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# TOWARDS A NEW APPROACH TO NATURE-INSPIRED DESIGN OF ARCHITECTURE

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**Abstract:** This paper proposes a new approach to architecture design, which enables nature-inspired modification of buildings prototypes. In the proposed method, analogy between a prototype and a class of natural objects (e.g. plant species) is found with the use of a knowledge base of natural forms. To define classes of natural objects, a generative tool called graph grammar is used. Matching a building prototype with a class of natural forms enables application of a graph grammar on the building model, which results in a nature-related aspects of an architectionic object. The main objective is to propose a method of computational design, which can be verified with regard to its capability of imitating human process of creatve design of architecture. This will help to learn more about alghoritmising of creative processes.

***Keywords:*** *artificial creativity, architecture design, computer-aided design*

## 1. Introduction

According to Amabile (2012), creativity is "the production of a novel and appropriate response, product, or solution to an open-ended task." Boden (2004) states that an effect of surprise, essential component of creativity, can occur under at least one of the following conditions: when an idea or an artefact combines familiar ideas in an unfamiliar way, when conceptual spaces are explored in order to find a non-obvious solution, or when conceptual spaces are transformed, so as a solution previously regarded as impossible comes to mind due to the change of thinking paths. Except from surprise, creativity brings novelty and value - only innovative ideas that respond adequately to a stated problem are regarded as creative. This approach corresponds well with two types of thinking required in a design process - divergent thinking that involves imagination and intuition, and convergent thinking which is logical and rational (Grabska, 2015).

This paper deals with computational creativity (CC) in architecture. The computer is used to generate prototypes of form designs that would be regarded as creative if produced by a designer alone (Boden, 2006). In other words, the model proposed here attempts to reconstruct some processes of human creativity in order to achieve a generator of both useful and imaginative prototypes of architectural objects. The main goal is to characterize a tool which would help designers to find inspiration in nature, however the knowledge base of inspirations does not necessarily have to be limited to natural forms.

Nature-inspired architecture is a popular concept that has been implemented in many different ways, one of the most fancy of them is probably A. Gaudi's Sagrada Familia. The tree-shaped columns filling in its interior combine an idea of a typical cylindrical column with a concept of a tree trunk which branches out into other cylinders (Figure 1a.). Such a construction has been chosen by Gaudi after careful research in order to improve the chapel's stability. In this paper we propose automatic modifications of architectonic structures by finding some natural associations during the design process, for instance, a standard column defined by a designer may be transformed into a tree trunk form. Although we do not aim to investigate detailed constructional aspects of a building in the manner the genius architect did, it is crucial for suggested modifications to fulfil functional criteria of the basic shape, i. e., a tree trunk should be able to uphold the roof. Figure 1b. shows another example of nature- inspired architecture design, Elbe Philharmonic Hall, which top storey has been inspired by ocean waves. This design solution gives an impression of diversity and coherence, typical for natural forms.

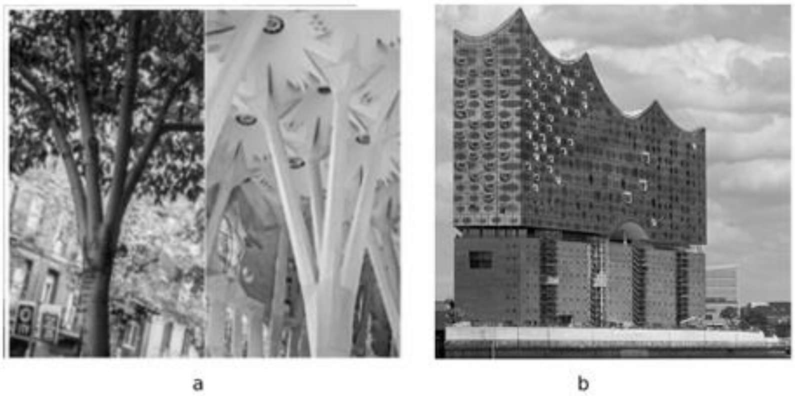


**Figure 1.** Sagrada Familia interior: tree-inspired columns (http://www.sagradafamilia.org/geometria) and Elbphilharmonie (https://en.wikipedia.org/wiki/Elbphilharmonie)

The pioneer of nature-inspired CC efforts was John Frazer who proposed computer-generated designs for building and urban centres (Frazer, 1995). Computational design requires to rationalize “irrational” natural forms. Some successful attempts of this process have been presented in (Kizilcan and Mennan 2016), where a nature-inspired modern art sculpture has been described with mathematical tools independently by several researchers. At this moment all these descriptions represent at most a class of very similar structures, therefore are not very useful in automatic design of wide variety of shapes. Among different ways of automatically designing nature-inspired artifacts probably the most popular are shape grammars and L-Systems, however, they have some limitations (Roncoroni and Crousse 2016). Based on a finished set of rewriting rules it is hard to achieve a true resemblance of a natural form, which is often characterized by a complex and irregular shape. More importantly, even if such a result was possible to obtain, for the purpose of architectural design one would need a tool to combine it with essential functionality – e.g., not all shell-shaped structures may be appropriate for a human being to live in. The method presented here is based on Biederman visual perception model and graph transformations (Biederman 1987, Grabska and Borkowski 1996). Biederman model – Recognition by Components Theory – divides a perceived object into components (elementary figures called geons) and determines relations between them. This allows to create a graph representation, in which graph nodes and edges correspond to geons and relations, respectively. In the presented method a knowledge base of graph rules generating representations of natural forms is defined. Such representation enables investigation of objects' structures in order to find associations. Once a wide enough knowledge base is provided, we obtain a powerful tool for combining shapes and creating new ideas. This paper may be treated as an attempt to develop a model which would be the basis of useful creative software supporting the designer during design process of nature-inspired artefacts.

## 2. Structural Representation of Architecture

Computer-aided design of architecture requires internal structure of a designed object. The main purpose of structural representation is to reflect designer's actions and constitute a basis for visualization, however the internal structure can also be transformed by automatic design process..

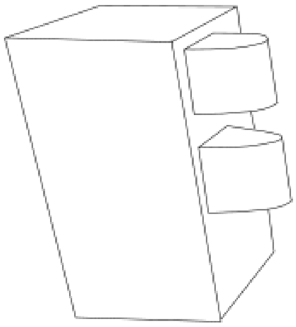

**Figure 2.** A sketch of a simple building

### 2.1. Recognition-By-Components

Recognition-By-Components (RBC) theory is a perception model which assumes that object recognition is performed by the analysis of its structure (Biederman 1987). This can correspond well with the need of internal representation in design, especially that people evaluate aesthetics of a designed object with the use of visual perception. According to RBC, human brain is supposed to be equipped with an alphabet of basic figures, that Biederman called geons for "geometric icons". They can be arranged in an infinite number of ways. Some of these arrangements are memorised as model objects, for instance, a cube with a pyramid on its top is associated with a concept of a house. What is interesting, we accept some modifications of this structure, like a flat roof or a cylinder instead of a cube. Only some solids' attributes and some spatial relations are crucial here - the roof should be on the top and both figures must have a base parallel to the ground. Biederman distinguishes four main attributes, that characterize geons: "three attributes of a cross section (curved vs. straight edges; constant vs. expanded vs. expanded and contracted size; mirror and rotational symmetry vs. mirror symmetry vs. asymmetrical) and one of the shape of the axis (straight vs. curved)". All of them are nonaccidental, i.e., can be perceived immediately and independently from the point of view, contrary to metric properties, that require more observer's attention and are easily miscalculated. There are also some nonaccidental relations between components like nature of join, which can be end-to-end or end-to-side (Figure 3.). Some exemplary geons differing from each other by non-accidental properties are presented in Figure 4.

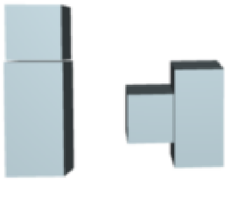

**Figure 3.** An end-to-end and an end-to-side relation between geons

**Figure 4.** Exemplary geons

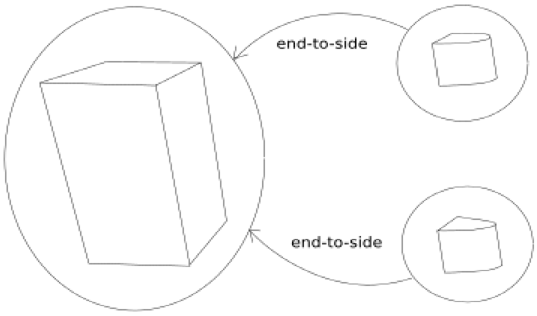


**Figure 5.** Graph representation of the building in Figure 2.

### 2.2. Graph representation

Structure of geons can be represented by a graph, as it is easy to manipulate and reflects relations between components. Figure 5. presents simplified graph of the building in Figure 2. The basic components – geons – are represented by graph nodes. Edges denote end-to-side relations between geons.

## 3. Structural Representation of Natural Forms

The presented methods of structural representation of architectonic objects do not seem sufficient for adequate representation of natural forms. Graphs representing relations between Biederman's geons in most cases are a satisfactory tool for describing artefacts, such as architectonic objects, which are usually a configuration of quite simple solids easily separated due to sharp concavities between each other. However, the problem occurs when natural forms are taken into account. Most of them are irregular, with plenty of repeating substructures (like e.g. cactus' spikes) and vague connections between geons.

### 3.1. Natural Forms Properties

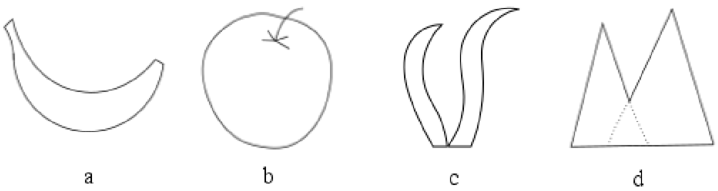


**Figure 6.** Relations in natural forms

It seems necessary to enrich Biedeman's perception model with new relations and attributes in order to represent more complex properties of natural objects. Let us consider natural objects presented in Figure 6. Smooth transition between a banana and its penducle (Figure 6a.) can be represented by a new attribute of an end-to-side relation – *smoothness* – representing lack of sharp concavities between geons. A spherical shape of an apple gives the impression of being deformed by a peduncle in Figure 6b. This led us to introduce a relation of *immersion,* in which one geon represents a simplified form of object's component and seems deformed by join with another component. A relation of two geons lying next to each other and aligned to a common plane, like aloe leaves in Figure 6c., can be defined by a *side-to-side* relation. Finally, *overlap* is another new relation between two geon nodes, indicating their superposition (e.g. overlaping mountains chain in Figure 6d.). These components reflect some natural forms' properties and can be applied for graph representation of architecture, which enables modification of a building solid described by a graph in order to imitate elements of nature. The methods of such modification are described further.

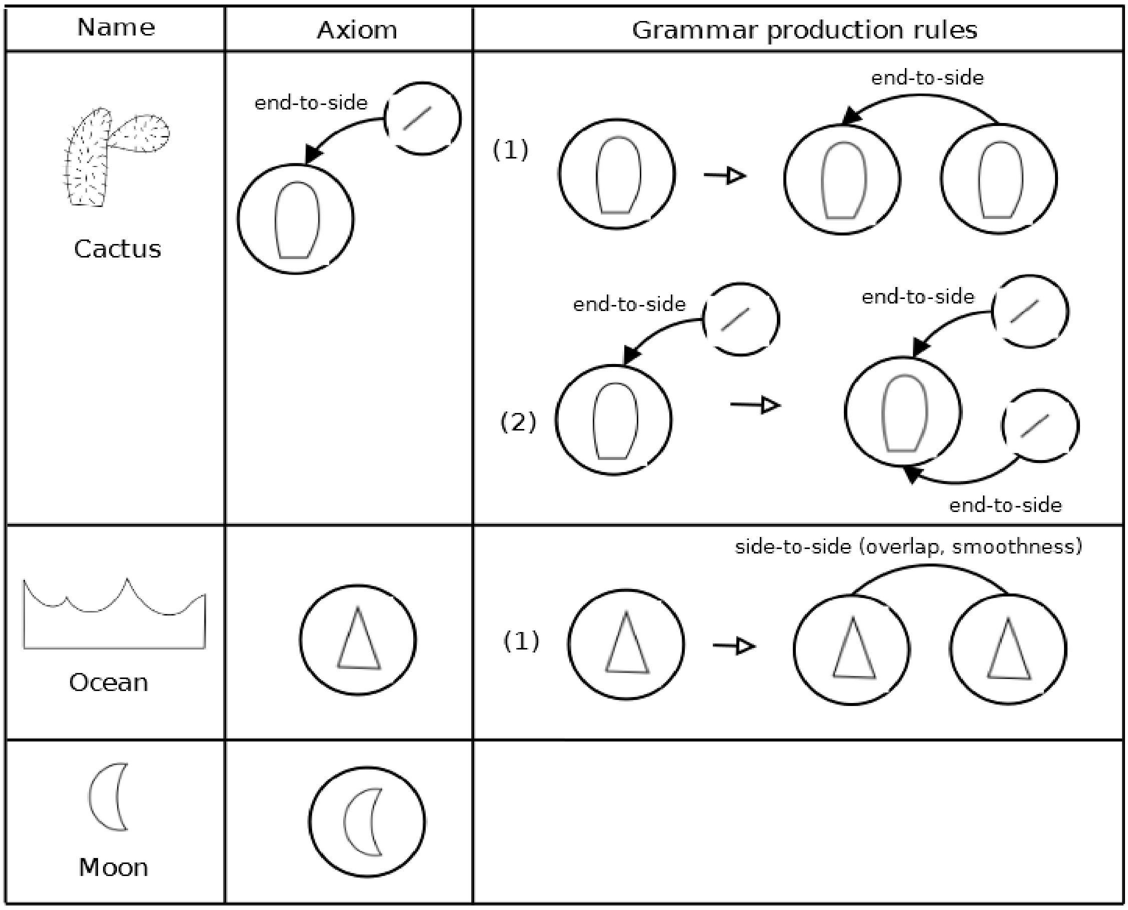


**Figure 7.** Graph grammars defining natural forms

### 3.2. Graph Grammars

We propose to use graph grammars as a generative tool in a knowledge base of natural forms. Natural structures very often consist of a number of similar elements or resemble fractals. Graph representations of such forms are very expanded and define only a specific instance – e.g., a cactus with one hundred spikes. In order to define the whole class of natural forms, like a species of cactuses, one can use a generative tool called graph grammar which provides a rewriting mechanism for graphs. It enables to replace subgraphs of a graph by applying the grammar rules called productions. A graph grammar contains an axiom describing a basic structure of an object and a set of productions enabling structural modifications, for instance expansion, i.e., adding multiple components of the same geon. Figure 7. shows an exemplary content of such a knowledge base with definitions of three natural objects – a cactus, an ocean and a moon. For clarity, graph matrixes have been presented as simplified pictures of graphs, with edges representing alignment relations only. Each natural form definition consists of a name, a graph grammar axiom and, if necessary, grammar production rules. The first row defines a cactus, with an axiom representing a plant having at least one leaf and at least one spike. Two production rules allow to multiply both axiom nodes in order define the whole class of cactuses, no matter how many leaves and spikes they have. The second row describes an ocean. Its axiom consists of a wave node, while one production rule enables to add the new wave nodes in a side-to-side relation attributed by overlap and smoothness. This results in a structure resembling a surface of a rough sea. The last definition regards a moon, which consists of a single geon with a curved axis and doesn't require any production rules.

## 4. Nature-Inspired Design

In the proposed nature-inspired design approach, the communication between a designer and a computer is performed through a design interface. The design interface allows the designer to create drawings representing early design solutions with the use of visual language with its vocabulary containing a set of geons. The design drawings are automatically transformed into their internal graph-based representations which enables to find similar graph patterns in the natural forms database and propose modification of the building structure to make it more similar to nature.

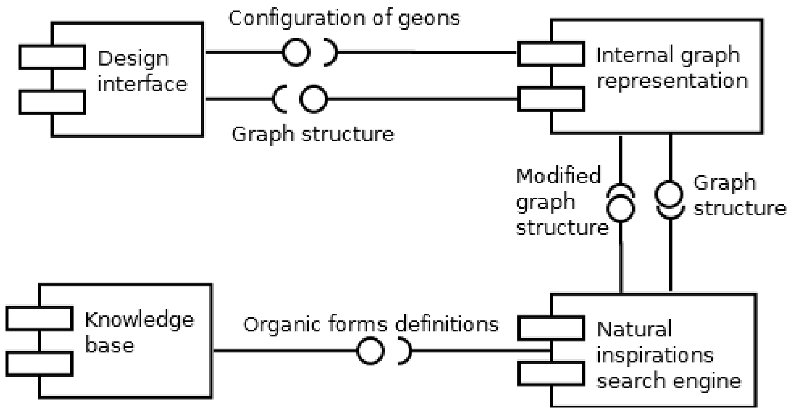


**Figure 8.** Nature-inspired design system components

Figure 8. presents a component diagram of the nature-inspired design system. The process of design consists of the following steps: in response to the user action – adding of a new component (geon) to the building structure, the project's graph is modified in the background. Further, the system knowledge base of natural objects is searched for the most appropriate axioms, i.e., those with a structure most similar to the project's graph structure. Once the natural forms with best-matching axioms are selected, it may be necessary to perform some production rules of the associated grammar in order to get a graph more congruent with the project's graph. Because the graph grammar may consist of more than one production rule, several production sets should be prepared and tested. Each production set must result in a final graph consisting of the same number of nodes as in the project's graph. In case of a large number of possible production sets for a grammar with many rules, it may be necessary to test only a limited number of them due to performance issues. In result of such selection

the best-matching final graph is chosen and mapped to the project's graph. This enables to perform some modifications on the project's graph – random attributes of nodes and edges are changed accordingly to the values of the attributes in corresponding entities of the natural form graph. Finally, the visualization of the modified building structure is created and presented to the user.
Let us come back to the building presented in Figure 2. Figure 9. presents the building's graph structure, as well as the resulting structure that has been obtained by its modification according to the cactus grammar (Figure 7.) The following operations have been applied:

1. The nodes have been mapped so as the main solid node of the building is associated with the cactus leaf node, while two balcony nodes are associated with spike nodes.
2. The main solid node attributes have been modified according to their corresponding leaf values – the cross section edges, as well as the axis type, have been changed from straight into curved.
3. The balcony nodes attributes have been modified according to the corresponding spike values, in which cross section size contracts.
4. Production rule 2 of the cactus grammar is used to create an additional component – another "spike".

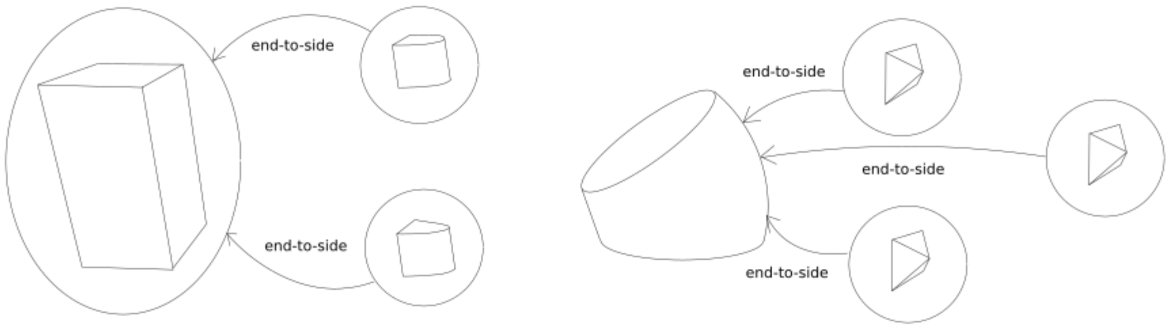


**Figure 9.** Nature-inspired modification of a graph structure

Figure 10. presents the visualization of the building modified by the system accordingly to natural inspiration.

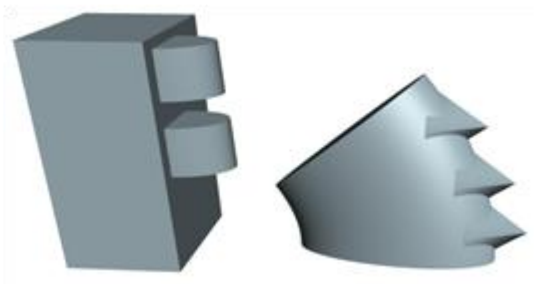

**Figure 10.** Visualization of structures in Figure 9.

## 6. Conclusion

The proposed nature-inspired design approach enables to find associations with natural forms which are not always obvious. This method can help the designer to find inspiration and perhaps create more interesting solutions. Application of graph grammars for generation of classes of natural objects is the novelty of this approach. Further work will concentrate on implementation of the described ideas as well as on expansion of the knowledge base structure – defining an ontology that will be used instead of the simple database in order to find more adequate solutions. This will ensure the nature concepts applied in the solid will be well associated with each other, to prevent a situation when one part of a building is inspired by e.g. a sea creature, while the other one by something completely different like a domestic plant.

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