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BIOLOGICAL INSPIRATION IN ARCHITECTURAL DESIGN: REVIEWING THE INFLUENCE OF THE LIVING WORLD ON ARCHITECTURAL THEORY AND PRACTICE

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Abstract
Analogy is a main cognitive source, which helps to understand new ideas and fosters creativity. Making analogy has a significant role in the architectural design thinking process and creating architectural concepts. The living nature has been always a great source of inspiration for the architects during history. Biological inspiration can be traced in various aspects of architectural theory and practice during the history. In the present research, different aspects of the influence of living nature and biology are investigated after an extensive literature review and classified in categories including as bio-utilization, inspiration in form, structure, mechanism, process, function, system, theory, abstract rule and concept. Accordingly, only some aspects of biological inspiration can be considered as biological analogies, including structure, mechanism, process, function, system, abstract rule and theory. Studying the history of bio-inspired architecture showed a gradual move from biological morphology, which was a superficial similarity, towards the deeper aspects of biological analogies in bionic design. It is because; bionic provides a deeper understanding of living nature. Besides, more efficient, optimized, and sustainable architecture could be achieved through the inspiration of deeper biological analogies in comparison to the superficial similarities.

Keywords: Analogy, concept Architectural Design, Bio-mimicry, biological morphology, Classification.

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INTRODUCTION
The world of living nature has always been a great source of inspiration for human beings in various fields of study and practice. The contribution of some biological concepts, such as evolution, morphology, taxonomy, behavior of dynamic systems, and the transmission of information through inheritance (genetics) in helping to develop new concepts and applications in the various branches of sciences, technology and human artifacts is considerable specially in recent years.

As a historical fact, among all of the sciences, it is the biology science that has a great role as the inspiration science for architectural design theorists and also for design practice. Many vocabularies in the architectural lexicon have borrowed from the field of biology and used in the architectural principles. The concepts borrowed from biology have been featured in all of the architectural theories of the past centuries till now. Most of the architectural texts in history have discussed the ideas and analogies derived from biology for architectural solutions. This continuous relationship between architecture and biology has been preserved until now. The characteristics of architectural design in terms of products and process have metaphorical similarities with biological concepts. The biological concepts are used significantly for the explanation and clarification of the architectural concepts such as totality, harmony, proportion, solidarity, correlation, integration, adaptation, and evolution. Besides, they are used to explaining similar qualities in architectural products. Among all the sciences, biology has addressed most of all to the fundamental issue of teleology in living nature. The design of any product results in achieving a goal or a purpose; therefore, it can be a reason for why biology has been considered mostly by designers (Steadman 2008).

ANALOGY AND ARCHITECTURAL DESIGN
Analogy and similarity are essential for human cognitive processes, although they are distinct from each other. Differences between analogy and similarity are determined by the degree of similarity of attributes and the degree of relational similarity. An analogy occurs when comparisons have a high degree of relational similarity that may also indicate a lower degree of similarity in the attributes (Gentner 1981; Dedre Gentner 1997). The similarity between the human face and a façade is illustrated in Fig. 1. The Beijing National stadium's structure is analogous to the bird's nest. The

analogy is shown in Fig. 2. Also, the analogy is a complex and intelligent process used in creative exploration, while similarity is an unconscious and non-argumentative perceptual process in which human beings share it with animal realm. New problems are solved using procedures derived from similar past problems which are saved in the human memory (Gentner 1981; Dedre Gentner 1997).

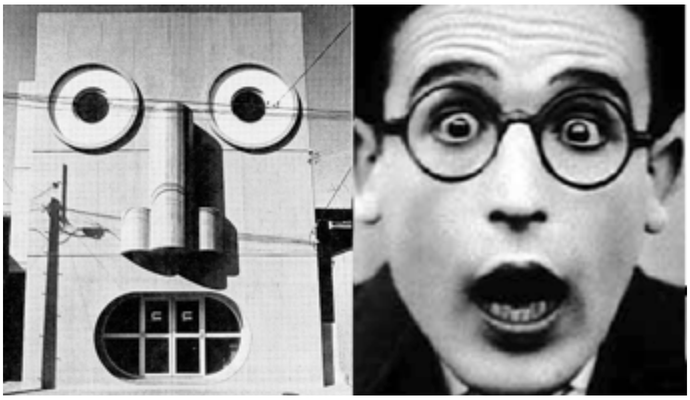


Fig. 1: Similarity between the human face and a façade design

Fig. 2: Analogy between bird nest and stadium structure

Researches in architectural design prove that analogy-based design is not a new subject and has been used by many great architects during history. Broadbent believes that analogy-based design is the most powerful source of creative ideas in architecture (Broadbent 1973). Cross classified different analogies in architectural design into four types of direct analogy, symbolic analogy, personal analogy, and imaginary analogy (K. Dorst 2001). Architectural professors urge students to use analogies to develop creative ideas. The analogy is used in architectural learning process for inspiring the physical form and to educate novice architects to think visually and graphically (Broadbent 1973). The process of creativity in architectural design involves combining ideas from different areas of knowledge with the application of visual analogies and imagery to create different alternatives (Cross 1995). Therefore, studying the common areas of architecture and biology can lead to creative architectural solutions.

In fact, the emulation of the living nature in architecture is initially shaped by creating analogies between some parts of the architecture field and the field of biology (Rossi 1976). This analogy can be created at different levels between the two domains. The levels refers to the level of causality or the degree of depth of relations between two domains in making analogies. Creating a comparison between the two areas of architecture and biology must be accompanied by the identification and distinguish of useful and illustrative cases from misleading and insignificant cases. Although there are many historical analogies, some of them have led to shortcomings and deviations in theories and practices. The most important misleading of the biological analogies in the past architectures was their being superficiality. But the analogy at deeper levels can be a fundamental source of inspiration and lead to the emergence of new ideas (Steadman 2008).

Comparing the relations between an organism and its environment with the building and its natural environment is called an ecological analogy. The adaptability of living organisms to the natural environment can be compared to the harmonious relationship of the building with its environment. The geographical and vernacular diversity of architecture around the world is comparable to the diversity of biological species, and ancient architectural styles can be compared with fossil species.

LEARNING FROM BIOLOGY FOR DESIGN DURING HISTORY

The history of living nature shows great influences on architectural theory. The term "bio-utilization" or "bio-use" means the direct use of biological factors for desired purposes including the use of plants around the building to provide evaporative cooling. In fact, the first effect of the living nature on architecture was the direct use of the living nature to provide shelter and its related needs.

Ancient Greek philosophers believed in living organisms and especially the human body as perfect examples of balance, harmony, and proportion. This belief is consistent with the classical concept of beauty. The analogy between living nature and architectural products was used to convey the natural beauty of the living creatures to the buildings. Aristotle compared the living organisms with artworks and considered both of them as patterns, which their components were in proportion to the whole entity. This artistic and philosophic view came from an abstract understanding of living nature, which realized in art and architecture through ideas and concepts.

The Roman architect Vitruvius opened the door to a bio-inspired design by comparing the proportions of the Roman temples to the human body, 2100 years ago (Vitrovius 1914). After eight centuries, Chinese used the bio-inspired approach to designing Hongcun village in the form of a cow and setting up its water supply system as the cow's digestive system. In the *Ten books of architecture*, Alberti described the history of the influence of biology on architecture and stated that The most professional artists, among the ancients were those who believed that building was like an animal and therefore it had to imitate its configuration (Alberti 1755).

Leonardo da Vinci realized the intelligent design of nature and its functional performance in some inventions such as a flying device. Descartes mechanistic view entered the rules and principles of mechanical science in the field of biology and described the function of living systems on the basis of mechanical principles and rules. He compared the church's structure directly analogous to the body of the animals (Agudin 1995).

The Industrial Revolution brought a new view into biology by emulation of living creatures' structures, which led to the creation of new designs. Among theseare, the Crystal Palace in London and the Lily House in Strasbourg which were designed by Joseph Paxton. In the mid-twentieth century, Ricolais developed structural models inspired by the structure of animals' body. These structural patterns were extracted by the German biologist Haeckel in the nineteenth century (Mertins 2004).

In the nineteenth century, the classification of buildings was carried out based on patterns and principles derived from the field of biology including functional, form-based classification, and even historical classifications. Viollet-le-Duc and Semper compared the natural evolution process with the process of architecture's evolution during history and defined building species based on primitive species (Agudin 1995). Also, Semper defined types or species for the buildings based on the principle that, having the same function leads to the same properties in form. In another concept, environmental conditions in different regions caused distinctions in species, and it was used to define the different styles in architecture (Hvattum 2004).

Peter Collins introduced two major categories in the functional aesthetic analogy including biological and mechanical analogy. He also developed three fundamental principles based on the characteristics of living organisms, including the relationship between the organism and its environment, the principle of the organ's correlation, and the relationship between form and function (Collins 1959; Collins 1987).

Cuvier explained some biologic facts in the comparative anatomy. He stated that the coordination of the internal components of the organism's body had relation to the external conditions of the outside environment. By adapting this fact to architecture, it is concluded that the climate study and the natural environment in which the building is located affects building design (Agudin 1995; Steadman 2008).

Biological thoughts were featured in the writings of many modern architects such as Le Corbusier and Frank Lloyd Wright. Frank Lloyd Wright introduced the organic architecture based on the assumption that the building was viewed as an organism and living entity. Frank Lloyd Wright was inspired by seashells for designing the Guggenheim Museum in New York (Njoo 2008). Another example is his office building with its mushroom-like columns inside. Le Corbusier noted that biology should be the main notion in architecture and planning. He created the modular system of measurement based on the human body's proportions to create proportionate and harmonious architectural forms. He also compared different systems of buildings to the human body systems including, ventilation with the respiration system, electrical circuits with the nervous system, telephone with the communication system in living creatures, and sewage system and waste disposal with digestive system(Dummett 2007; Gruber 2011). Le Corbusier forced architects to nurture their imagination by studying and drawing natural organisms like shells. From Le Corbusier's point of view, the traditional wall bearing is comparable to the external skeleton or external bony crust of crustaceans, such as crabs and tortoises, and the modern skeletal structure is in accordance with the vertebral structure of the skeletal system, in which walls have the role of skin and membrane of organisms (Dummett 2008).

The late twentieth century was the era of developing advanced technologies, nanotechnology, artificial intelligence, information, and telecommunications. It was the time to value the new dimensions of bio-inspired design such as emulation of processes and systems, beyond the appearance and superficial aspects. Portoghesi gathered a large collection of natural analogies in architectural forms (Potoghesi 2000). In 1963, Victor O'glige introduced a model in which design process results from the interaction of architecture with biology and climatology (Victor Olgyay 1963). Alexander made benefit from the concepts of the biology for defining and clarifying the architecture design process. He presented an analytical-based design approach based on an adaptation of living systems to the environment. He decomposes the design problem into smaller problems, thus organizing problems in a hierarchy allows the limited changes and modifications without changing the overall design and solution (Alexander 1964; Steenson 2010). In the sixties, Kurokawa introduced Metabolism movement to apply the dynamic change, exchange, and renewability of living world to architecture by inspiration of organisms' growth. A strategic research was performed on the overlapping areas of architecture and biology by Lebedev in 1971, which resulted in a comprehensive set of natural structures. Mumford believed that the future would belong to the bio-inspired architecture, which is characterized by flexibility, changeability, and opportunity for growth. Besides, he described the bio-inspired architecture properties in making lighter building structures through simplification and decentralization of mechanical facilities. Also, he predicted the possibility of utilizing a local sewage system and solar reflectors as auxiliary heating, which was realized in the Technological movements of the seventies (Steadman 2008).

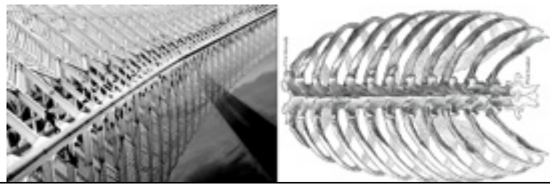
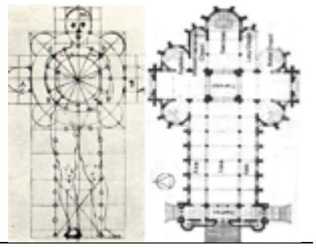
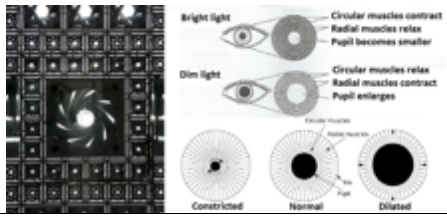
Bertalanffy compared living organisms with mechanical machines to develop the systems theory and stated that organisms and machines both possessed systemic properties. He defined organisms as open systems with complex, dynamic, non-linear and auto-responses to external stimuli (Bertalanffy 1968). Eventually, Yeang introduced the building as a system that interacted with its surroundings (Alexander Laszlo 1998). The interaction of a building with its surroundings included inputs and outputs from the building to the environment and vice versa (Ying, 1995).

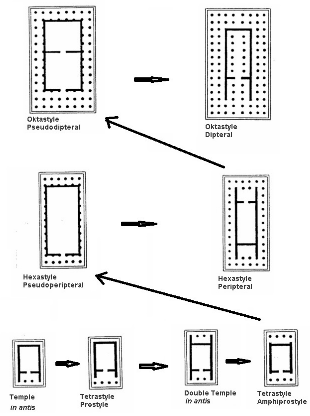
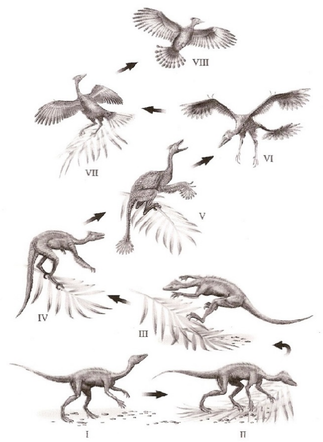
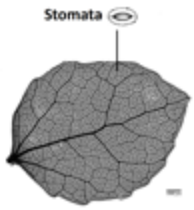
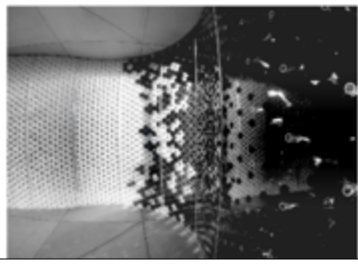
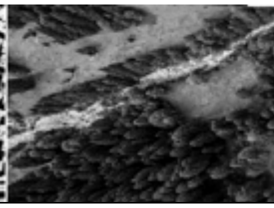
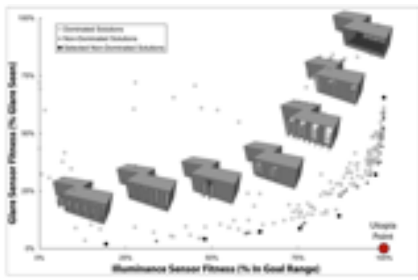
Negroponte argued that architecture could take advantage of the computer science in structures and spaces and could create better-performing buildings that led to the emergence of a new definition of architecture, which is known as the Responsive Architecture (Negroponte 1970). Such interactive intelligent-based systems are integrated into the physical components of the building, which allowed the building to be adapted to the natural environment and users (Steenson 2010). This attitude opened a new way towards buildings with living characteristics. New structural systems such as deployable, folded, expandable, and kinetic structures can change the geometry of the building envelopes' general form by allowing the building to be adapted to the climatic conditions and outdoor changes. Today, sensors and processors are used in the structures of the building envelopes to trace the environmental changes and calculate the appropriate reactions to them. The introduction of new design processes inspired by evolutionary processes of living nature opened a new way for computer-based design. The evolutionary process was developed by computer programs in different algorithms including genetic algorithm, evolutionary strategies, evolutionary planning, and genetic programming. Nowadays, genetic algorithm (GAS) are the most well-known algorithms for searching and optimization based on adapting process (Philippe Marin 2008), which are used to optimize energy consumption and thermal performance of the building envelopes. The contradictory functions of thermal inertia and thermal insulation of the envelope can be optimized using the GAS (V. Sambou a 2009).

Three design principles were derived from living nature to create a climate-friendly design. These principles include adaptation, interaction, and integration, which provide a framework for the architects to design climate-friendly buildings (Sandeep Arora 2009). Van der Ryn introduced ecological design process to eliminate environmental destructive impacts by emulation of ecosystems or living processes (Fan Shu-Yang 2004).

In the present study, by considering the relationship between biology and architecture during history, different categories of biological applications in architectural theory and practice were recognized and introduced in Table I.

Table II: Classification of different biological applications in architecture

Bio-utilization	Trees for shading	
Form	Lotus like building	
Structure	Structure of building as skeleton	
Abstract rule	The invisible geometry of the church is inspired by human body proportions	
Concept	The flapping wings of bird inspired the design concept	
Mechanism	pupil muscles inspired resizing holes of facade to control solar radiation	

Theory	The theory of evolution of species, borrowed from biology for architectural theory	 
Function	Transferring the gases between indoor and outdoor inspired by leaf stoma	 
System	Designing the built-environment by applying ecological principles	 
Process	Genetic Algorithms as computational technique is used in architectural design to solve complicated problems.	 

FORM BIOLOGICAL MORPHOLOGY TOWARDS BIO-MIMICRY (BIONIC)

Architects have often benefited from living nature as a library of diverse forms. Architectural decorations were originally shaped by inspiration from nature, especially from plants. In modern architecture, most of the unusual forms and symbols in architecture were inspired by nature.

Biological morphology or "bio-morphology" was shaped in art domains and design disciplines based on emulation of the living organisms' shapes. This branch of organisms' study has had the greatest impact on architecture over the whole history. In the early 20th century the root of the bio-morphology architecture could be found in Gaudi's architecture (Gruber 2011).

Lebedev believed that the nature's principles that state the integrity of form, function, and structure was very effective and efficient. This integrity was attained through the interaction of the organism with the outside environment to achieve more adaptation and responsiveness. The final form of organisms in nature is the product of the adaptive process and the result of the integrity of form, structure and function. Therefore, form-based bio-morphology and mere superficial perceptions face with lack of credibility and value, because it cannot achieve the inherent qualities of natural organisms (Stroble Nagel 2010).

Bio-mimetic means the smart use of living nature for the development of innovative ideas, which was first used by Benyus (Benyus 1997). Architectural bio-mimetic does not merely indicate bio-morphology. Mere emulation of shape and form cannot lead to fundamental and sustainable solutions in architecture. But the new orientation should be towards applying the principles of living nature, which explores the deeper aspects of organisms. Therefore, there should be a significant distinction between "bio-mimetic emulation" and "bio-morphology". The reason for the distinction between bio-morphology and bionic or biotechnology is due to the need for a functional revolution of its kind that can take three fundamental changes, including to increase the resource efficiency, the transfer of fossil fuels to the solar economy and the shift from the linear use of resources to cyclic use. Therefore, the bio-mimicry is a better option than "bio-morphology", which reveals it has the many required solutions (Pawlyn 2011).

Bio-morphology aims to find superficial similarities between biological and architectural domains. But bio-mimicry seeks analogies in the two domains of biology and architecture. The requirements of today's architecture for being more efficientsustainable and adaptive, caused the necessity of moving from bio-morphology to bio-mimicry. It can be interpreted that we need to move from emulation of superficial similarities to deeper analogies.

Many innovative solutions have laid in the evolution of organisms. It is essential to study the deep nature of the organisms for finding the answer to all the questions of technology. Simple duplication of natural patterns is not a biotechnology method.

In the sixties, a new branch of engineering emerged, which was called Bionics. It is the systematic study of the biological phenomena that can be applied to design of man-made machines and devices (Gerardin 1968). The purpose of employing bio-mimetic in the architecture field is to use it as a tool in architectural design (Gruber 2011). Innovative solutions of biology help to solve architectural problems, as well as the creation of new ideas and concepts and even new design processes. According to bio-mimicry, traditional and vernacular architectures are noteworthy for their evolutionary process and adaptation to the natural environment.

At present, the application of biological inspirations in architecture is getting closer to analogical approaches, which can be addressed in the categories such as function, process, mechanism, structure and system categories. These biological applications are beside other applications which were mainly used during the history which includes bio-utilization, form inspiration, abstract rule extraction, concept creation and theorizing. Different types of biological inspirations are categorized in Table III, according to their historical or new applications.

Table IV: Historical applications versus new analogical approaches of biological inspirations in architecture

Historical applications	Bio-utilization	Form	Structure	Abstract rule	Theory
New analogical approaches	Function	Process	Mechanism	Concept	System

CONCLUSIONS

As a historical fact, it is the science of biology among other sciences that has the most influence on architectural theories and practice. Among all the sciences, it is biology that refers to the fundamental issue of teleology in nature. Innovative solutions of biology help to solve architectural problems, as well as the creation of new ideas and concepts and even new design processes. This paper investigates and classifies the architectural inspiration from bio-science into several categories including bio-utilization, inspiration in form, structure, mechanism, process, function, system, theory, abstract rule, and concept. These inspirations are based on similarities and analogies made between biology and architecture domains. Historical applications of the living world in architecture consist of bio-utilization, the inspiration of form, structure, abstract rule, concept and theory. While present and future applications would focus mostly on inspiring deep analogical aspects of the bioscience such as structure, mechanism, process, function and system.

Form is the result of process and function. As a result, a deeper understanding of biologic phenomena would help deeper understanding of the causalities. There is a tendency to move toward applying deeper biological analogies than employing superficial similarities in architectural practice. It causes a movement from bio-morphology to bionic design. This attitude can lead to more efficient, adaptive and sustainable solutions in architecture**.** It is because that there is a need for fundamental changes, including increasing the resource efficiency, the transfer of fossil fuels to the solar economy, and the shift from the linear use of resources to cyclic use.

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