing and Beijing National Stadium uses formal and structural clues together on behalf of their structural system; however, the structural sources are the primal ones. Different than the other examples, Beijing National Stadium's analogical process is an outstanding one with its two steps; design has started with the formal inspiration and the output leads another and dominant biological mapping which improves the overall design and solves the structural systems. In addition to the analogical transfers, these examples representing the spaciousness and lightness of soap bubbles, the porous and self-standing structure of bird nests, and the load distribution in tree branches are used in building structure design where biological instances structural organizations imitated with larger scale constructions having different materiality. Even though the scale and the materiality were not the same, structural logics are carried out from nature to architecture.

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[28] Retrieved from: http://en.structurae.de/photos/index.cfm?JS=16766

[29] Source: Flamur Ahmeti's thesis, 2007

4.1.3. Buildings inspired from the materials of Nature

Materiality is a crucial element for both natural and man-made structures. The way nature using the materiality is different than the one followed by human designers. Nature uses the materials it is containing, and designers uses the raw materials obtained from nature, process it then use it. Since human designers do not hold the material that they are designing as a part of their body, they need to get familiarized first to the material and its capacities, which is not necessary for Nature as a design task. This does not always lead to a negative start to a design but sometimes material studies can become starting points to an exploratory and open-ended design process (Menges, 2012).

Architects search for materials corresponding to achieve desired formal and structural concerns, like Frei Otto who was famous for his material studies to achieve certain structures. Contemporary architects changed their scope of material understanding from only achieving the traditional structural concerns, but also intelligent, adaptive and more effective use of the materials (Di Salvo, 2018). This is considerably a newer approach to material studies are held towards more sustainable and ecological solutions. In this section the new materialistic properties used in architecture and other design disciplines inspired from the precedents of nature will be illustrated.

4.1.3.1. Superhydrophobicity - Lotus effect

The "lotus effect" is the self-cleaning and waterproof effect of materials. It was first discovered by botanist Professor Wilhem Barthlott in 1970. He studied the effect of the lotus leave under the electron microscope when a water droplet hits to its surface. The process is defined by Minsolmaz Yeler and Yeler (2017) as: "The drop briefly remains in a small indentation in the center of the leaf, as if slightly undecided. It then slides off the leaf like a miniature spherical hovercraft, without leaving a damp trace behind." (p.146)

Figure 26. Water droplet and solid surface energy diagram by Ensikat, Ditshe-Kuru, Neinhuis, & Barthlott (2011)

This effect is called as "superhydrophobicity" through which water droplet changes its perfect spherical shape to maximize the area touching to another surface and by this way it is able to catch the small particles and cleans the surface (Jordan, 2016). Superhydrophobicty is used by the plant to keep its outer surface of the leave dry and clean, to increase the sunlight gain by rinsing away the dirt (Ensikat, Ditshe-Kuru, Neinhuis, & Barthlott, 2011). Slippery surfaces that do not let any pollutant to stick are commonly used on textiles, plastics, glass or other materials by changing the chemical compounds or as a topcoat.

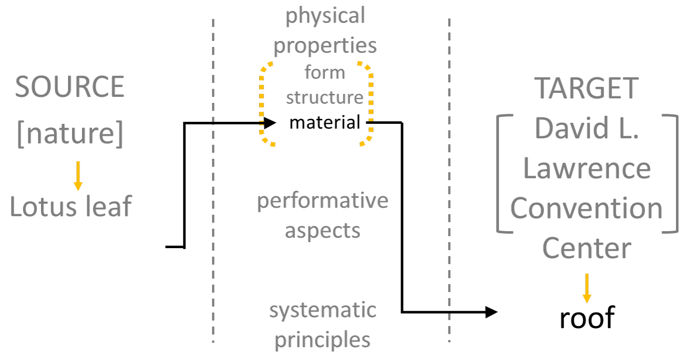
Figure 27. David L. Lawrence Convention Center in Pittsburgh[30]

David L. Lawrence Convention Center in Pittsburgh, Pennsylvania designed by Rafael Vinoly Architects and completed in 2003. It has a hydrophobic stainless-steel roof which helped to reduce the cost of heating and cooling by controlling the solar heat gain and stabilizing the solar reflection yearlong by its always clean surface (Deuschle et al.,

[30] Source: https://architizer.com/idea/136842/

2018). The building is famed with its energy efficiency and has earned Gold LEED award in 2003 and LEED Platinum Certificate in 2012.

Table 12. Bio-inspired design approaches used in David L. Lawrence Convention Center



The use of nature in the overall design is seemingly less; however, the effect created by it is considerably high in means of the benefits provided by it. The lotus leaf's anti-pollutant and water-resistant wax-like surface materiality is duplicated on the roof material by a special top coating applied on stainless-steel. It is a very good example for biomimicry by achieving imitation from nature for sustainable solutions.

4.1.3.2. Photobioreactor algae

Environmental impacts of glass facades are not ignorable because of their high heat loss and unwanted heat gain, so the architects, material engineers and building system designers are looking for more sustainable and ecological solutions. One of the solutions developed by building engineers and designers is to use active solar leaves in a building façade (Fytrou-Moschopoulou, 2015). It was used in a building as a façade system in the BIQ "Bio-Intelligent Quotient" house in Hamburg, Germany, designed by the joint venture between Splittwerk Architects, Arup, Colt International and Strategic Science Consult between 2009-2011.

The BIQ house is a solid structure of stonework and concrete with its innovative bioreactor façade. The construction had started in 2011 and completed in 2013. Bioreactors are used only in southeast and southwest facades and covers approximately

200 square meters and fulfills various functions at the same time including airtight, watertight, structural support, energy piton, daylight controller and defining an aesthetical characteristics for the building (Kim, 2013a). Algae façade is achieved by the replacement of regular glazing system with algae bioreactor systems placed in between two layers of the double-glazing system (Kim, 2013b).

Figure 28. Algae House photo by Colt International, rotating louvers around a vertical axis to track sunlight, SSC GmbH, BIQ- AirLift-System bubbles rising in the SolarLeaf Louvers[31]

The BIQ house is a solid structure of stonework and concrete with its innovative bioreactor façade. The construction had started in 2011 and completed in 2013. Bioreactors are used only in southeast and southwest facades and covers approximately 200 square meters and fulfills various functions at the same time including airtight, watertight, structural support, energy piton, daylight controller and defining an aesthetical characteristics for the building (Kim, 2013a). Algae façade is achieved by the replacement of regular glazing system with algae bioreactor systems placed in between two layers of the double-glazing system (Kim, 2013b).

The transparent surface contains growing algae that can control light entering to building and provides sun filtering effect when needed. This need is aligned with algae's propagation depending on the sunlight, when there are more light algae grows and filters the sun, when there is fewer light algae does not grow so much and lets the light in (Mora, 2013).

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[31] Source: https://www.architonic.com/en/project/arup-biq-house/5101636

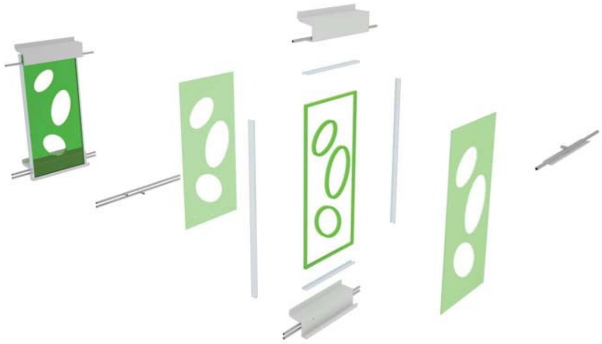
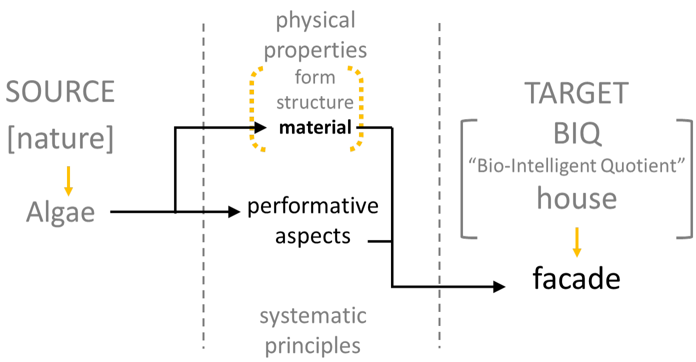


Figure 29. Growing algae facade system[32]

The analogical transfer from algae to a building component uses its material properties as design initiator; however, this material's performance, which is the growth under specific heat and light condition, is inseparable from it. Both properties were used in the building design as an add-on to the existing glazing system.

Table 13. Bio-inspired design approaches used in BIQ "Bio-Intelligent Quotient" house.



These two innovative nature-inspired materials are using solution-based approaches while conducting analogies between nature and buildings. They share the results having advanced sustainable achievements surpassing the initial states of the sources triggering the analogical approaches. In addition to the inventions of new materials, scientists can have chances to observe environmental changes by measuring the changes in the material performances, such as; the sun exposure can be detected by

[32] Source: https://www.architonic.com/en/project/arup-biq-house/5101636

measuring the algae covering's mass or surface area or yearly precipitation ratio can be measured by tracing David L. Lawrence Convention Center's seasonal heat gain.

4.2. Performative aspects of the Nature inspiring building designs

The projects taking part below are the examples which are inspired from the performative aspects of the natural entities. The behavioral characteristics of biological organisms are imitated mechanically in these buildings systems. These systems are intended to change their state against to the environmental factors like sunlight, heat, wind, rain and change their initial position according to predetermined (or tested and programmed) phases of the process.

4.2.1. One Ocean Thematic Pavilion Expo 2012

One Ocean Expo Pavilion was designed and built for Expo 2012 in Yeosu, South Korea. The design was selected via an open international competition; the winner was SOMA whose conceptual approach was based on the Expo's theme "The Living Ocean and Coast". Their design was composed of two different sides, the one embracing the ocean has a fragmented view consists of three vertical cones, and the other side is continuous but the dynamic one.

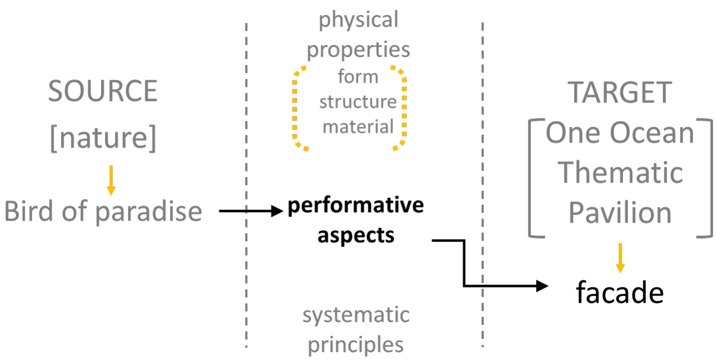
Figure 30. (a) One Ocean Thematic Pavilion, (b) Bird of paradise

Jan Knippers from ITKE was involved in the design process of the façade design contributing with his researches on modifiable surface elements, that matches with the initial design theme of SOMA, the specific kinetic façade system composed of lamellas The design inspiration comes from the kinematics found in the bird of paradise flower, an abstracted hingeless flapping device with a valvular pollination mechanism, Flectofin that is a created by Knippers Helbig Advanced Engineering (Lienhard et al., 2011).

Figure 31. Lamellas of kinetic façade

IKTE research group were working on the Flectofin mechanism in advanced SOMA was searching for a façade system which is modifiable, so the analogy is conducted with a problem-driven approach. The flectofin mechanism was found suitable for SOMA's building façade with its adjustability. In order to preserve interior luminosity and temperature, the mechanism is applied on the pavilions' facades. The pavilion's dynamic façade is composed of 105 vertical lamellas up to 15-meter-tall and made out of glass-fiber reinforced polymers. These moving lamellas creates a shading system which adapts itself to the changes of sunlight conditions.

Table 14. Bio-inspired design approaches used in One ocean Thematic Pavilion



4.2.2. 30 St. Mary Axe: London, Swiss Re Tower

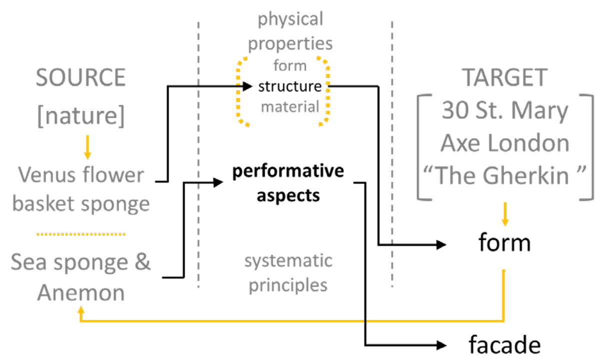
30 St. Mary Axe: London, Swiss Re Tower known as Gherkin was designed by Sir Norman Foster. 180-meter height towers construction was completed in 2004. The building is considered as the first environmentally progressive high rise building in London.

Figure 32. (a)The Gherkin, (b) Venus flower basket sponge

The design inspiration comes from a special sponge, the Venus flower basket sponge, whose exoskeleton glows like a glass lattice underwater. Building's structure is designed as a lattice arranged exoskeleton and arisen with its helical shape. Because of it's the helical structures constructing the lattice, diamond shaped panelization is acquired for the enclosure. The building has to contain natural ventilation system and the breathing performance of sea sponges and anemones opening and closing the holes in their bodies for ventilation were used as reference for the passive ventilation system achieved by the diamond shaped glasses.

Problem-driven analogical approaches were conducted in both stages of the biological transfer. First a tower like structure is searched in the catalog of nature and the overall structure is determined, then a precedent for the skin performance is searched that can be applied to the diamond shaped façade elements in order to enable natural ventilation.

Table 15. Bio-inspired design approaches used in 30 St. Mary Axe: London



The two examples use the way natural species behave or react to some specific conditions. They are imitating the action process of the natural entities with mechanic or kinetic systems embedded into their envelope, which is interacting or reacting towards the environment. They are trying to achieve to deal with the external impacts of the environment to sustain the comfort zone created within its envelope.

4.3. Building design inspirations from the systematic principles of Nature

The systematic understanding of and representation nature is becoming an outstanding topic which allows researchers and practitioners join forces in the field of bio-inspired design. In order to understand the working principles of this complex system, mathematicians, biologists, mechanical engineers, computer engineers and designers work together. Although it is not possible yet to fully understand and solve how nature works as a whole, researchers conduct their studies on representing natural mechanisms which are abstracted in the form of algorithms. In the design world, the algorithmic approach aims at encapsulating the relation between the shapes and their relation between the environment. Virtual environment, as a novel form of representation, is seen as a non-physical world in which researchers can try to establish relations existing in nature as forms, structures, behaviors. (Chu, 2010; Frazer, 1995; Lynn, 2000). Moreover, there are further efforts to model some smaller systems inspired by nature's principles represented in the form of shapes whose relations are sometimes tested via prototypes.

The examples covered in this section are the ones which are developed by systematic understanding of nature's principles. They are inspired from natural systems' self-organizing logics behind their survival in means of construction, adaptation and economy.

4.3.1. Eden Project

Eden Project is an innovative greenhouse project designed by Grimshaw Architects and Michael Pawlyn. The project location is Cornwall, UK; total project area is 23.000 sqm, the construction was completed in 2001. The design is composed of dome shaped enclosures called biomes housing over 1000 species of plants that is open to visit by the pathways and catwalks. It is lightweight structure is sitting on partial geodesic domes interconnected in the shape of bubbles ("Architecture at Eden,"). Each partial geodesic dome is connected to the other ones via giant steel girders and constructed via smaller and lighter hexagonal structures connected to each other that are covered with spherical sectioned transparent plastic ETFE (ethylenetetrafluoroethylene) bubble panels.

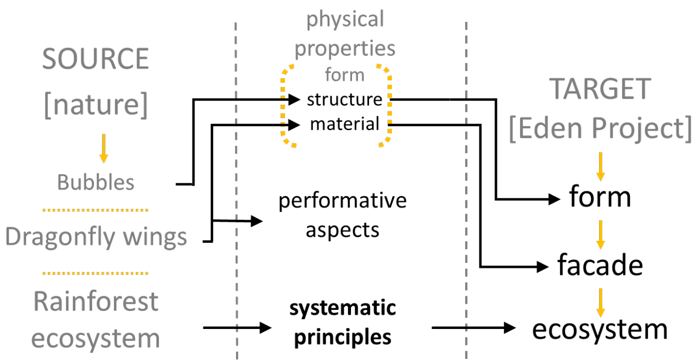
Figure 33. Eden Project (a) view from outside, (b) view from inside

The design of the Eden Project uses more than one biological reference belonging to different analogical categories. The initial design idea was to create a greenhouse where a vast of plants can be collected from diverse climates and live together. Bubble structures were used for their allowance to cover large span enclosures which can be self-standing. In order to climatize the enclosure, ETFE panels were used for the covering by their lightness and allowance to the sunlight as in its biological analogous Dragonfly Wings.

Although the bubbles and dragonfly wings were derived via a problem-driven approach, creation of the forest for all climates can be considered as a solution-based approach since the forest ecosystem is used as a design initiator.

Eden Project is considered as a good example where biophilic design meets with biomimetic design. While it enables users to experience the natural rainforest effect through a walk on paths and catwalks, its lightweight structure and energy efficient sustainable solutions the metaphorical reflection of nature.

Table 16. Bio-inspired design approaches used in Eden Project.



4.3.2. Al Bahr Tower

Al Bahr Towers are designed by Aedas Architects as twin office towers located in Abu Dhabi. The design was selected via an international design competition for Abu Dhabi Investment Council Head Quarters Building. Aedas architects using the cultural clues and technological advancements won the competition and design development period had started in 2008 in collaboration with ARUP. The construction was completed in 2012 and towers rise to 145 meters in total (Cilento, 2012).

The most interesting feature of the tower is the reactive façade. It was designed by the combination of *'mashrabiya'*, the regular lattice work window shading device commonly used in Arab homes and adaptive flowers. Aedas's parametric design department developed a kinetic façade controlling the solar heat gain by its movement together with the sun. Mashrabiya shaped shading components are opening and closing via actuators, mimicking the folding and unfolding of leaves and flower petals in response to sun (Cilento, 2012).

Figure 34. Al Bahr Towers image by Christian Richters

Figure 35. (a) Al Bahr tower design principle, (b) view from the dynamic façade

Flower petal's folding and unfolding behavior in response to sun acts as a mechanism and considered as a common systematic principle shared amongst the flowers reacting in the same way by closing and opening their petals. This biological principle of the system was abstractly represented into design decisions as algorithmic inputs and simulated to achieve desired envelope conditions that can work with the real loads of the structure.

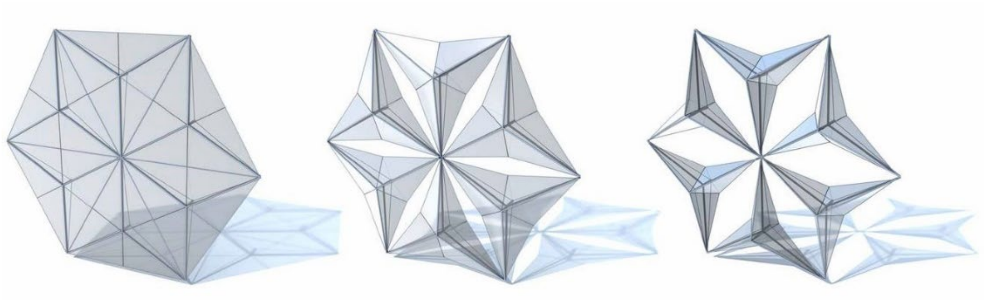
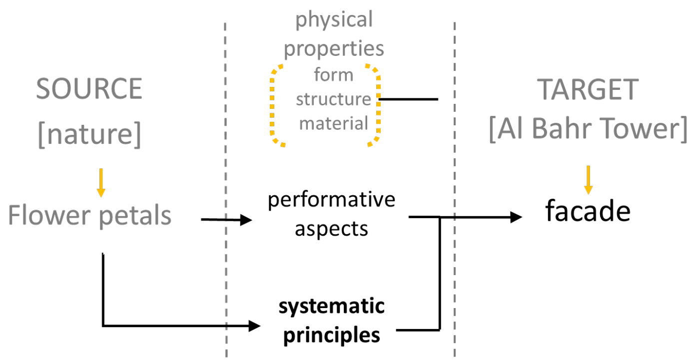


Figure 36. Working principle of façade

The two examples explained above shows two different approaches to the nature's systematic principles. The first one prefers to approach from the perspective which brought together the necessary conditions for the artificial forest start to act as a self-organizing ecosystem. The second one deals with a generalization and approaches it as a computable function by defining nature's principle's and applying it to an artificial entity. The linkage between these two different approaches is their understanding of nature as a system and metaphorically using the principles of the system as design inputs.

Table 17. Bio-inspired design approaches used in Al Bahr Tower.



4.4. Interpretations

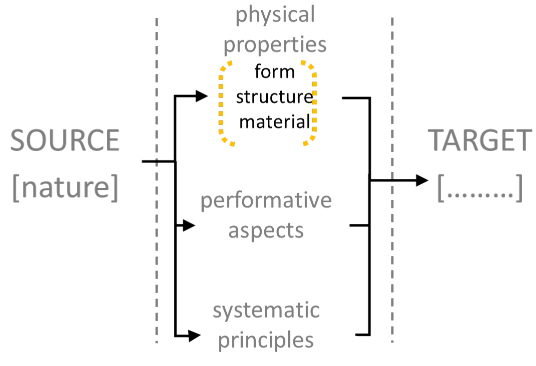
The projects reviewed above were among the most striking built examples from architectural practice either by opening a totally new path for later studies and constructions or by being the most advanced built examples. Although they are classified in categories and subcategories, these examples have shown us that the categorization is not preventing the interaction inside and outside of the categories. For instance, the part explained through subsection 4.1 consisted of three subcategories, namely form, structure and material. Even the initial inspiration lies behind these subcategories, the overall design depends on both. Like nature, building forms are very much depending on the materials that they are built out of, also to achieve those forms, specific structures needed to be used. So, it will not be wrong to say form, structure and materiality are the three inseparable constituents of a construction, natural or man-made. In addition to this, natural behaviors or performances are depending on again the physical organization of form structure and material. For example, if algae do not have light receptors it would not perform photosynthesis and grow. Also, its form and structure let it to grow without dismantling which enables it to cover a large surface when needed.

Moreover, the inner logic of natural organisms acts as a holistic system and has a control over all constituents. The differentiation in nature is shaped by the algorithms directing physical and performative qualities. Such as the leaves, they are commonly sharing the similar materiality and perform to make photosynthesis and let the plant breath, sometimes protect it from external impacts; however, all plants have different type of leaves according to their needs, these needs are determined by the genetic algorithm of the plant and the plant is shaped accordingly. Also, this genetic algorithm is evolving in years according to the external impacts via adaptations and mutations, so the performance also evolves and change. The architects working with the logical inspirations are fascinated by this evolutionary aspect of the nature.

On the other hand, the examples presented in this chapter demonstrate that the analogies constructed between natural entities and building design can use simple or compound analogies. Single stepped analogical transfer between source and target is meant by the simple analogies. Compound analogies seem to occur in multiple steps, by using different natural sources It can be said that the depth of these analogies are deeper than the single step analogies by looking at their level of abstraction.

Single stepped analogical transfer can use one or more design clue inspired by different aspects of a natural entity (Table 17); however, these aspects are belonging to the same thing. For example, the biological inspirations used in the Helix Bridge's design are coming from the DNA. The form is inspired from the parallel helices intertwined around a common axis as in the DNA chain. The structure holding these two intertwined spirals are inspired from the phosphate-sugar base backbone relation (Table 7).

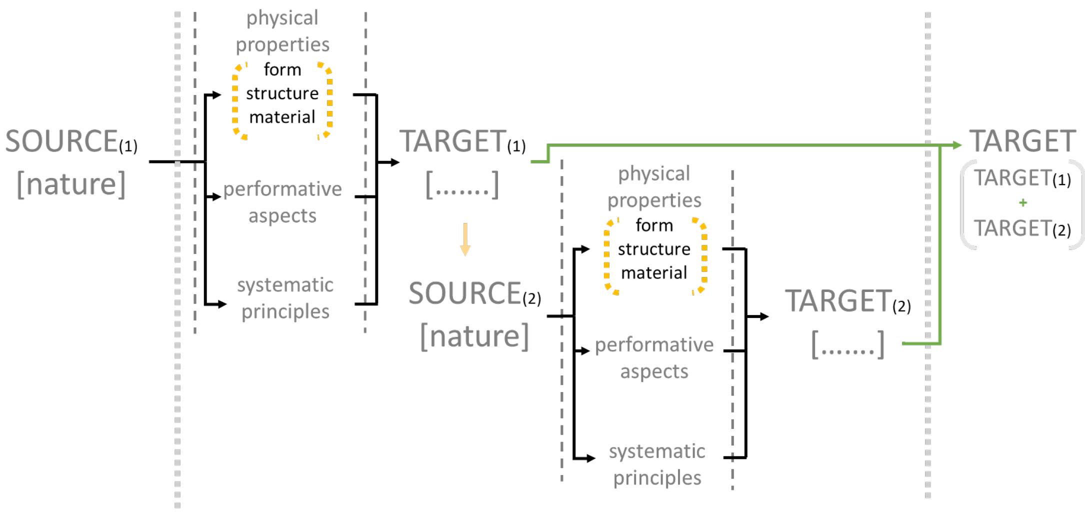
Table 18. Single step analogical transfer between natural phenomena and building/component design.



Compound analogies are composed of multiple analogical transfers, constructing at least two analogies or more referencing the previous one (Ashok Goel, Vattam, Wiltgen, & Helms, 2014). Design clue or clues of a natural organism has the potential in leading to a design idea. The idea, then, can be reinterpreted and utilized to lead to further insights which may be considered through a different natural phenomenon (Table 18). National Stadium in Beijing uses this kind of compound analogies with Ai Wei Wei's reinterpretation to Herzog & de Meuron's design idea, which is a pattern wrapped around a vessel inspired by heavily veined Chinese scholar stones, by seeing it as a bird sitting in a nest on a tree.

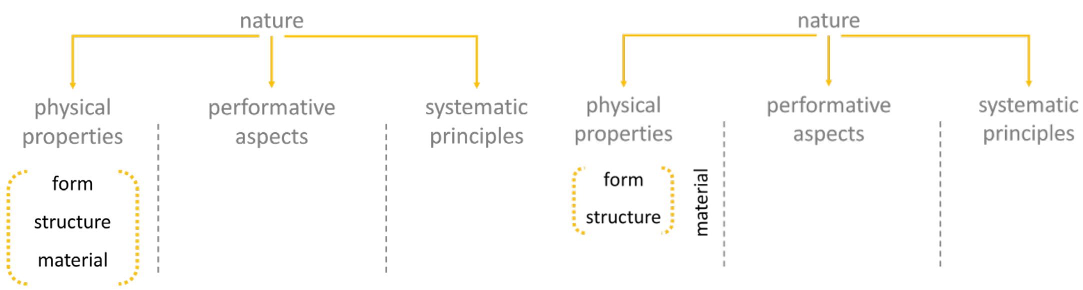
Previous examples offer several key methods for transfers concerning form and structure. Although the relation constructed between form, structure and material were considered as inseparable elements of an architectural piece traditionally; nowadays with the help of the technology, the designers can design the building forms else than the representation of its structure. Natural inspiration from the materiality seems to stand between the physical properties and performative aspects of nature, close to the physical properties, with its undeniable effect on the way biological entities and their analogous ones behave. So, our table for categorization can be reinterpreted as shown in the Table 19.

Table 19. Complex / multistep analogical transfer between natural entities and building design.



In addition to being a consolidating feature, materialistic properties of the natural products are vastly investigated and used by the researchers whose works concentrate on the innovative building and construction techniques (Hensel, 2006b; Nerdinger, 2005; Weinstock, 2006). Frei Otto's experiments with soap bubbles, leave cells, spider nets were the early examples of it. The more contemporary experiments conducted by Michael Hensel, Michael Weinstock and Achim Menges are carrying nature's materiality in virtual environment by algorithmicizing it (Hensel, 2006b; Lienhard et al., 2011; Menges, 2012). This particular body of research is also concerned with the imitation of nature's behaviors as a building performance (Hensel, 2006b; Knippers & Speck, 2012; Schleicher, 2015) and simulating it via computers and prototypical mechanisms first and applied to building structures. Systematic understanding of nature leads designers and computer engineers to represent nature's principles in a software which is considered as the virtual equivalent of natural environment and act as a system whose principles are defined by the designers.

Table 20. (a) initial categorization, (b) re-interpreted categorization.



CHAPTER 5

BIO-INSPIRED DESIGN COURSES IN ARCHITECTURAL CURRICULA

Searching for solutions for design problems by taking inspiration from nature is considered as an approach to be supported in design education with its innovative nature that endeavors creative thinking (Amer, 2018). Recently, bio-inspired design's position in architectural education is highly discussed in architectural communities (Bruck et al., 2006; Schleicher, 2015; Zari, 2007). Accelerating number of articles, theses, conference papers point out that bio-inspired design attracting the education and academics who are in search of how to integrate this rapidly raising phenomenon into their curricula (Amer, 2018; Bruck et al., 2006)

Experimental integration of biological inspirations to design studios is now a valid topic for both graduate and undergraduate levels in architecture and neighboring disciplines. Schön (1985) claims that the design studio is an environment where students learn about designing and learn about learning to design (Schön, 1985). Academicians following Schön's idea look biomimicry as a potential field for a new path to learn to design by discovering nature's designs and their potentials (Bruck et al., 2006). This immeasurable source is involved in architectural education sometimes holistically sometimes partially with its system setting an example for computational design, sustainable design strategies and form-structure related grandiosity (Yazıcı, 2015).

In this chapter bioinspired movement in architectural curricula is explored through an overlook to the research projects conducted and courses related to bio-inspired design given in top 50 architecture schools in the world according to QS-World University Rankings 2018[33].

[33] See appendix fort he list

Table 21. Bio-Inspired Design Courses and Research Groups in Top 50 Architecture Schools given as Appendix 3

World Ranking (Top 100)	World Ranking on Architecture (Top 50)	Name	Country	Research Group / Project	Course	Courses Available (biomimetics, biomimicry, bi inspired, biologically	Published on Web	Language - English (E)/ Native (N)	In Department of Architecture	In other Departments	Interaction with Department of Architecture	Deptartment Name	Program Name	Program Level	Course Code	Course Name / Project Name	Year / Semester	Instructor(s)	Graduate / Undergraduate	Brief Available	Syllabi Available	Assignments Available	Assignments in Detail	Readings Available	Lecture Notes Available
1	1	Massachusetts Institute of Technology (MIT)	USA		x	x	x	E		x		Aeronautics and Astronautics		M.Sc./ Ph.D.	16.982	Bio-Inspired Structures	2009/ Spring	Leo Daniel	G	x	x	x	0	x	x
					x	x	x	E		x		Mechanical Engineering		B.Sc.	2.A35	Biomimetic Principles and Design	2013/ Fall	Michael Triantafyllou	U	x	x	x	0	x	0
				x		0	x	E	x	x	x		MIT Media Lab			Mediated Matter Group		Neri Oxman							
					x	x	x	E			x		MIT Media Lab	M.Sc./ Ph.D.	MAS.650-DAS	Design Across Scales & Disciplines	2016/ Spring	Neri Oxman, Meejin Young	U	x	x	0	0	x	0
7	2	UCL (University College London)	UK	x			0	E	x	x	x	Biochemical Engineering	B-Pro (Bartlett Prospective)			Bio-Integrated Design		Professor Frédéric Migayrou							
						0	0	E	x	x	x	Bartlett School of Architecture / Biochemical Engineering	Bio-Integrated Design (Bio-ID)	M.Arch./ M.Sc.	0	0		Marcos Cruz, Brenda Parker	G	0	0	0	0	0	0
54	3	Delft University of Technology	Netherlands		x	0	0	E / N			x	Applied Sciences	Master in Nanobiology	M.Sc.	NB4130TU	BioLogic: Learning from living systems	2018/ Fall	H. J. E. Beaumont	G	0	0	0	0	0	0
				x								Mechanical engineering				BITE- Bio-Inspired Technology Group		Paul Breedveld							
					x	x	x	E/ N		x	x	Mechanical, Maritime and Materials Engineering	Master in Mechanical Engineering	M.Sc./ Online	ME41095 / WB2436-12	Bio Inspired Design	2016-2017	Paul Breedveld	G	x	x	0	0	x	x
10	4	ETH Zurich - Swiss Federal Institute of Technology	Switzerland	x			x	E / N		x	x	Material Sciences	Complex Materails Group			Materials inspired by Nature		André R Studart							
					x	x	x	E / N		x	x	Material Sciences		M.Sc.	327-1221-00L	Biological and Bio-Inspired Materials	2018/ Fall	A. R. Studart, I. Burgert, E. Cabane, R. Nicolosi Libanori	G	0	0	0	0	x	0
27	5	University of California, Berkeley (UCB)	USA		x	x	x	E		x	x	Integrative Biology		B.Sc.	IB32	Bio-Inspired Design	2018/ Spring	Robert Full	U	x	x	x	0	x	0
				x			x	E		x	x	Bioengineering and Materials Science and Engineering	Bioinspired materials science and bioengineering			Massersmith Lab		Philip B. Massersmith							
					x	x	0	E	x				Studio One	M.Arch./ M.Sc.			2014-2015	Kyle Steinfield, Etienne Turpin, Sara Dean	G	0	0	0	0	0	0
3	6	Harvard University	USA	x			x	E		x		Wyss Institute for Biologically Inspired Engineering / SEAS	Aizenberg Biomineralization and Biomimetics Lab					Joanna Aizenberg							
				x				E		x		Wyss Institute for Biologically Inspired Engineering / SEAS	Mooney Lab- Laboratory for Cell and tissue Engineering					David Mooney							
				x				E		x		Wyss Institute for Biologically Inspired Engineering / SEAS	Bertoldi Group- Materials and Structures by Design					Katia Bertoldi							
						x	x	E	x	x		GSD/Wyss Institute for Biologically Inspired Engineering / SEAS		M.Sc./ Ph.D.	GSD-SCI-6477, SEAS-ES291	Nano Micro Macro: Adaptive Material Laboratory	2017/ Fall	Salmaan Craig Joanna Aizenberg	G	x	x	x	x	0	x
	7	Manchester School of Architecture	UK		x	x	0	E	x	0			Biomimetic BArch Studio Unit	B.Arch. - 5th year			2010	Siobhan Barry	G	0	0	0	0	0	0
5	8	University of Cambridge	UK					E																	
	9	Politecnico di Milano	Italy					N																	
15	10	National University of Singapore (NUS)	Singapore	x		x		N		x			Bioinspired Functional Materials Laboratory												
25	11	Tsinghua University	China					N																	
26	12	The University of Hong Kong	Hong Kong		x	x	x	E / N	0	x		Mechanical and Biomedical Engineering		B.Sc.	GE1330	Learning From Nature	2017-2018		U	x	x	0	0	0	0
18	13	Columbia University	USA					E																	
28	14	The University of Tokyo	Japan					N																	
33	15	University of California, Los Angeles (UCLA)	USA	x		x	0	E				Bioengineering	Biomimetic Research Lab					Wentai Liu							
50	16	The University of Sydney	Australia					E																	
12	17	EPFL - Ecole Polytechnique Federale de Lausanne	Switzerland		x	x	x	E / N		x		Life Sciences and Bioengineering		M.Sc.	BIO-460	Bioinspired approaches to engineering	2017-2018		G						
					x	x	x	E / N		x			IDEAS Minor	M.Sc.		Nature inspired Architecture	2017-2018		G						
	18	Tongji University	China	x				E / N	x	x		School of Design and Innovation	BiDL Biomimetic Design Lab					Pius Luba dit Galland	G	x	0	0	0	0	0
70	19	Georgia Institute of Technology	USA	x			x	E	x	x	x	Center for Biologically Inspired Design	Design Intelligence Lab			Biologically-Inspired Design		Ashok Goel	G	x					
					x	x	x	E		x		Biology, Mechanical Engineering		M.Sc./ Ph.D.	BIOL/ME 4740	Biologically Inspired Design	2015- 2018	Jeanette Yen	G	x	x	0	0	x	0
95	19	The Hong Kong Polytechnic University	Hong Kong					E / N																	
41	21	The University of Melbourne	Australia		x			E	x				Master of Architecture		ABPL90147	Speculative Systems			G	0	0	x	0	0	0
	22	Universitat Politècnica de Catalunya	Spain		x	x	x	E / N		x		Material Science and Metallurgy	Master's Degree in IndustrialEngineering - Barcelona School of Engineering (ETSEIB)	MSc	240IMA11	Biomaterials	2014	Maria Pau Ginebra Mollins	G	x	x	0	0	0	0
45	23	The University of New South Wales (UNSW Sydney)	Australia		x			E	x			School of Built Environment	Master of Sustainable Built Environment	M.Arch	ARCH7213	High Performance Building Systems	2018-2019	Francesco Fiorito	G	x	0	0	0	0	0
							x	E	x			School of Built Environment		B.Arch.	CODE2132	Computational Design Studio IV (Proficiency)	2018-2019		U	0	0	0	0	0	0
98	24	KTH Royal Institute of Technology	Sweden		x	x	x	E / N		x		School of Engineering Sciences in Chemistry, Biotechnology and Health	Msc Industrial and Environmental Biotechnology	M.Sc.	BB2520	Bioprocess Design	Fall/2019	Antonius Van Maris	G	x	x	0	0	0	0
						x	x	E / N	x			Architecture and Built Environment		B.Arch.		Biomimicry	2011/ Fall 2012/ Spring	Anna Maria Orru	U	0	0	0	0	0	0
14	25	Cornell University	USA		x		x	E	x				Master of Science, Matter Design Computation	M.Sc.				Jenny Sabin	G	x	0	0	0	0	0
	26	RMIT University	Australia		x	x	x	E		x		Aerospace, Mechanical & Manufacturing Engineering		B.Sc.	115H / 172H	Biomaterials and Tissue Engineering	2015- 2018	Richard Williams	U	x	x	0	0	0	0
2	27	Stanford University	USA	x	0		x	E	0	x		School of Engineering	Mechanical Engineering			Lentink Lab		David Lentink	G	x	0	0	0	0	0
				x	0		x	E	0	x		School of Engineering	Mechanical Engineering			Biomimetics & Dexterous Manipulation Lab		Mark R. Chutkosky	G	x	0	0	0	0	0
	28	Universidade de São Paulo	Brazil					N																	
64	29	Technical University of Munich	Germany					N																	
82	30	The University of Sheffield	UK					E																	
	31	Universidad Politécnica de Madrid	Spain					N																	
51	32	University of British Columbia	Canada					E																	
	33	Pontificia Universidad Católica de Chile	Chile					N																	
36	34	Kyoto University	Japan					N																	
13	35	Princeton University	USA					E																	
36	35	Seoul National University	South Korea					E																	
21	37	University of Michigan	USA					E																	
19	37	University of Pennsylvania	USA					E																	
69	39	University of Illinois at Urbana-Champaign	USA					E																	
67	40	University of Texas at Austin	USA					E																	
	41	Politecnico di Torino	Italy		x	x	x	N	x	x	x	Civil Engineering & Architecture	Architectural and Landscape Heritage	PhD	01TAERL	The Innovative Approach of biomimicry in architecture and in urban and lanscapae redevelopment	2019/ March-April	Caterina Mele, Paolo Piantanida, Valentina Villa	G	0	x	0	0	0	0
						x	x	N		x		Biomedical Engineering		MSc	01NENMV	Biomimetic Systems	2014- 2015	Chiara Tonda Turo	G	0	x	0	0	0	0
	41	Technische Universität Berlin (TU Berlin)	Germany		x	x	x	E / N		x		Summer University	Cultural Pogram			Intrduction to BioDesign	2019/ Summer	Mirela Alistar		x	x	0	0	x	0
	43	University of Reading	UK		x	x	x	E		x		School of Biological sciences	Biological Sciences	MSc/PhD	BI2BI17	Biologically Inspired Computing	2018/ Fall	Slawomir Nasuto	G	x	x	0	0	0	0
31	43	University of Toronto	Canada		x		x	E		x		Mechanical Engineering		MSc	MIE 440	Design of Innovative Products	2018/ Fall	L. H. Shu	U / G	x	x	0	0	x	x
	45	Eindhoven University of Technology	Netherlands	x		x	x	E	x			Department of the Built environment	Innovative Structural Design	MSc PhD		Bio Based Composite Materials in Pavilion and Canopy Design		Patrick Teuffel	G	x	0	0	0	0	0
				x			0	E		x		Mechanical Engineering	Mechanics of Materials / Microsystems	MSc		Multiscale Lab		Jaap M. J. Toonder/ Johan Hoefnagels	G	0	0	0	0	0	0
	46	Aalto University	Finland		x	x	x	E	x	x	x		Aalto University Digital Design Laboratory		A-9.3000	Biomimic Design	2013/ Oct–Dec	Hannu Hirsi	G	0	0	0	0	x	0
					x	x		E		x		Bioproducts and Biosystems		MSc	CHEM-E5135	Biomimetic Materials and Technologies	2016/ Spring	Päivi Laaksonen, Kirsi Yliniemi	U / G	x	x	0	0	x	0
	46	Cardiff University	UK					E																	
71	46	KU Leuven	Belgium		x	x		E		x		Bioscience Engineering	Mechatronics, Biostatics and Sensors (MeBioS)	MSc	B-KUL-I0O79B	Biomaschines and Biomimetics		Wauter Saeys	G	x	x	0	0	0	0
	49	Universidad Nacional Autónoma de México (UNAM)	Mexico					N																	
47	50	The University of Queensland	Australia					E																	

The investigation suggests that the bio-inspired subjects are not yet highly visible in architectural curricula; however, several universities have ongoing research run by experts exploring these topics in other disciplines. Their researches can help the researchers from the field of architecture even these subjects are not included into their standardized curriculum. For this reason and in consideration of the infiltration of new topics to the curriculum, research projects are considered as the initiators of the topic within the community. When the topic is digested well enough by the experts; more graduate students can benefit from the new trends in the research first, then it will become a presentable as a heard subject for undergraduate students.

Within the scope of this research, multiple classifications of courses were held. The first criteria to look at is the accessibility of the courses since some courses have very few or even no online documents published. Although the names seen as the most appealing ones, the ones which have online documents published far from giving an idea about how course has been conducted are not included in the sampling. The second criterion is to look at whether the course is given in department of architecture or an extracurricular course. The third criteria is to look at how the course is conducted, application or theory based courses. The final criterion involves understanding the integration to curriculum is detected by looking at course whether is mandatory or elective.

5.1 Research Groups & Projects

The research activities cluster academicians working on the similar subjects together and in some of the universities these academic actions are performed in groups or laboratories specific to that topic. In this section of the research, QS Top 50 Architecture Ranking Universities are investigated on the researches carried out in the field of bio-inspired, biomimetic topics. The Universities having at least one research group or research lab focusing on bio-inspired design/ technologies/productions are shown in the Table 3: The Universities having at least one research group or research lab focusing on bio-inspired design/ technologies/productions. According to Table 3, the research groups and laboratories working under the department of architecture or conducting in collaboration with architecture department are explained through this section.

Table 22. The Universities having at least one research group or research lab focusing on bio-inspired design/ technologies/productions

Name	In Dept. of Architecture	In other Departments	Interaction with Dept. of Arch.	Deptartment Name	Institute or Program Name	Researc Group / Laboratory Name	Project Name	Director(s)/ Coordinator(s)
Massachusetts Institute of Technology (MIT)			x			MIT Media Lab- Mediated Matter Group	Design Across Scales & Disciplines	Neri Oxman
UCL (University College London)	x	x	x	Biochemical Engineering		B-Pro (Bartlett Prospective)	Bio-Integrated Design	Frédéric Migayrou
Delft University of Technology				Mechanical engineering		BITE- Bio-Inspired Technology Group		Paul Breesveld
ETH Zurich - Swiss Federal Institute of Technology		x	x	Materials Science		Complex Materails Group	Materials inspired by Nature	André R Studart
University of California, Berkeley (UCB)		x	x	Bioengineering and Materials Science and Engineering	Bioinspired materials science and bioengineering	Massersmith Lab		Philip B. Massersmith
Harvard University	0	x	x	School of Engineering and Applied Sciences (SEAS)	Wyss Institute for Biologically Inspired Engineering	Aizenberg Biomineralization and Biomimetics Lab		Joanna Aizenberg
	0	x		School of Engineering and Applied Sciences (SEAS)	Wyss Institute for Biologically Inspired Engineering	Mooney Lab- Laboratory for Cell and tissue Engineering		David Mooney
	0	x		School of Engineering and Applied Sciences (SEAS)		Bertoldi Group- Materials and Structures by Design		Katia Bertoldi
National University of Singapore (NUS)		x		School of Chemical and Biomedical Engineering		Bioinspired Functional Materials Laboratory	Bioinspired Materials	Song Juha
University of California, Los Angeles (UCLA)		x		Bioengineering		Biomimetic Research Lab		Wentai Liu
Tongji University	x	x	x	School of Design and Innovation		BiDL Biomimetic Design Lab		Pius Luba dit Galland
Georgia Institute of Technology	x	x	x	Center for Biologically Inspired Design		Design Intelligence Lab	Biologically-Inspired Design	Ashok Goel
Stanford University	0	x		Mechanical Engineering		Lentink Lab		David Lentink
	0	x		Mechanical Engineering		Biomimetics & Dexterous Manipulation Lab		Mark R. Chutkosky
Eindhoven University of Technology	0	x		Mechanical Engineering	Mechanics of Materials / Microsystems Engineering	Multiscale Lab		Jaap M. J. Toonder/ Johan Hoefnagels

5.1.1. MIT Media Lab – Mediated Matter Group

MIT Media Lab is an "antidisciplinary" research lab working on to invent the future of multiple disciplines or topics. MIT Media Lab contains various groups concentrated on different area of interests like; biomechatronics, city science, affective computing, mediated matter, nano-cybernetic biotrek. These groups are conducting various projects and programs act as a conductive role between initiatives and researchers.

The Mediated Matter group is directed by Neri Oxman. Oxman defines the group's main focus as: "Nature-inspired design and design-inspired Nature" and explains their scope of researches includes computational design, digital fabrication, materials science, and synthetic biology, where the researchers operate to "design across scales - from the micro scale to the building scale". The relation and interaction between natural and man-made environments are increased through the biologically inspired and engineered design fabrication tools, technologies and structures created by the Mediated Matter group.

The course is mainly using the systematic principles extracted from the biological sources in their system design with compound analogies. Their approach to the physical properties of the natural sources is from the perspective that they tried to understand the system lies behind the formation and the mechanistic processes.

5.1.2. B-Pro (Bartlett Prospective)

B-Pro is a group composed of UCL- Bartlett's five graduate programs; Architectural Design, Urban Design, Architectural Computation, Architecture and Digital Theory, and Bio-Integrated Design. The group is directed by Professor Frédéric Migayrou, the Chair of The Bartlett School of Architecture. The overall aim of the group is to create a creative community to access and share the researches by collaborative works. Even though five graduate programs follow different agendas, they met in a common ground where intellectual exchange is revealed between the students and academics via the yearlong developed seminars, workshops, lectures and public events. The students have found chance to discuss and synthesize personal design approaches which they want to carry research on, and by the help of public events they may find a chance to set research partnerships.

5.1.3. BITE- Bio-Inspired Technology Group

BITE- Bio Inspired Technology Group is part of the department of BioMechanical Engineering of the Mechanical, Maritime and Materials Engineering (3mE) Faculty in TU Delft. The group is led by Professor Dr. Paul Breedveld whose expertise is developing innovative technical systems inspired by smart solutions in nature. BITE's researches concentrated on biological organisms with smart constructions and mechanisms and seek proper technological methods to apply upon artificial mechanisms (Breedveld, 2019). BITE is collaborating with the faculty of architecture and built environment in some research projects where building engineers and architects work on fabrication mechanisms that are inspired from nature's production.

As mentioned by Breedveld (2019), BITE's works are targeting the nature's performative aspects and materialistic properties that provokes these behaviors. Although the mechanics of how nature works and how manmade system works are not intended to be matching, their aim is to create the similar performance with artificial mechanisms that they produce.

5.1.4. Complex Materials Group

Complex Materials Group is a research group works within the Department of Materials of ETH Zurich Swiss Federal Institute of Technology. It is directed by Professor André R. Studart who defines the groups objective as investigating the engineering approaches directed towards fabrication by investigating complex artificial materials having the capacity to contain the features of natural biological materials (Studart, 2019).

The group has four main research subjects that are, Colloidal assembly and microfluids, materials inspired by nature, 3D printing, Science-driven engineering. Materials inspired by nature and 3D printing researches are held in collaboration with the building scientist and architects and the findings of these researches are set basis for the field of architecture questioning the designs for these new materials. Studart (2019)'s focus is on the material properties of natural entities and how to carry the natural behaviors by the materiality into the man-made world caused.

5.1.5. Aizenberg Biomineralization and Biomimetics Lab

Aizenberg Lab is a part of Wyss Institute for Biologically Inspired Engineering of Harvard University School of Engineering and Applied Sciences. It is established by Joanna Aizenberg who is *"one of the pioneers of rapidly developing field of biomimetic inorganic materials synthesis"* (Aisenberg, 2018).

Aizenberg Lab offers variant research topics including biomineralization, self-assembly, adaptive materials, crystal engineering, nanofabrication, biomaterials, and biomechanics. These differentiated interests are researched with the aim of discovering the basic principles of biological architectures, their compositional organizations, and how to achieve multifunctional adaptability within a single material. So, Aizenberg Lab is not only concentrated on the materialistic properties but the formation procedures and systematic principles driving them.

Aizenberg Lab is one of the main collaborators of Harvard Graduate School of Design both within the scope of a workshop course "Nano Micro Macro: Adaptive Material Laboratory"; during which design students are challenged with the translation and the application of new materials across different scales.

5.1.6. Design Intelligence Lab

Design Intelligence Laboratory is a part of Center for Biologically Inspired Design (CBID) have direct connection with Georgia Institute of Technology. Professor Ashok Goel is coordinating the research lab and defines the main interest is concentrated into computational design and creativity. Design intelligence Lab is focusing on the systematic principles of nature as Goel mentions in the brief that creative design of physical systems like biologically inspired designs, design of self-adaptive software agents and visual cognitions form the context for their research (A. Goel, 2019).

Biologically-Inspired Design is a research project held by Design& Intelligence Lab, and defined as: *"a kind of design by analogy, requires that engineers understand complex biological systems as analogues for design"* (A. Goel, 2019). Goel and his team developed a software called DANE (Design by Analogy to Nature Engine) that provides designers to maintain descriptions of biological systems. Goel and his team are collaborating with architects and other designers in their researches, where they can provide ease to designers for extracting information from biological systems and researchers gain access to designers' creative design process to use in their researches.

These six different research programs conducted in different universities having a common ground of rooting their researches on biology, whether they are interested in the cognitive process of biological occurring and emulation of them into the virtual environment by conducting analogies with the systematic principles of nature, or using biology as sample of their inventive material technologies, or more abstract synthesis of holistic design approach of nature by investigating new methods of including them into their design process as imitating natural processes.

5.2. Graduate Level Courses

Graduate level courses are investigated by their relevance to the field of architecture, some of them belong to distant disciplines yet they might lead novel knowledge accumulation to architects in specific fields of biomimicry. This section presents an overview for the six out of twelve graduate level core and elective courses offered by relevant or related disciplines to the department of architecture/ built environment.

Table 23. The Universities having at least one graduate level course focusing on bio-inspired design

World Ranking (Top 100)	World Ranking on Architecture (Top 50)	Name	Country	Core Course (C) / Elective Course (E) / Program (P)	In Dept. of Architecture	In other Departments	Interaction with Dept. of Architecture	Deptartment Name	Program Level	Program Name	Course Code	Course Name / Project Name	Year	Instructor(s)
1	1	Massachusetts Institute of Technology (MIT)	U.S.A.	E		x		Aeronautics and Astronautics			16.982	Bio-Inspired Structures	2009	Leo Daniel
				E	x	x	x		M.Sc.	MIT Media Lab	MAS.650-DAS	Design Across Scales & Disciplines	2016	Neri Oxman
7	2	UCL (University College London)	U.K.	P	x	x	x	Bartlett School of Architecture / Biochemical Engineering	M.Arch. / M.Sc.	Bio-Integrated Design (Bio-ID)				Marcos Cruz, Brenda Parker
54	3	Delft University of Technology	Netherlands	E		x		Applied Sciences	M.Sc.	Master in Nanobiology	NB4130TU	BioLogic: Learning from living systems	2018	H. J. E. Beaumont
				E		x	x	Mechanical, Maritime and Materials Engineering	M.Sc./ Online	Master in Mechanical Engineering	ME41095 / WB2436-12	Bio Inspired Design	2016-2017	Paul Breedveld
10	4	ETH Zurich - Swiss Federal Institute of Technology	Switzerland	E		x		Material Sciences	M.Sc. / Ph.D.		327-1221-00L	Biological and Bio-Inspired Materials	2018	A. R. Studart, I. Burgert, E. Cabane, R. Nicolosi Libanori
27	5	University of California, Berkeley (UCB)	U.S.A.	C	x		x	Architecture	M.Arch. / M.Sc.	Studio One			2014-2015	Kyle Steinfield, Etienne Turpin, Sara Dean
3	6	Harvard University	U.S.A.	E	x	x	x	GSD/Wyss Institute for Biologically Inspired Engineering / SEAS	M.Sc. / Ph.D.		GSD-SCI-6477 / SEAS-ES291	Nano Micro Macro: Adaptive Material Laboratory	2017	Salmaan Craig, Joanna Aizenberg
12	17	EPFL - Ecole Polytechnique Federale de Lausanne	Switzerland	E		x			M.Sc.	IDEAS Minor		Nature inspired Architecture	2017-2018	
				E		x		Life Sciences and Bioengineering	M.Sc.		BIO-460	Bioinspired approaches to engineering	2017-2018	
70	19	Georgia Institute of Technology	U.S.A.	E		x	x	Biology, Mechanical Engineering	M.Sc.		BIOL/ME 4740	Biologically Inspired Design	2015- 2016- 2017- 2018	Jeanette Yen
	22	Universitat Politècnica de Catalunya	Spain	E		x		Material Science and Metallurgy	M.Sc.	Master's Degree in IndustrialEngineering - Barcelona School of Engineering (ETSEIB)	240IMA11	Biomaterials	2014	Maria Pau Ginebra Mollins
45	23	The University of New South Wales (UNSW Sydney)	Australia	E	x		x	School of Built Environment	M.Arch. / M.Sc.	Master of Sustainable Built Environment	ARCH7213	High Performance Building Systems	2018- 2019	Francesco Fiorito
98	24	KTH Royal Institute of Technology	Sweden	E		x		School of Engineering Sciences in Chemistry, Biotechnology and Health	M.Sc.	Msc Industrial and Environmental Biotechnology	BB2520	Bioprocess Design	2019	Antonius Van Maris
14	25	Cornell University	U.S.A.	P	x				M.Sc.	Master of Science, Matter Design Computation				Jenny Sabin
	41	Politecnico di Torino	Italy	E	x	x	x	Civil Engineering & Architecture	Ph.D.	Architectural and Landscape Heritage	01TAERL	The Innovative Approach of biomimicry in architecture and in urban and lanscapae redevelopment	2019	Caterina Mele, Paolo Piantanida, Valentina Villa
	43	University of Reading	U.K.	C		x		School of Biological Sciences	M.Sc./ Ph.D.	Biological Sciences	BI2BI17	Biologically Inspired Computing	2018	Slawomir Nasuto
	46	Aalto University	Finland	E	x	x	x	Architecture	M.Sc.	Aalto University Digital Design Laboratory	A-9.3000	Biomimic Design	2013	Hannu Hirsi
71	46	KU Leuven	Belgium	C		x		Bioscience Engineering	M.Sc.	Mechatronics, Biostatics and Sensors (MeBioS)	B-KUL-I0O79B	Biomaschines and Biomimetics	2018	W+A1:T18auter Saeys

5.2.1. Design Across Scales & Disciplines – MAS.650-DAS

Design Across Scales & Disciplines is a course is an elective course given under the postgraduate program Media Art & Sciences at the MIT Media Lab; however undergraduate students might enroll to class under the specific conditions. The course was taught by Neri Oxman and Meejin Yoon in Spring 2016 and held twice a week and each session took two hours, so four hours in total. One session in each week was designated for lectures by the instructors or the guest lecturers, students were expected to come prepared with the readings. The other session was designed as a lab session to teach students new tools to improve students tool sets. Course structure was given in detail with all scheduled lectures from the department of architecture and Media Matter Group with complimentary readings in relation to topics.

According to the Syllabus of Spring 2016; the course aims to explore the relationship between science and engineering from the perspective of a designer by examining how technological developments in science and technology affects the design thinking process (Oxman & Young, 2016). The course starts with "Designing Data" and step by step evolves to "Design Materiality", "Designing Life" and "Designing Nature"; the design of the natural matter, design of the synthetic matter and redesigning nature topics will be covered in different periods of the class to integrate nature as a design data. Oxman and Young (2016)'s course includes parts that they synthesize the systematic principles of nature into a coded set of information that can run in a virtual environment.

5.2.2. Bio-Integrated Design – Bio-ID

Bio-Integrated Design is a new master's program of B-Pro started in 2018 that will be jointly taught by UCL (University College London) Bartlett School of Architecture and Biochemical Engineering departments, so graduates of this program will hold March or MSc degree. The aim of the program is to combine design experiments with scientific methods, to explore the advances in material sciences and synthetic biology and understand how it is changing the design production practices. The program is directed by Professor Marcos Cruz from Bartlett and Dr. Brenda Parker from the Biochemical Engineering. Various seminars, workshops, lectures and public events will be held to integrate students more with the particular biological design approaches growing significantly. Program is open to full-time or flexible- mode admissions. By looking at the studio results published in B-Pro yearbook, it is observed that Bio-ID students are focusing on nature's systematic principles that leads their formation processes. There is no information found upon how these students are using nature's physical properties and performative aspects.

Marcos Cruz explains how the program explores new modes of simulation and production of architecture by integrating the new sense of materiality and hybrid technologies brought into the design scene. Early processes of design involve modelling and simulation pf the nature in computer environment simultaneous to the organic growth of the prototypes in real laboratory environments. An example shown below Figure 38, where participants observe and manipulate the growth of a natural organism in different stages of the research, and they are also conducting a virtual and larger scale experiment via the software.

Figure 37. Myco-Mense Laboratory based growth testing developed by Research Cluster 7[34]
(Source: Bartlett B-Pro Show 2018 Catalogue)

5.2.3. Bio Inspired Design – ME41095 / WB2436-12

Bio Inspired Design Course is given by Professor dr. Paul Breedveld in the scope of master's in mechanical engineering program offered by Biomechanical Engineering Department of Mechanical, Maritime and Materials Engineering Faculty(3mE) TU-Delft.

[34] (Source: Bartlett B-Pro Show 2018 Catalogue)

The course was held also online in 2011 in TU-Delft-Open Course Ware. It is an elective course with the duration of four hours. Course syllabus[35] does not reveal a lot of information about the course content; however, weekly given lectures are open to public access by TU-Delft-Open Course Ware.

Professor Breedveld defines the course objectives as to give an overview of non-conventional mechanical approaches in nature that can lead to simples, smaller and robust solutions by looking at biological organisms' smart constructions and mechanisms. The bio-inspired analogies used in this course are based mostly on the physical properties of the nature and presents an overview of the methods that can lead architects to achieve those properties. This elective course is attracting graduate level architecture students and researchers who are working on biomaterials and fabrications inspired from natural mechanisms.

5.2.4. Nano Micro macro – SCI 6477

Nano Micro Macro: adaptive Material Laboratory was an elective course co-taught by the GSD (Graduate School of Design) and SEAS (School of engineering and Applied Sciences) in Harvard University in Fall 2017-18. It was held as a 3-hour workshop by Joanna Aizenberg from SEAS (Wyss Institute) together with Salman Craig (GSD) in 2017 and Jonathan Grinham (GSD) in 2018.

According to course syllabus, main purpose of the course is to bring together scientists, engineers and designers together and learn about other disciplines concerns, working principles and design processes via observing different scales of materiality and their use. The syllabus is designed like a primer, and explains the necessary terminology, objectives, main topics, assignments, weekly schedule and references thoroughly. Syllabus also includes as section where authors are directing students to research groups for further studies.

[35] ME41095 Bio Inspired Design Course syllabus can be accessed from: https://studiegids.tudelft.nl/a101_displayCourse.do?restoreContext=true&SIS_SwitchLang=en&course_id=41090

5.2.5. Biologically Inspired Design – BIOL/ME 4740

Biologically Inspired Design is an elective course given by Jeanette Yen in under the Mechanical Engineering Department of Georgia Institute of Technology as a department elective, which has started to be given in 2006 and regularly available in every Fall semester. In the scope of course participants are examining the evolutionary adaptations for engineering design inspiration.

The course is considered as a pool course for BIOL, BMED, ISyE (Industrial and Systems Engineering), ME and PTFE departments and it is highly chosen by the graduate students of design and architecture that are interested in new design methods and approaches in the field of research.

According to the syllabus of Fall 2017, the course aims to students to practice the functional analogies between the biology and engineering via case studies and analyses. As an outcome, students will learn how to see biological world as potential bearer design inspiration both in terms of functionality and working principles. The syllabus includes the topics that will be covered in 13-week period. The only textbook indicated in syllabus is Steven Vogel, Cat's Paws and Catapults. There is no further reference for the structure of the course; however, Yen, Weissburg, Helms, and Goel (2011) state that the course was used to support Georgia Tech's Center for Biologically Inspired Design's one of the primary goals which is sustainable design. Throughout the long journey of the class starting from 2006, CBID researchers observed that the course has been providing both problem-driven design and solution-based design approaches (Vattam, Helms, & Goel, 2008) with compound analogies.

5.2.6. Biomimic Design – A-9.3000

Biomimic Design course is an elective workshop that is a part of the core studio course of Aalto University's Digital Design Laboratory held between October – December 2013, it was conducted by Hannu Hirsi and the course code was A-9.3000. The course was open to all master-level students of School of Arts, Design and Architecture. The main aim of the course was to experiment with an array of viewpoints and approaches to biomimetic design in different scales of architecture by getting familiarized with the materials and tools used in the field.

Figure 38. Final model samples from the Biomimic Design Workshop Course

During the course period students were generating series of botanical architectural species by utilizing their structures (see Figure 30) and processes by using the techniques of nature such as: aggregation, accumulation, repetition, mutation and transformation in different scales varied from micro to macro.

The graduate level courses share a primal ground of teaching bio-inspired design with hands on application-based method of conduction. They also mostly concentrated on the physical properties of nature which is the form and the systematic principles that can lie beneath the formation of those botanical entities which they used computational techniques to experiment on those logics in virtual environment enabling students to involve in across scales experimentation.

5.3. Undergraduate Level Courses

This section presents an overview of undergraduate level courses. The four courses out of seven courses either offered by department of architecture or eligible for architecture students; so, they are the ones examined in the scope of this research.

Table 24. The Universities having at least one undergraduate level course focusing on bio-inspired design

World Ranking (Top 100)	World Ranking on Architecture (Top 50)	Name	Country	Core Course (C) / Elective Course (E) / Program (P)	In Department of Architecture	In other Departments	Interaction with Department of Architecture	Deptartment Name	Program Name	Program Level	Course Code	Course Name / Project Name	Year / Semester	Instructor(s)
1	1	Massachusetts Institute of Technology (MIT)	U.S.A	E		x		Mechanical Engineering		B.Sc.	2.A35	Biomimetic Principles and Design	2013/ Fall	Michael Triantafyllou
27	5	**University of California, Berkeley (UCB)**	**U.S.A**	**E**		**x**	**x**	**Integrative Biology**		**B.Sc.**	**IB32**	**Bio-Inspired Design**	**2018/ Spring**	**Robert Full**
	7	**Manchester School of Architecture**	**U.K.**	**C**	**x**		**x**	**Architecture**	**Biomimetic B.Arch. Studio Unit**	**B.Arch. 5th year**			**2010**	**Siobhan Barry**
45	23	The University of New South Wales (UNSW Sydney)	Australia	C	x		x	School of Built Environment		B.Arch.	CODE2 132	Computational Design Studio IV (Proficiency)	2018-2019	
98	24	**KTH Royal Institute of Technology**	**Sweden**	**E**	**x**		**x**	**Architecture and Built Environment**		**B.Arch.**		**Biomimicry**	**2011/ Fall 2012/ Spring**	**Anna Maria Orru**
	26	**RMIT University**	Australia	**E**		**x**	**x**	**Aerospace, Mechanical & Manufacturing Engineering**		**B.Sc.**	**115H / 172H**	**Biomaterials and Tissue Engineering**	**2015/ 2018**	**Richard Williams**
31	43	University of Toronto	Canada	E		x		Mechanical Engineering		B.Sc. M.S.c	MIE 440	Design of Innovative Products	2018/ Fall	L. H. Shu

5.3.1. Bio Inspired Design – IB 32

Biologically Inspired Design course is an elective course offered by Integrative Biology Department in University California of Berkeley in Spring 2016/2018 by Professor Robert Full. The course does not have any prerequisites, so it is open to all undergraduate students by aiming to involve students of mainly from the departments of biology, engineering and architecture generate an interdisciplinary vision of how animals and plants function in their environment.

The course concentrates on the process of learning from Nature the innovation strategies to translate functional, performance and aesthetical principles. Although the course is a theory based one, it provides an exemplification of the designs inspired by nature's physical properties, performative aspects and systematic principles in a holistic way. Lectures are covering biomimetic design processes of scientific discoveries; gecko inspired adhesives, artificial muscles, prosthetics given with their proper terminology. The course in the introductory level overviews the concepts of BioDiscovery, BioDesign, Bio Constraints, BioScaling,BioSelection and BioComplexity. This was followed by the scientific discoveries BioAdhesion, BioWalk, BioSensing, BioMaterials, BioAnimation and BioArchitectures. The last part of the course is focusing on the term project.

5.3.2. Biomimetic Unit

Biomimetic Unit is a core studio course held in the 5th year of BArch program at Manchester School of Architecture in 2011. The course concentrates on biomimicry processes and sustainability in architectural designs proposing dynamic relationship between climate and living organisms. 5th year studio is centered around the development of a knowledge base in Biomimetic design.

Throughout the course students are expected to develop biomimetic design proposals individually by following the principle of using nature as a 'model, measure and mentor' for design. During the course period Michael Pawly and Jerry Tate have contributed with their lecture on biomimetic architecture. Students attend a field trip organized by Manchester School of Architecture entitled "Learning from the Eden Project". The methodological approaches in the scope of this course is not mentioned on internet so we cannot conclude which of the categories of bio-inspired analogies are used.

5.3.3. Comprehensive Studio – Workshop: Building Envelopes_ materials and technologies

Building Envelopes: materials and technologies workshop was held in winter 2013 as a part of 415 Comprehensive Studio in Architecture and Urban Design Faculty of University of California, Los Angeles (UCLA). As the workshop was a part of a core studio, participation was mandatory. The participants of the workshop had chance to explore building envelope design with modelling techniques and experiment through prototyping. The fabrication process enables participants to develop advanced physical-digital models and detailed drawings to express the innovation extracted from the biomimetic studies and their resulting proposals to be manufactured. Students were expected to come up with a final envelope design which will be analyzed via computational techniques for the admit of assembly. With this course students were expected to build analogies by using nature's physical properties especially the materialistic capacities that they interpreted on the forms using these materials.

Illaria Mazzoleni described workshops intents on her website as follows: *"students to interact with the professionals from other fields of engineering and design that are interested in biological strategies used principally or materially."* During the workshop the theoretical principles are explained by material scientists, aerospace engineers, building engineers and architects.

5.3.4. Biomaterials and Tissue Engineering – 115H / 172 H

Biomaterials and Tissue Engineering course is an undergraduate level elective course offered by two departments that are Aerospace, Mechanical & Manufacturing Engineering, and School of Engineering at RMIT. The course is taught by Dr. Richard Williams. According to course overview published on web[36], the main focus of the course concentrates on functional biomaterials, growing / manufacturing of tissues by using scaffolds or with the help of more advanced 3D printing techniques which are using the systematic principle lies behind the growth strategies of natural entities. Throughout the course students will receive seminars upon topics and attend multiple workshops boosting their knowledge and prepare laboratory report in the form of project.

The course aims to teach students how to first learn, then mimic natural biological phenomena in order to increase effective growing and repairing of biological materials including tissues, organs and bones. RMIT's design and architecture students who are in BSc level or members of D-Lab who are interested in bio-inspired design are taking this course as an elective to learn about natural growth strategies.

In this chapter research projects, graduate level courses and undergraduate level courses were presented according to the way they have been conducted. The way they have been dealing with bio-inspired approaches are examined according the levels of education. Their interests are differing in each level. Research projects main interests focusing on the innovative approaches and concentrated on how to make them come applicable in field. The graduate level courses are the concerned more with the

[36] See course overview from: http://www1.rmit.edu.au/courses/050519

experimental studies including the computational understanding of natural environment, and undergraduate level courses are trying to give the basic knowledge upon biomimicry and tries to introduce design methods in relation to that.

5.4. Results and Discussion

After the completion of the study, research findings are interpreted by the author according to initial determinant criteria; accessibility, validity for architecture field, classification of subject according to target groups, major method of administration, and whether the activity is compulsory or selection basis. In contrary to the listing above, discussion will start from undergraduate level and move towards the research groups/projects.

The section covering undergraduate level courses is consisted of four courses; IB 32, Biomimetic Unit, Building Envelopes: materials and technologies, and Biomaterials and Tissue Engineering. IB 32 is an across disciplines theory based elective course also aiming to give students basic knowledge on how plants and animals function in their environments and how to translate this knowledge to design strategies over the examples. Biomimetic Unit is an application-based course which covers whole semester as a core architectural design studio concentrated on biomimicry's sustainability aspects that can be applied to architectural designs. Building Envelopes: materials and technologies is a fifteen day workshop within the scope of Comprehensive Studio, application-based core studio, through which students are experimenting on the biological strategies with physical and digital models. Biomaterials and Tissue Engineering is an application-based course which is an elective for architecture students. Concentration is on biological growth strategies and methods to apply them on by humans' hands as mentioned in the syllabus of Design Across Scales and Disciplines Course and Bioprocess Design Course.

The undergraduate level courses are using biomimicry in a way that helps accumulation of architectural knowledge as mentioned by Tavsan, Tavsan & Sönmez's (2014) thoughts mentioned before in this chapter. It is observed that application-based courses dominating the undergraduate level biomimetic courses since students are better learn about design by making it in design studios (Schön, 1985). The nature of these application-based courses includes digital design and fabrication technologies that help students to abstract and simplify nature's principled into computable algorithms, either manually or digitally. Another prominent fact can be the sustainability issue underlined in both theory-based and application-based courses. All of the courses have sensitivity to economic use of the material, which is one of the key principles of biomimicry. The common thing was "design learning" through the investigation of nature.

The part covering graduate level courses is consisted of six courses that are: DAS, Bio-ID, Bio Inspired Design, Nano Micro Macro, BIOL/ME 4740, and Biomimic Design. DAS, Design Across Scales & Disciplines is an elective course that holds both theory and application included in its structure. The course embraces nature from the perspective of design thinking. Nature is considered as data, material, process and system which is examined with computational tools taught in the scope of this class. Bio-ID, Bio-Integrated Design is a master program, that holds again both theoretical and application-based courses. The program offers exploration of biological systems with computer-based simulations and biological materials via digital fabrication. ME41095/WB2436-12, Bio Inspired Design is an across disciplines elective course, which becomes an open source course by being published online. It is an extensive introductory course with embedded theoretical knowledge. Although the course is open to all disciplines, it follows an approach that uses *"mechanical analogies"*(Collins, 1978b). The course also provides a test environment for CBID to observe teaching, learning and designing processes by being held more than 12 years. SCI 6477, Nano Micro Macro: Adaptive Material Laboratory combines theory and application together as an elective course with two months duration. The course doe not only teaches about the biomimicry and investigates materiality in different scales but also searches for how to combine concerns of different disciplines raised from same biological entity. BIOL/ME 4740, Biologically inspired design course is also a theory-based elective focusing on functionality of biomimetic examples and their working principles. A-9.3000, Biomimic Design is six weeklong elective workshop within the scope of Digital Design Laboratory, application-based core studio, emphasis is on growth and forms imitating nature in different scales via digital computing and fabrication technologies.

Graduate level courses are also primarily integrating bio-inspired design with also hands on application-based courses. Concentration is on computational technologies, specifically indicated in Design Across Scales and Disciplines in MIT and Bioprocess Design Course in KTH, that enable to simulate and interpret on nature's principles, by approaching nature's design process as a problem solving process (Helms et al., 2008) which can be mapped into virtual environment. Different than the undergraduate level courses, duration of biomimetic part is way shorter. As a result of this, it can be said that courses are conducted not only on the basis of understanding biomimicry, but considerably longer periods are left for students to apply biomimetics in architectural designs. Another prominent observation is the courses effort on introducing new materials within the scope of both theory and application-based courses. In addition to introduction of new materials, application-based courses are including exercises of how to apply these materials in different scales.

Research Groups / Projects part covers seven research group/lab whose works are leading the bio-inspired developments, these are; Mediated Group, B-Pro, BITE, complex Materials Group, Aizenberg Lab, BiDL, Design Intelligence Lab. MIT Media Lab Mediated Matter Group is focusing their research on the relation between natural and manmade environments and searches for new methods of increasing the similarities. B-Pro is focusing on computational technologies used in the field of architecture and acts as a transitory between researchers and potential partners in the field. BITE's architectural branch is concentrating their works on biological organisms's construction mechanisms and they are artificially simulating them and bring it to the field. Complex materials group is working on new materials with multiple capacities. Their works are highly patented and consolidated with the material companies. Aizenberg Lab is working on biomimetic inorganic materials and challenges of multifunctional adaptability of a single material. Design Intelligence Lab's main approach is the simulation of biological design processes in the basis of computational thinking.

The research groups / projects are highly integrated to the field with their findings. For example, the works of Jan Knippers on flectofin is had direct grants from the manufacturers and they also support further researches to improve the system and the material. It is observed that nowadays the researches are concentrated on new and multi-functional materials, production of them and production with them like ETFE. Material studies led to open ended explorative studies as mentioned by Menges (2012) whose works on material studies in Institute for computational Design at Stuttgart Technical University and application of them brings innovative paths to follow and links to the second key topic of the researches which is robotic fabrication and sustainable structures are under the investigation of researchers. Knippers and Speck (2012) points out architecture and nature have different procedural orderings for structural design. This is reasoned by nature's capacity to work alone while buildings cannot build themselves. In order to reduce the human impact on building process, materials are advanced by containing self-structured organization and built by robotic fabrication, that can optimize the building process.

As a result of these findings stated above, we may conclude research has a mediator position between practice and education in terms of bio-inspired design. Our researchers cannot provide a clear evidence to state who initiated the bio-inspired design first; practice or research; however, according to the results of the study, interaction between practice and research is obvious. The research projects conducted in the universities that are put on a fast track and improved with the application in the field, as in the example of Jan Knipper's Flectofin design was improved with during application process. These kinds of examples are showing us the strength of the practice which can gather multidisciplinary experts together easier than the academic research environment. It is caused by the pace of the production process that can step over the bureaucratic engagements that needed to be constructed to gather multidisciplinary research groups together.

In addition to the relation of practice and research, there is the direct impact of research on education whn bio-inspired approaches are concerned. Even if it is not structured and fully integrated into curricula, bio-inspired design research cases are taken as a study cases in design and engineering faculties. Also, the built examples using theses research outputs are included in the precedents lists of the syllabi. Practice also interacts indirectly with education with the practitioners visiting academic conferences and courses, and students attend internships in those companies are setting initiative links.

Figure 39. Bio-Inspired Design; Interacting domains

In addition to our research findings, the literature on bio-inspired design education helped us to understand the tendencies of the curricular integration of bio-inspired design into design education; including engineering design, architectural design and the other fields of design.

CBID researchers led by Ashok Goel describes the integration of biological inspired design into engineering design curricula encourages designers to view traditional problems from new perspectives (A. Goel, 2015), which is the perspective of Nature. According to their researchers, biological analogies are useful in the stages of preliminary design. Designers are using natural resources in concept generation, design analysis, redesign and problem reformulation (Vattam, Helms, & Goel, 2010). Our research findings are parallel to this view. Especially in the graduate level courses present us that concept generation, design analysis, problem reformulation stages are intentionally included into syllabus in order to help students understand the evolutionary approach of biomimetic design, which needed to be analyzed well after the initial problem definition and open to constant changes throughout the process as nature does.

CHAPTER 6

CONCLUSION

The aim of this thesis was to explore the integration of biomimicry into the architectural design by looking at it in two divisions; architectural education including both education and research, practice, and inquire the question: how this new trend opens up new paths for both research and practice, and architectural design education. To investigate the topic, two perspectives were presented. Initially, the terminology within the literature of bio-inspired design was elaborated. This was followed by a historical overview of bio-inspired approaches in architecture. Then nature of this exploratory study is explained and direct readers towards the main research concentrating on projects including bio-inspired design approaches in their design processes, and bio-inspired design courses contained in architectural education.

Firstly, it is observed that the concept of biology has involved into design process far before the rising bio-centric approaches tractable in Aristotle and Leonardo da Vinci's works. It is increased in 1950's after Darwin and Heackel's works recognition by the modernists. They are penetrating more and more everyday into the design process that is understood from the increased use of new terminology used in design communication derived from the biology.

In the body of this research, bio-inspired design needed to be analyzed in a structured way. Chapter 4 provides a classification of architectural approaches concerning their formulation of bio-inspired design. The first category is the buildings that have design inspirations from the physical qualities found in nature. This has three sub-sections explaining the formal, structural and material properties of natural organisms used as source of design, each property is explained through three built examples. The second class includes buildings designed with a focus on performance inspired from the natural systems. The third category comprises of buildings designed following logical principals extracted from nature and used as design strategy.

Following the account presented in Chapter 4, the classification of architectural approaches concerning their formulation in bio-inspired design is examined. There main categories are introduced according to the initial starting point for bio-inspired design inspirations, these are inspirations from the physical properties of nature, performative aspects of the nature that inspires building performances, and inspirations from the systematic principles of nature. At the end of the study it can be suggested that rather than a strict classification at the end of this study permeability of the classifications is possible. Even if the qualities of nature inspiring architecture can be detectable in design processes and buildings, the nature holds it all together in its body. The material is informing the structure and form at the same time it defines how and what to react, plus the relationship between the parts and the whole. The wholeness of nature should be the thing inspiring architects and designers, or it can be a destination to be reached.

Chapter 5 presents the bio-inspired trends in architectural education in three sub-chapters: research projects, graduate and undergraduate programs. Research projects are not conducted in a classic course format however, the graduate and undergraduate courses include the essential course structures with their briefs, syllabuses and method of conductions. As a result of the research on educational impacts taking part in Chapter 5 and investigating the prominences of biological inspiration in architectural education, it is observed that the courses oriented towards bio-inspired design is visible in curricula of major schools of architecture, although they are not fully integrated in a well-structured way. Most of them are integrating bio-inspired design approaches with the use of computational methods that is highly rising in the design environment.

The way schools followed to include biomimicry in design studios still seems experimental and unprompted; however, it is possible to see the use of analogical approaches according to the level of education. It can be concluded as undergraduate courses are more concentrated on the physical properties of the nature and try to imitate the forms and structures in major and search on the materialistic properties that can influence the materiality of the building elements. On the other hand, graduate level courses are including more performative aspects of the nature to achieve more sustainable solutions. In addition, they look at the systematic principles lies behind the formal, structural and behavioral principles.

Even though they have courses in both graduate and undergraduate level, it is observed that the top 50 architecture schools do not have extended curricular activities to draw a holistic plan to enrich the field. This is caused because of rarely seldom found experts that work in academic positions. The need for staff is met by the external experts that are mostly the architects and engineers working on biomimetic approaches, which brought the involvement of researchers and people with different expertise more and more and connects academy, research and practice on this basis. It also brought a fresh breath to architectural education, which has not been changed a lot after the Bauhaus System and opens up discussions on the curricular activities of architectural schools and the position of architects and multidisciplinary experts in these curriculums.

From this perspective, researchers seem to act as middlemen to close the gap between the practice and the academia. While their studies open up new paths for companies to be followed, which increases year by year by the leading companies' investments on researches; these new findings are widening the horizon for the field of academia. The more researchers involve in the architectural education, the more integration the topic seems possible to the architectural curriculum.

On the other hand, it is inevitable to give credit to the practice's effect and influences on both research and academic field with its multidisciplinary organization. Although the body of research have laid a foundation for bio-inspired or integrated design solutions, generally the practice is the one which makes it real. While doing that it holds the capacity to bring different experts together in a quickest way, which surpasses the classical relations that can be created in the university environment. With these properties and the others mentioned above in this section, it would not be wrong to say that the practice seems to carry the education into the field of bio-inspired design with its significant productions.

6.1. Implications of the Study

This thesis research can improve our understanding on how to improve and implement biomimetics or biological inspirations to architecture studio. The literature presented over the previous implications in architectural practice and a can serve as a recourse catalog. In addition to that the projects realized in last fifteen years are presented to provide a general understanding of the intentions in the field. The research conducted on education is a novel contribution of this thesis by presenting the courses in a structurally classified array that can be used as to start a model by readers of this thesis.

6.2. Limitations

The study was made distant from to the data sources; therefore, it depends upon the web-published documents which are highly limited. The research projects and course details were not published in detail because of the protection of intellectual rights on them. Depending on the web published documents limits our research to include only course syllabuses, briefs, some studio results and it is not possible to cover the method of conduction for each course with the given information and assignments.

Another restriction is the limitation of the courses and research projects that can be included in this research. Since the main pool for the research is framed by the first 50 architecture schools in the world, the famous and influential architecture schools, like Architectural Association, SCI-Arc, Pratt Institute School of Architecture, and IAAC have to be neglected as they are private institutions not connected to mainstream universities and included in the rankings. Moreover, the works of the universities that are not in top 50 lists, like University of Texas Dallas, Oregon state University, Minnesota University, cannot be included, who are also lashing out with their courses on bio-inspired design.

The other limitation is to conduct a research that hasn't been treated in the same direction before. The topic is considerably new and unexplored to consult from numerable findings, that creates fuzziness in the boundary for our research. Since the research is new it is also difficult to define the scope of it properly. Moreover, this research is analyzing two sets which haven't been analyzed together before in the literature. The data related these two sets are floating and the research needed to wire them together that brought a careful examination of the all information in order to track the relative keywords underlining the similar topics in a different phrase.

6.3. Future Work

This study forms a basis for a more detailed study on the position of biological inspirations used in architectural education. Since the researcher has been geographically distant from the leading architectural schools offering bio-inspired design courses in their curriculum, it was not possible to observe the integration process directly. A future study can be conducted by investigating the architecture studios with introspective case studies to understand the level of integration and to understand the fields to be improved.

Another work which may follow this thesis research can be a detailed investigation of the projects examined as the pioneering ones by interviewing with the design teams upon the design process. In order to draw out how they used biological inspirations and in which stages of the design process, whole design process can be re-examined with the ones involved in it.

A further step which can be originated from this thesis research can be an investigation of a project which has been conducted by practice and academy together which involves experts, academicians and students in design team. Each parties knowledge basis, their level of interaction and their use of biological sources can be observed throughout this investigation.

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APPENDICES

Appendix 1. The Times Higher Education World University Rankings 2018

The Times Higher Education World University Rankings 2018 - SUBJECT: ARCHITECTURE							
World Ranking	**World Ranking offering Architecture**	**Name**	**Country**	No. of FTE Students	No. of students per staff	International Students	Female:Male Ratio
2	1	University of Cambridge	United Kingdom	18,389	10.9	35%	45:55:00
5	2	Massachusetts Institute of Technology	United States	11,177	8.7	34%	37 : 63
6	3	Harvard University	United States	20,326	8.9	26%	n/a
7	4	Princeton University	United States	7,955	8.3	24%	45:55:00
10	5	ETH Zurich	Switzerland	19,233	14.6	38%	31 : 69
10	6	University of Pennsylvania	United States	20,361	6.5	20%	50:50:00
12	7	Yale University	United States	12,155	4.3	21%	49:51:00
14	8	Columbia University	United States	26,587	6.1	32%	n/a
15	9	University of California, Los Angeles	United States	39,279	9.6	17%	53:47:00
16	10	UCL	United Kingdom	30,304	10.5	49%	56:44:00
18	11	University of California, Berkeley	United States	36,182	13.1	17%	52:48:00
19	12	Cornell University	United States	21,850	9.8	24%	49:51:00
20	13	Northwestern University	United States	17,466	12.8	18%	48:52:00
21	14	University of Michigan	United States	41,818	8.6	16%	48:52:00
22	15	National University of Singapore	Singapore	30,602	17	30%	51:49:00
22	16	University of Toronto	Canada	69,427	18.7	17%	n/a
24	17	Carnegie Mellon University	United States	12,676	13.5	45%	39 : 61
25	18	University of Washington	United States	44,945	11.4	16%	52:48:00
27	19	University of Edinburgh	United Kingdom	26,759	12.5	40%	59:41:00
27	20	New York University	United States	43,860	9.6	26%	56:44:00
27	21	Peking University	China	42,136	8.9	16%	47:53:00
30	22	Tsinghua University	China	42,089	13.7	9%	32 : 68
31	23	University of California, San Diego	United States	29,633	12.8	17%	46:54:00
32	24	University of Melbourne	Australia	42,116	26.6	40%	55:45:00
33	25	Georgia Institute of Technology	United States	20,773	20.7	27%	31 : 69
34	26	University of British Columbia	Canada	51,889	18.1	29%	54:46:00
37	27	University of Illinois at Urbana-Champaign	United States	43,402	22.8	23%	46:54:00
38	28	École Polytechnique Fédérale de Lausanne	Switzerland	9,928	11.2	55%	28 : 72
40	29	University of Hong Kong	Hong Kong	18,364	18	42%	54:46:00
41	30	Technical University of Munich	Germany	38,689	54.4	23%	34 : 66
42	31	McGill University	Canada	30,940	13.3	26%	57:43:00
43	32	University of Wisconsin-Madison	United States	38,960	10.7	12%	51:49:00
46	33	The University of Tokyo	Japan	26,000	6.7	10%	n/a
47	34	KU Leuven	Belgium	44,412	37.1	15%	50:50:00
49	35	University of Texas at Austin	United States	48,561	17.1	10%	51:49:00
50	36	Brown University	United States	8,898	10.7	20%	n/a
50	37	Washington University in St Louis	United States	12,600	7.5	17%	n/a
54	38	University of California, Davis	United States	37,365	13.8	10%	56:44:00
54	39	University of Manchester	United Kingdom	35,318	14.6	38%	52:48:00
56	40	University of Minnesota Twin Cities	United States	60,949	17.4	11%	51:49:00
58	41	Chinese University of Hong Kong	Hong Kong	18,072	17.3	31%	n/a
60	42	Purdue University	United States	38,770	17.4	23%	42:58:00
61	43	University of Sydney	Australia	44,553	21.6	32%	57:43:00
63	44	Delft University of Technology	Netherlands	17,057	19.6	27%	28 : 72
65	45	University of Queensland	Australia	38,968	35.7	26%	55:45:00
66	46	University of Southern California	United States	38,380	12.8	23%	53:47:00
67	47	Leiden University	Netherlands	24,825	18.2	12%	57:43:00
69	48	University of Maryland, College Park	United States	31,772	16.5	10%	48:52:00
70	49	Boston University	United States	24,833	8.6	25%	60:40:00
70	50	Ohio State University	United States	53,190	12.7	13%	49:51:00

Appendix 2. QS- Quacquarelli Symonds-World University Rankings 2018

QS- Quacquarelli Symonds- World University Rankings 2018								
World Ranking	World Ranking on Architecture	Name	Country	OVERALL SCORE	ACADEMIC REPUTATION	EMPLOYER REPUTATION	CITATIONS PER FACULTY	H-INDEX CITATIONS
1	1	Massachusetts Institute of Technology (MIT)	United States	98.5	100	97.2	93.9	93.5
7	2	UCL (University College London)	United Kingdom	97.1	98.4	91.9	96.6	93.5
54	3	Delft University of Technology	Netherlands	93.6	93.4	94.6	90.5	97.3
10	4	ETH Zurich - Swiss Federal Institute of Technology	Switzerland	92	93.4	84.3	93.9	88.2
27	5	University of California, Berkeley (UCB)	United States	90.4	89	83.4	100	97.3
3	6	Harvard University	United States	89	90.5	98.9	83.8	74
	7	Manchester School of Architecture	United Kingdom	88.6	87.2	99.4	93.1	83
5	8	University of Cambridge	United Kingdom	87.7	86.1	100	93.2	80.7
	9	Politecnico di Milano	Italy	85.5	84.4	98.7	83.6	81.9
15	10	National University of Singapore (NUS)	Singapore	85.3	83.2	82.8	95.6	92.6
25	11	Tsinghua University	China	85.2	82.7	93.2	87.7	91.8
26	12	The University of Hong Kong	Hong Kong	84.5	82.4	86.2	91.9	90.1
18	13	Columbia University	United States	83.6	83.5	80.1	89	81.9
28	14	The University of Tokyo	Japan	82.3	83.8	93.2	74.1	69.1
33	15	University of California, Los Angeles (UCLA)More	United States	82.2	82.3	82.7	86.5	76.9
50	16	The University of Sydney	Australia	82	78.2	81.7	96.1	94.3
12	17	EPFL - Ecole Polytechnique Federale de Lausanne	Switzerland	81.9	77.9	85.3	99.7	89.1
	18	Tongji University	China	81.7	81.1	79.1	77.4	92.6
70	19	Georgia Institute of Technology	United States	81.5	79.3	70.1	94.8	95
95	19	The Hong Kong Polytechnic University	Hong Kong	81.5	78	70.7	98	100
41	21	The University of Melbourne	Australia	81.2	79.3	79.1	92.7	85.2
	22	Universitat Politècnica de Catalunya	Spain	80.1	79.1	81.4	86.3	79.5
45	23	The University of New South Wales (UNSW Sydney)	Australia	79.8	79.2	80.6	81.8	80.7
98	24	KTH Royal Institute of Technology	Sweden	79.5	78.6	66.8	90.6	87.2
14	25	Cornell University	United States	79.2	79	78.5	83.4	76.9
	26	RMIT University	Australia	79.1	78.9	83.4	82.5	72.5
2	27	Stanford University	United States	79	74.9	91.6	93.3	80.7
	28	Universidade de São Paulo	Brazil	78.2	77.4	81.1	83.1	75.5
64	29	Technical University of Munich	Germany	78.1	77.8	75.5	82.4	78.2
82	30	The University of Sheffield	United Kingdom	77.9	76	66.1	95	86.2
	31	Universidad Politécnica de Madrid	Spain	77.7	75.7	85.3	83.1	78.2
51	32	University of British Columbia	Canada	77.6	75.1	71	95.3	84.1
	33	Pontificia Universidad Católica de Chile (UC)	Chile	77.4	75.3	84.6	82.6	79.5
36	34	Kyoto University	Japan	76.6	75.1	90	78.2	72.5
13	35	Princeton University	United States	76.3	76.2	78.1	78.9	72.5
36	35	Seoul National University	South Korea	76.3	74.1	90.3	81	72.5
21	37	University of Michigan	United States	75.8	73.5	70.9	87.2	85.2
19	37	University of Pennsylvania	United States	75.8	77.8	71.4	76.4	65.4
69	39	University of Illinois at Urbana-Champaign	United States	75.7	74.2	61.4	88.9	87.2
67	40	University of Texas at Austin	United States	75.4	71.7	72.6	92	87.2
	41	Politecnico di Torino	Italy	74.9	70.7	80.1	90	84.1
	41	Technische Universität Berlin (TU Berlin)	Germany	74.9	78.5	54.8	76.9	67.3
	43	University of Reading	United Kingdom	74.8	72.2	75.4	89	78.2
31	43	University of Toronto	Canada	74.8	70.3	72.5	95.7	87.2
	45	Eindhoven University of Technology	Finland	74.5	68	74.3	99.3	95
	46	Aalto University	Finland	74.3	72.3	64.8	92.8	79.5
	46	Cardiff University	United Kingdom	74.3	70.5	77.6	93.8	78.2
71	46	KU Leuven	Belgium	74.3	71	67.2	94.6	84.1
	49	Universidad Nacional Autónoma de México (UNAM)	Mexico	74.2	75.5	87.6	62.6	63.4
47	50	The University of Queensland	Australia	73	70	74.5	88.2	76.9

Appendix 3. Bio-Inspired Design Courses and Research Groups in Top 50 Architecture Schools According to QS- Quacquarelli Symonds- World University Rankings 2018.

World Ranking (Top 100)	World Ranking on Architecture (Top 50)	Name	Country	Research Group / Project	Course	Courses Available (biomimetics, biomimicry, bi inspired, biologically	Published on Web	Language - English (E)/ Native (N)	In Department of Architecture	In other Departments	Interaction with Department of Architecture	Deptartment Name	Program Name	Program Level	Course Code	Course Name / Project Name	Year / Semester	Instructor(s)	Graduate / Undergraduate	Brief Available	Syllabi Available	Assignments Available	Assignments in Detail	Readings Available	Lecture Notes Available	Accessed via
1	1	Massachusetts Institute of Technology (MIT)	USA		x	x	x	E		x		Aeronautics and Astronautics		M.Sc./ Ph.D.	16.982	Bio-Inspired Structures	2009/ Spring	Leo Daniel	G	x	x	x	0	x	x	https://ocw.mit.edu/courses/aeronautics-and-astronautics/16-982-bio-inspired-structures-spring-2009/syllabus/
					x	x	x	E		x		Mechanical Engineering		B.Sc.	2.A35	Biomimetic Principles and Design	2013/ Fall	Michael Triantafyllou	U	x	x	x	0	x	0	https://ocw.mit.edu/courses/mechanical-engineering/2-a35-biomimetic-principles-and-design-fall-2013/index.htm
				x		0	x	E	x	x	x		MIT Media Lab			Mediated Matter Group		Neri Oxman								https://www.media.mit.edu/groups/mediated-matter/overview/
					x	x	x	E			x		MIT Media Lab	M.Sc./ Ph.D.	MAS.650-DAS	Design Across Scales & Disciplines	2016/ Spring	Neri Oxman, Meejin Young	U	x	x	0	0	x	0	https://architecture.mit.edu/subject/spring-2018-4110 http://web.media.mit.edu/~neri/DAS/Syllabus/02162106___1030.pdf
7	2	UCL (University College London)	UK	x			0	E	x	x	x	Biochemical Engineering	B-Pro (Bartlett Prospective)			Bio-Integrated Design		Professor Frédéric Migayrou								https://www.ucl.ac.uk/bartlett/architecture/about-us/b-pro
						0	0	E	x	x	x	Bartlett School of Architecture / Biochemical Engineering	Bio-Integrated Design (Bio-ID)	M.Arch./ M.Sc.	0	0		Marcos Cruz, Brenda Parker	G	0	0	0	0	0	0	https://www.ucl.ac.uk/bartlett/architecture/programmes/postgraduate/bio-integrated-design-bio-id-march-msc
54	3	Delft University of Technology	Netherlands		x	0	0	E / N			x	Applied Sciences	Master in Nanobiology	M.Sc.	NB4130TU	BioLogic: Learning from living systems	2018/ Fall	H. J. E. Beaumont	G	0	0	0	0	0	0	https://studiegids.tudelft.nl/a101_displayCourse.do?course_id=48047
				x								Mechanical engineering				BITE- Bio-Inspired Technology Group		Paul Breedveld								https://www.bitegroup.nl/
					x	x	x	E/ N		x	x	Mechanical, Maritime and Materials Engineering	Master in Mechanical Engineering	M.Sc./ Online	ME41095 / WB2436-12	Bio Inspired Design	2016-2017	Paul Breedveld	G	x	x	0	0	x	x	https://studiegids.tudelft.nl/a101_displayCourse.do?restoreContext=true&SIS_SwitchLang=en&course_id=41090
10	4	ETH Zurich - Swiss Federal Institute of Technology	Switzerland	x			x	E / N		x	x	Material Sciences	Complex Materails Group			Materials inspired by Nature		André R Studart								https://complex.mat.ethz.ch/our-group.html
					x	x	x	E / N		x	x	Material Sciences		M.Sc.	327-1221-00L	Biological and Bio-Inspired Materials	2018/ Fall	A. R. Studart, I. Burgert, E. Cabane, R. Nicolosi Libanori	G	0	0	0	0	x	0	http://www.vvz.ethz.ch/Vorlesungsverzeichnis/lerneinheit.view?semkez=2018W&ansicht=KATALOGDATEN&lerneinheitId=124638&lang=en
27	5	University of California, Berkeley (UCB)	USA		x	x	x	E		x	x	Integrative Biology		B.Sc.	IB32	Bio-Inspired Design	2018/ Spring	Robert Full	U	x	x	x	0	x	0	http://polypedal.berkeley.edu/wp-content/uploads/Syllabus_IB32_S18.pdf
				x			x	E		x	x	Bioengineering and Materials Science and Engineering	Bioinspired materials science and bioengineering			Massersmith Lab		Philip B. Massersmith								https://bioinspiredmaterials.berkeley.edu/
					x	x	0	E	x				Studio One	M.Arch./ M.Sc.			2014-2015	Kyle Steinfield, Etienne Turpin, Sara Dean	G	0	0	0	0	0	0	https://ced.berkeley.edu/academics/architecture/programs/studio-one-2014/course-descriptions
3	6	Harvard University	USA	x			x	E		x		Wyss Institute for Biologically Inspired Engineering / SEAS	Aizenberg Biomineralization and Biomimetics Lab					Joanna Aizenberg								https://aizenberglab.seas.harvard.edu/
				x				E		x		Wyss Institute for Biologically Inspired Engineering / SEAS	Mooney Lab-Laboratory for Cell and tissue Engineering					David Mooney								https://mooneylab.seas.harvard.edu/
				x				E		x		Wyss Institute for Biologically Inspired Engineering / SEAS	Bertoldi Group-Materials and Structures by Design					Katia Bertoldi								https://bertoldi.seas.harvard.edu/
						x	x	E	x	x		GSD/Wyss Institute for Biologically Inspired Engineering / SEAS		M.Sc./ Ph.D.	GSD-SCI-6477, SEAS-ES291	Nano Micro Macro: Adaptive Material Laboratory	2017/ Fall	Salmaan Craig Joanna Aizenberg	G	x	x	x	x	0	x	https://canvas.harvard.edu/courses/34146
	7	Manchester School of Architecture	UK		x	x	0	E	x	0			Biomimetic BArch Studio Unit	B.Arch. - 5th year			2010	Siobhan Barry	G	0	0	0	0	0	0	https://petersproulearch.wordpress.com/barch-5th-year/ https://petersproulearch.files.wordpress.com/2011/01/design-report-year-5-biomimetics.pdf
5	8	University of Cambridge	UK					E																		
	9	Politecnico di Milano	Italy					N																		
15	10	National University of Singapore (NUS)	Singapore	x		x		N		x			Bioinspired Functional Materials Laboratory													http://www3.ntu.edu.sg/home/songjuha/index.html
25	11	Tsinghua University	China					N																		NOT ACCESSIBLE BEACAUSE OF LANGUAGE RESTRICTIONS
26	12	The University of Hong Kong	Hong Kong		x	x	x	E / N	0	x		Mechanical and Biomedical Engineering		B.Sc.	GE1330	Learning From Nature	2017-2018		U	x	x	0	0	0	0	https://www.cityu.edu.hk/catalogue/ug/201718/course/GE1330.pdf
18	13	Columbia University	USA					E																		
28	14	The University of Tokyo	Japan					N																		NOT ACCESSIBLE BEACAUSE OF LANGUAGE RESTRICTIONS
33	15	University of California, Los Angeles (UCLA)	USA	x		x	0	E				Bioengineering	Biomimetic Research Lab					Wentai Liu								http://164.67.24.13/wordpress/
50	16	The University of Sydney	Australia					E																		
12	17	EPFL - Ecole Polytechnique Federale de Lausanne	Switzerland		x	x	x	E / N		x		Life Sciences and Bioengineering		M.Sc.	BIO-460	Bioinspired approaches to engineering	2017-2018		G							https://moodle.epfl.ch/enrol/index.php?id=15498
					x	x	x	E / N		x			IDEAS Minor	M.Sc.		Nature inspired Architecture	2017-2018		G							
	18	Tongji University	China	x				E / N	x	x		School of Design and Innovation	BiDL Biomimetic Design Lab					Pius Luba dit Galland	G	x	0	0	0	0	0	https://webcache.googleusercontent.com/search?q=cache:kehCAIIlOEYJ:https://bidl.tongji.edu.cn/+&cd=1&hl=tr&ct=clnk&gl=tr
70	19	Georgia Institute of Technology	USA	x			x	E	x	x	x	Center for Biologically Inspired Design	Design Intelligence Lab			Biologically-Inspired Design		Ashok Goel	G	x						http://dilab.gatech.edu/biologically-inspired-design/
					x	x	x	E		x		Biology, Mechanical Engineering		M.Sc./ Ph.D.	BIOL/ME 4740	Biologically Inspired Design	2015-2018	Jeanette Yen	G	x	x	0	0	x	0	https://www.me.gatech.edu/files/ug/me4740.pdf
95	19	The Hong Kong Polytechnic University	Hong Kong					E / N																		
41	21	The University of Melbourne	Australia		x			E	x				Master of Architecture		ABPL90147	Speculative Systems			G	0	0	x	0	0	0	https://handbook.unimelb.edu.au/2017/subjects/abpl90147/print
	22	Universitat Politècnica de Catalunya	Spain		x	x	x	E / N		x		Material Science and Metallurgy	Master's Degree in IndustrialEngineering - Barcelona School of Engineering (ETSEIB)	MSc	240IMA11	Biomaterials	2014	Maria Pau Ginebra Mollins	G	x	x	0	0	0	0	https://guiadocent.etseib.upc.edu/guiadocent/profile/default/action/fitxa.php?code=240IMA11&lang=en&degree=1092
45	23	The University of New South Wales (UNSW Sydney)	Australia		x			E	x			School of Built Environment	Master of Sustainable Built Environment	M.Arch	ARCH7213	High Performance Building Systems	2018-2019	Francesco Fiorito	G	x	0	0	0	0	0	https://www.handbook.unsw.edu.au/postgraduate/courses/2019/ARCH7213/?browseByInterest=68b44253db96df002e4c126b3a961980&
							x	E	x			School of Built Environment		B.Arch.	CODE2132	Computational Design Studio IV (Proficiency)	2018-2019		U	0	0	0	0	0	0	https://www.handbook.unsw.edu.au/undergraduate/courses/2019/code2132/?q=biomi
98	24	KTH Royal Institute of Technology	Sweden		x	x	x	E / N		x		School of Engineering Sciences in Chemistry, Biotechnology and Health	Msc Industrial and Environmental Biotechnology	M.Sc.	BB2520	Bioprocess Design	Fall/2019	Antonius Van Maris	G	x	x	0	0	0	0	https://www.kth.se/student/kurser/kurs/BB2520?l=
						x	x	E / N	x			Architecture and Built Environment		B.Arch.		Biomimicry	2011/ Fall 2012/ Spring	Anna Maria Orru	U	0	0	0	0	0	0	http://annamariaorru.com/filter/Teaching/KTH-Biomimicry-elective-course
14	25	Cornell University	USA		x		x	E	x				Master of Science, Matter Design Computation	M.Sc.				Jenny Sabin	G	x	0	0	0	0	0	https://aap.cornell.edu/academics/architecture/graduate/mdc
	26	RMIT University	Australia		x	x	x	E		x		Aerospace, Mechanical & Manufacturing Engineering		B.Sc.	115H / 172H	Biomaterials and Tissue Engineering	2015-2018	Richard Williams	U	x	x	0	0	0	0	http://www1.rmit.edu.au/courses/050519
2	27	Stanford University	USA	x	0		x	E	0	x		School of Engineering	Mechanical Engineering			Lentink Lab		David Lentink	G	x	0	0	0	0	0	http://lentinklab.stanford.edu/welcome/biological_inspiration
				x	0		x	E	0	x		School of Engineering	Mechanical Engineering			Biomimetics & Dexterous Manipulation Lab		Mark R. Chutkosky	G	x	0	0	0	0	0	http://bdml.stanford.edu/Main/HomePage
	28	Universidade de São Paulo	Brazil					N																		
64	29	Technical University of Munich	Germany					N																		
82	30	The University of Sheffield	UK					E																		
	31	Universidad Politécnica de Madrid	Spain					N																		
51	32	University of British Columbia	Canada					E																		
	33	Pontificia Universidad Católica de Chile	Chile					N																		NOT ACCESSIBLE BEACAUSE OF LANGUAGE RESTRICTIONS
36	34	Kyoto University	Japan					N																		
13	35	Princeton University	USA					E																		
36	35	Seoul National University	South Korea					E																		
21	37	University of Michigan	USA					E																		
19	37	University of Pennsylvania	USA					E																		
69	39	University of Illinois at Urbana-Champaign	USA					E																		
67	40	University of Texas at Austin	USA					E																		
	41	Politecnico di Torino	Italy		x	x	x	N	x	x	x	Civil Engineering & Architecture	Architectural and Landscape Heritage	PhD	01TAERL	The Innovative Approach of biomimicry in architecture and in urban and lanscapae redevelopment	2019/ March-April	Caterina Mele, Paolo Piantanida, Valentina Villa	G	0	x	0	0	0	0	https://didattica.polito.it/pls/portal30/gap.pkg_guide.viewGap?p_cod_ins=01TAERL&p_a_acc=2019&p_header=S&p_lang=IT
						x	x	N		x		Biomedical Engineering		MSc	01NENMV	Biomimetic Systems	2014-2015	Chiara Tonda Turo	G	0	x	0	0	0	0	https://didattica.polito.it/pls/portal30/sviluppo.guide.visualizza?p_cod_ins=01NENMV&p_a_acc=2015&p_lang=EN
	41	Technische Universität Berlin (TU Berlin)	Germany		x	x	x	E / N		x		Summer University	Cultural Pogram			Intrduction to BioDesign	2019/ Summer	Mirela Alistar		x	x	0	0	x	0	https://www.tu-berlin.de/menue/summer_university/summer_university_term_2/introduction_to_biodesign/
	43	University of Reading	UK		x	x	x	E		x		School of Biological sciences	Biological Sciences	MSc/PhD	BI2BI17	Biologically Inspired Computing	2018/ Fall	Slawomir Nasuto	G	x	x	0	0	0	0	https://www.reading.ac.uk/modules/document.aspx?modP=BI2BI17&modYR=1819
31	43	University of Toronto	Canada		x		x	E		x		Mechanical Engineering		MSc	MIE 440	Design of Innovative Products	2018/ Fall	L. H. Shu	U / G	x	x	0	0	x	x	https://www.coursehero.com/file/39997458/MIE440-Syllabus18-1pdf/
	45	Eindhoven University of Technology	Netherlands	x		x	x	E	x			Department of the Built environment	Innovative Structural Design	MSc PhD		Bio Based Composite Materials in Pavilion and Canopy Design		Patrick Teuffel	G	x	0	0	0	0	0	https://www.tue.nl/en/research/research-groups/innovative-structural-design/projects/bio-based-composite-materials-in-pavilion-and-canopy-design/
				x			0	E		x		Mechanical Engineering	Mechanics of Materials / Microsystems	MSc		Multiscale Lab		Jaap M. J. Toonder/ Johan Hoefnagels	G	0	0	0	0	0	0	https://www.tue.nl/en/research/research-groups/
	46	Aalto University	Finland		x	x	x	E	x	x	x		Aalto University Digital Design Laboratory		A-9.3000	Biomimic Design	2013/ Oct–Dec	Hannu Hirsi	G	0	0	0	0	x	0	http://addlab.aalto.fi/education/add-topics/biomimic-design-a-9-3000
					x	x		E		x		Bioproducts and Biosystems		MSc	CHEM-E5135	Biomimetic Materials and Technologies	2016/ Spring	Päivi Laaksonen, Kirsi Yliniemi	U / G	x	x	0	0	x	0	https://oodi.aalto.fi/a/opintjakstied.jsp?html=1&Kieli=6&Tunniste=CHEM-E5135
	46	Cardiff University	UK					E																		
71	46	KU Leuven	Belgium		x	x		E		x		Bioscience Engineering	Mechatronics, Biostatics and Sensors (MeBioS)	MSc	B-KUL-I0O79B	Biomaschines and Biomimetics		Wauter Saeys	G	x	x	0	0	0	0	https://onderwijsaanbod.kuleuven.be/syllabi/e/I0O79BE.htm#
	49	Universidad Nacional Autónoma de México (UNAM)	Mexico					N																		NOT ACCESSIBLE BEACAUSE OF LANGUAGE RESTRICTIONS
47	50	The University of Queensland	Australia					E																		

Appendix 2. Research projects focusing on bio-inspired design in Top 50 Architecture Schools According to QS-World University Rankings 2018.

Name	In Dept. of Architecture	In other Departments	Interaction with Dept. of Arch.	Deptartment Name	Institute or Program Name	Researc Group / Laboratory Name	Project Name	Director(s)/ Coordinator(s)	Accessed via
Massachusetts Institute of Technology (MIT)			x			MIT Media Lab- Mediated Matter Group	Design Across Scales & Disciplines	Neri Oxman	https://www.media.mit.edu/groups/mediated-matter/overview/
UCL (University College London)	x	x	x	Biochemical Engineering		B-Pro (Bartlett Prospective)	Bio-Integrated Design	Frédéric Migayrou	https://www.ucl.ac.uk/bartlett/architecture/about-us/b-pro
Delft University of Technology				Mechanical engineering		BITE- Bio-Inspired Technology Group		Paul Breesveld	https://www.bitegroup.nl/
ETH Zurich - Swiss Federal Institute of Technology		x	x	Materials Science		Complex Materails Group	Materials inspired by Nature	André R Studart	https://complex.mat.ethz.ch/our-group.html
University of California, Berkeley (UCB)		x	x	Bioengineering and Materials Science and Engineering	Bioinspired materials science and bioengineering	Massersmith Lab		Philip B. Massersmith	https://bioinspiredmaterials.berkeley.edu/
Harvard University	0	x	x	School of Engineering and Applied Sciences (SEAS)	Wyss Institute for Biologically Inspired Engineering	Aizenberg Biomineralization and Biomimetics Lab		Joanna Aizenberg	https://aizenberglab.seas.harvard.edu/
	0	x		School of Engineering and Applied Sciences (SEAS)	Wyss Institute for Biologically Inspired Engineering	Mooney Lab- Laboratory for Cell and tissue Engineering		David Mooney	https://mooneylab.seas.harvard.edu/
	0	x		School of Engineering and Applied Sciences (SEAS)		Bertoldi Group- Materials and Structures by Design		Katia Bertoldi	https://bertoldi.seas.harvard.edu/
National University of Singapore (NUS)		x		School of Chemical and Biomedical Engineering		Bioinspired Functional Materials Laboratory	Bioinspired Materials	Song Juha	http://www3.ntu.edu.sg/home/songjuha/index.html
University of California, Los Angeles (UCLA)		x		Bioengineering		Biomimetic Research Lab		Wentai Liu	http://164.67.24.13/wordpress/
Tongji University	x	x	x	School of Design and Innovation		BiDL Biomimetic Design Lab		Pius Luba dit Galland	https://webcache.googleusercontent.com/search?q=cache:kehCAIlIOEYJ:https://bidl.tongji.edu.cn/+&cd=1&hl=tr&ct=clnk&gl=tr
Georgia Institute of Technology	x	x	x	Center for Biologically Inspired Design		Design Intelligence Lab	Biologically-Inspired Design	Ashok Goel	http://dilab.gatech.edu/biologically-inspired-design/
Stanford University	0	x		Mechanical Engineering		Lentink Lab		David Lentink	http://lentinklab.stanford.edu/welcome/biological_inspiration
	0	x		Mechanical Engineering		Biomimetics & Dexterous Manipulation Lab		Mark R. Chutkosky	http://bdml.stanford.edu/Main/HomePage
Eindhoven University of Technology	0	x		Mechanical Engineering	Mechanics of Materials / Microsystems Engineering	Multiscale Lab		Jaap M. J. Toonder/ Johan Hoefnagels	https://www.tue.nl/en/research/research-groups/

Appendix 3. Graduate level courses focusing on bio-inspired design in Top 50 Architecture Schools According to QS-World University Rankings 2018.

World Ranking (Top 100)	World Ranking on Architecture (Top 50)	Name	Country	Core Course (C) / Elective Course (E) / Program (P)	In Dept. of Architecture	In other Departments	Interaction with Dept. of Architecture	Deptartment Name	Program Level	Program Name	Course Code	Course Name / Project Name	Year	Instructor(s)	Accessed via
1	1	Massachusetts Institute of Technology (MIT)	U.S.A.	E		x		Aeronautics and Astronautics			16.982	Bio-Inspired Structures	2009	Leo Daniel	file:///C:/Users/cansu/AppData/Local/Temp/Rar$EXa0.350/16-982-spring-2009/contents/index.htm
				E	x	x	x		M.Sc.	MIT Media Lab	MAS.650-DAS	Design Across Scales & Disciplines	2016	Neri Oxman	http://web.media.mit.edu/~neri/DAS/Syllabus/02162106_1030.pdf
7	2	UCL (University College London)	U.K.	P	x	x	x	Bartlett School of Architecture / Biochemical Engineering	M.Arch. / M.Sc.	Bio-Integrated Design (Bio-ID)				Marcos Cruz, Brenda Parker	https://www.ucl.ac.uk/bartlett/architecture/programmes/postgraduate/bio-integrated-design-bio-id-march-msc
54	3	Delft University of Technology	Netherlands	E		x		Applied Sciences	M.Sc.	Master in Nanobiology	NB4130TU	BioLogic: Learning from living systems	2018	H. J. E. Beaumont	https://studiegids.tudelft.nl/a101_displayCourse.do?course_id=48047
				E		x	x	Mechanical, Maritime and Materials Engineering	M.Sc./ Online	Master in Mechanical Engineering	ME41095 / WB2436-12	Bio Inspired Design	2016-2017	Paul Breedveld	https://studiegids.tudelft.nl/a101_displayCourse.do?restoreContext=true&SIS_SwitchLang=en&course_id=41090
10	4	ETH Zurich - Swiss Federal Institute of Technology	Switzerland	E		x		Material Sciences	M.Sc. / Ph.D.		327-1221-00L	Biological and Bio-Inspired Materials	2018	A. R. Studart, I. Burgert, E. Cabane, R. Nicolosi Libanori	http://www.vvz.ethz.ch/Vorlesungsverzeichnis/lerneinheit.view?semkez=2018W&ansicht=KATALOGDATEN&lerneinheitId=124638&lang=en
27	5	University of California, Berkeley (UCB)	U.S.A.	C	x		x	Architecture	M.Arch. / M.Sc.	Studio One			2014-2015	Kyle Steinfield, Etienne Turpin, Sara Dean	https://ced.berkeley.edu/academics/architecture/programs/studio-one-2014/course-descriptions
3	6	Harvard University	U.S.A.	E	x	x	x	GSD/Wyss Institute for Biologically Inspired Engineering / SEAS	M.Sc. / Ph.D.		GSD-SCI-6477 / SEAS-ES291	Nano Micro Macro: Adaptive Material Laboratory	2017	Salmaan Craig, Joanna Aizenberg	https://canvas.harvard.edu/courses/34146
12	17	EPFL - Ecole Polytechnique Federale de Lausanne	Switzerland	E		x			M.Sc.	IDEAS Minor		Nature inspired Architecture	2017-2018		
				E		x		Life Sciences and Bioengineering	M.Sc.		BIO-460	Bioinspired approaches to engineering	2017-2018		
70	19	Georgia Institute of Technology	U.S.A.	E		x	x	Biology, Mechanical Engineering	M.Sc.		BIOL/ME 4740	Biologically Inspired Design	2015- 2016- 2017- 2018	Jeanette Yen	https://www.me.gatech.edu/files/ug/me4740.pdf
	22	Universitat Politècnica de Catalunya	Spain	E		x		Material Science and Metallurgy	M.Sc.	Master's Degree in IndustrialEngineering - Barcelona School of Engineering (ETSEIB)	240IMA11	Biomaterials	2014	Maria Pau Ginebra Mollins	https://guiadocent.etseib.upc.edu/guiadocent/profile/default/action/fitxa.php?code=240IMA11&lang=en&degree=1092
45	23	The University of New South Wales (UNSW Sydney)	Australia	E	x		x	School of Built Environment	M.Arch. / M.Sc.	Master of Sustainable Built Environment	ARCH7213	High Performance Building Systems	2018- 2019	Francesco Fiorito	https://www.handbook.unsw.edu.au/postgraduate/courses/2019/ARCH7213/?browseByInterest=68b44253db96df002e4c126b3a961980&
98	24	KTH Royal Institute of Technology	Sweden	E		x		School of Engineering Sciences in Chemistry, Biotechnology and Health	M.Sc.	Msc Industrial and Environmental Biotechnology	BB2520	Bioprocess Design	2019	Antonius Van Maris	https://www.kth.se/student/kurser/kurs/BB2520?l=en
14	25	Cornell University	U.S.A.	P	x				M.Sc.	Master of Science, Matter Design Computation				Jenny Sabin	https://aap.cornell.edu/academics/architecture/graduate/mdc
	41	Politecnico di Torino	Italy	E	x	x	x	Civil Engineering & Architecture	Ph.D.	Architectural and Landscape Heritage	01TAERL	The Innovative Approach of biomimicry in architecture and in urban and lanscapae redevelopment	2019	Caterina Mele, Paolo Piantanida, Valentina Villa	https://didattica.polito.it/pls/portal30/gap.pkg_guide.viewGap?p_cod_ins=01TAERL&p_a_acc=2019&p_header=S&p_lang=IT
	43	University of Reading	U.K.	C		x		School of Biological Sciences	M.Sc./ Ph.D.	Biological Sciences	BI2BI17	Biologically Inspired Computing	2018	Slawomir Nasuto	https://www.reading.ac.uk/modules/document.aspx?modP=BI2BI17&modYR=1819
	46	Aalto University	Finland	E	x	x	x	Architecture	M.Sc.	Aalto University Digital Design Laboratory	A-9.3000	Biomimic Design	2013	Hannu Hirsi	http://addlab.aalto.fi/education/add-topics/biomimic-design-a-9-3000
71	46	KU Leuven	Belgium	C		x		Bioscience Engineering	M.Sc.	Mechatronics, Biostatics and Sensors (MeBioS)	B-KUL-I0O79B	Biomaschines and Biomimetics	2018	W+A1:T18auter Saeys	https://onderwijsaanbod.kuleuven.be/syllabi/e/I0O79BE.htm#

Appendix 4. Undergraduate level courses focusing on bio-inspired design in Top 50 Architecture Schools According to QS-World University Rankings 2018.

World Ranking (Top 100)	World Ranking on Architecture (Top 50)	Name	Country	Core Course (C) / Elective Course (E) / Program (P)	In Department of Architecture	In other Departments	Interaction with Department of Architecture	Deptartment Name	Program Name	Program Level	Course Code	Course Name / Project Name	Year / Semester	Instructor(s)	Accessed via
1	1	Massachusetts Institute of Technology (MIT)	U.S.A	E		x		Mechanical Engineering		B.Sc.	2.A35	Biomimetic Principles and Design	2013/ Fall	Michael Triantafyllou	https://ocw.mit.edu/courses/mechanical-engineering/2-a35-biomimetic-principles-and-design-fall-2013/index.htm
27	5	University of California, Berkeley (UCB)	U.S.A	E		x	x	Integrative Biology		B.Sc.	IB32	Bio-Inspired Design	2018/ Spring	Robert Full	http://polypedal.berkeley.edu/wp-content/uploads/Syllabus_IB32_S18.pdf
	7	Manchester School of Architecture	U.K.	C	x		x	Architecture	Biomimetic B.Arch. Studio Unit	B.Arch. 5th year			2010	Siobhan Barry	https://petersproulearch.wordpress.com/barch-5th-year/ https://petersproulearch.files.wordpress.com/2011/01/design-report-year-5-biomimetics.pdf
45	23	The University of New South Wales (UNSW Sydney)	Australia	C	x		x	School of Built Environment		B.Arch.	CODE2132	Computational Design Studio IV (Proficiency)	2018-2019		https://www.handbook.unsw.edu.au/undergraduate/courses/2019/code2132/?q=biomi
98	24	KTH Royal Institute of Technology	Sweden	E	x		x	Architecture and Built Environment		B.Arch.		Biomimicry	2011/ Fall 2012/ Spring	Anna Maria Orru	http://annamariaorru.com/filter/Teaching/KTH-Biomimicry-elective-course
	26	RMIT University	Australia	E		x	x	Aerospace, Mechanical & Manufacturing Engineering		B.Sc.	115H / 172H	Biomaterials and Tissue Engineering	2015/ 2018	Richard Williams	http://www1.rmit.edu.au/courses/050519
31	43	University of Toronto	Canada	E		x		Mechanical Engineering		B.Sc. M.S.c	MIE 440	Design of Innovative Products	2018/ Fall	L. H. Shu	https://www.coursehero.com/file/39997458/MIE440-Syllabus18-1pdf/