Article

Establishing Analogy Categories for Bio-Inspired Design [†]

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Abstract: Biological systems have evolved over billions of years and cope with changing conditions through the adaptation of morphology, physiology, or behavior. Learning from these adaptations can inspire engineering innovation. Several bio-inspired design tools and methods prescribe the use of analogies, but lack details for the identification and application of promising analogies. Further, inexperienced designers tend to have a more difficult time recognizing or creating analogies from biological systems. This paper reviews biomimicry literature to establish analogy categories as a tool for knowledge transfer between biology and engineering to aid bio-inspired design that addresses the common issues. Two studies were performed with the analogy categories. A study of commercialized products verifies the set of categories, while a controlled design study demonstrates the utility of the categories. The results of both studies offer valuable information and insights into the complexity of analogical reasoning and transfer, as well as what leads to biological inspiration versus imitation. The influence on bio-inspired design pedagogy is also discussed. The breadth of the analogy categories is sufficient to capture the knowledge transferred from biology to engineering for bio-inspired design. The analogy categories are a design method independent tool and are applicable for professional product design, research, and teaching purposes.

Keywords: bio-inspired design; biomimicry; analogy; classification

1. Introduction

To create novel engineering solutions, a designer applies engineering principles as well as creative thought and intuition. Thus, engineering design is often viewed as both a science and an art. Analogical reasoning is commonly used in engineering design to provide a means for understanding new or abstract concepts by pointing out similarities to a known concept, such as using the analogy of building a brick wall to describe layering in 3-D printing [1]. Biological systems can provide engineering design inspiration [2–9]. Evolution has refined biological systems through billions of years of evolution and adaptation that can inspire innovative engineering solutions (e.g., self-heating and cooling buildings, Velcro©, digital displays viewable in bright sunlight, etc.).

Concept generation methods and tools help stimulate creativity during concept development and encourage exploration of the solution space beyond an individual designer's knowledge and experience [10–18]. Applying analogies across different engineering disciplines is common for engineers and is a standard strategy. Bio-inspired design, however, requires the designer to form analogies across subject domains, which often occurs by chance (e.g., story of Velcro©). The literature

defines two processes of bio-inspired design including problem-driven (top down) and biology-driven (bottom up) paths [19–23]. Regardless of the path, when analogies are applied it is recommended to use current knowledge to understand something new. Tools or methods that assist with identification and application of promising analogies are needed [21]. One existing method for using analogies is called "structure-mapping theory." It explains analogical reasoning as the process of identifying similarities in "relational structure from one system of knowledge (the source) onto a new system (the target)" [24]. This reveals two main challenges for analogy use: (1) identifying useful analogies; and (2) accurately matching the similarities from the base to the target concept.

Dahl & Moreau (2002) determined the conceptual distance between the source and target domain of the information used to establish an analogy can be classified as near- or far-field. Near-field analogies are considered within domain as the source originates from the same domain as the target, whereas far-field analogies are between domains as the source originates from a different domain than the target. Features tend to be similar for near-field analogies, and different for far-field analogies, which contributes to their effectiveness at driving innovation [25,26].

Research suggests that using far-field biological analogies is not an easy cognitive task. Multiple studies in bio-inspired design have found that observable biological features distract designers from abstracting the non-physical biological information [19,27–29]. Furthermore, one study found that the large conceptual distance of biological stimuli resulted in lower utilization rates because the attributes could not be easily transferred [30]. Investigation of bio-inspired design literature from the lens of design-by-analogy classified the current state of bio-inspired design research, and reported novices have a more difficult time recognizing or creating the analogies from biological systems, often falling victim to design fixation [31]. The fixation is on the observable aspects or surface-level attributes and causes a failure to identify the relevant analogy or the wrong information is mapped between the source and target.

A key challenge that impacts fixation is that biological systems follow the principle of "form follows function," meaning nature uses shape to define system functionality [32,33]. For example, bone cells provide structure and heart muscle cells expand and contract, thus cells have a diversity of size, texture, and shape based on their purpose [34]. The form and function dependency allow biological systems to be efficient, effective, and multifunctional without adding more energy or material to produce similar outcomes [35]. This is in opposition to how engineers are trained, which challenges their mental models. Furthermore, inspiration for overcoming technical problems in design exists at the levels of a biological system, from the scale of the cell, through to tissue, organ, and system. This multi-level complexity provides many more possibilities for analogies that can overwhelm a designer used to working on one scale of design. Thus, a tool or method for efficient and insightful access to biological analogies will support the use of bio-inspired design. Linsey and Viswanathan [29] suggest the creation of solution categories as well as encouraging thinking of higher-order relations over features to overcome the cognitive challenge of fixation. This research addresses both recommendations.

When used during engineering design, the effectiveness of selected analogies are assessed based on the successful mapping to the initial design task [36]. Analogies are used to transfer knowledge at multiple levels of information or abstraction including: direct transfer to a new context, transfer of structure, partial transfer of functionality, and analogy as a stimulus [36,37]. Analogical reasoning is also a subset of case-based reasoning, which has two main model classification schemes (e.g., direct transfer or schema-driven). Again, these schemes focus on the level of abstraction and not the relational context of the analogies [38,39]. Engineering design theory research points to the classifications of behavior, structure, and function, but no scheme or model exists for fostering and contextualizing the analogy with respect to the biological information transferred in bio-inspired design.

This research formalizes categories of analogy as a practical tool to address the issue of fixation as well as offer a model that guides learning and transfer of biological knowledge to solve a problem. It is hypothesized that proper understanding of the types of analogies available from biological systems

provides improved analogical reasoning during bio-inspired design. It is also posited that exposure to the full range of analogies possible from biological systems provides a rich and diverse opportunity for analogical transfer.

2. Analogy Categories

Several sources were analyzed to understand the knowledge transfer context from biology to engineering, including biology literature, bio-inspired design innovation literature, engineering design theory literature, and Biomimicry 3.8 Institute literature. The information from these sources was analyzed and synthesized into the seven analogy categories summarized in Table 1 [40].

Table 1. Analogy Category Definitions and Examples [40].

Category	Definition	Example
Form	Visual features including shape, geometry, and aesthetic features; external morphology	Mercedes-Benz bionic car inspired by fish body shape or a high speed train inspired by kingfisher beak
Architecture	How objects are interconnected or structured, geometry that supports the form; internal morphology	Woodpecker inspired shock absorption or pigment free color
Surface	Attributes that relate to topological properties; surface morphology	Sharklet Technologies anti-bacterial surfaces or gecko-inspired dry adhesive
Material	Attributes or substances that relate to material properties	PureBond Adhesive
Function	The actions of the system or what the biological system does; physiology	Termite mound inspired self-heating and cooling buildings or IR detection inspired by fire beetles
Process	Series of steps that are carried out; behavior	Photosynthesis based solar cells or locomotion for robotics
System	High level principle, strategy, or pattern; when multiple categories are present	Wind farm design inspired by schooling fish

Engineering design research has developed multiple taxonomies to represent physical artifacts. These representations usually span a hierarchy from the very abstract of behaviors to the components that fulfill specific behavior. Using the representations offered aids in developing a deeper understanding of the design task, which is necessary in the early stages of design [41–46]. Classes of function, structure (e.g., form), and behavior are engineering domain independent. Only a coarse equivalence can be made to representations of biological systems. Comparing the categories of representations demonstrates that artifact representations are less complex than the representations of biological systems. For example, consider the descriptions of behavior for an artifact and a biological system. An artifact's behavior is its interaction with its use environment. An artifact has no other purposeful actions. The behavior of a biological system includes instinctual actions of protecting, reproducing, and sustaining life, the behaviors needed to survive. What an artifact does as a complete system is intended behavior, otherwise known as function. An artifact's form is defined by physical characteristics. An artifact's components, geometry, architecture, and material, and their relationships, taken together are defined as form or structure. State transitions and functionality of the structure is defined as behavior. Research in compositional analogy points out that different information can be gleaned from shape and structure [47]. Shape is synonymous with form. Structure refers to spatial relations and is related to form. In short, biological systems are much more complex than physical artifacts as sources for analogy.

To understand categories of biological information, how biological systems fulfill the instinctual actions of protect, reproduce, and sustain life are considered. Morphology, physiology, and behavior

are the three biological classifications for coping with a changing environment [34,48]. Inherent in all biological systems is the need to obey instinct. Thus, a biological system will learn a new behavior, adapt a new form (morphology), or adapt new functionality (physiology). Functions of living systems, sub-systems, and their parts are defined as physiology. Form, geometry, and shapes of living organisms, and the relationships between them, are defined as morphology. The way a biological system reacts in response to a stimulus is defined as behavior. In general, these three biological classifications align with the domain independent classes found in engineering design literature.

The Biomimicry 3.8 Institute [32,49] classifies biological information for inspiration as systems, processes, and forms. These three classes of natural models are considered during discovery of inspiration to be abstracted. Three-dimensional shapes are defined as forms. The biological method of producing an outcome or object is defined as process. The parts that interact within or are associated with multiple aspects of the biological system is defined as system. Biological system complexity is also acknowledged in the AskNature database [50] as entries represent a range of scales (e.g., systems level, macro scale, nanoscale).

The engineering design theory, Biomimicry 3.8 Institute, and biology literature point to the categories of system, process, function, form, and architecture. Books that survey innovations related to bio-inspired design [2,51–60] not only reinforce these categories, but also point to the categories of surface and material. Biological inspiration from structures, geometries, forms, surfaces, and chemical substances were the most common in the reviewed books. Thus, the categories of surface and material are significant sources of inspiration in bio-inspired design. The reviewed books also provided innovations inspired by biological systems, processes, locomotion, patterns of movement, functions, and patterns of geometry.

Table 1 provides the definitions and examples from literature of the seven proposed analogy categories of bio-inspired design. What the system is designed to do or does as a result of its design is a functional analogy. In mechanical engineering, function is the subset of intended behaviors, while behavior encompasses an artifact's environmental interactions. The description of how objects are structured or interconnected is an architecture analogy, whereas a form analogy is related to external geometry or aesthetics. The texture or topology of an object's surface, at any biological scale, is a surface analogy. Biological substances or substrates result in material analogies. A sequence of actions, such as navigation, fabrication, or communication, is a process analogy. The essence of a biological system, a characteristic associated with the whole such as a pattern, or a combination of the other categories, is a system analogy.

The analogy transfer categories are not mutually exclusive. Form, surface, architecture, and material are related as they focus on physical characteristics, and often answer the "how" of the non-physical characteristics of system, process, and function. The surface, architecture, and material categories are more detailed physical characteristics of form. The breakdown of physical and non-physical characteristics and their relationships is supported by current literature on innovations related to bio-inspired design as well as engineering design theory literature. Analogies can be identified at each biological level (i.e., cell, organ, ecosystem, etc.), thus understanding how biological knowledge is interrelated and transferable offers a designer insight on how to manage the non-engineering domain information such that it can best aid the design process.

Prior work on knowledge transfer in bio-inspired design supports the proposed analogy categories as shown in Table 2. Mak and Shu [61] defined a hierarchal classification of the biological phenomena descriptions excerpted from a biology textbook and used in their study. Principle is at the top of the hierarchy followed by behavior and form, in that order. Moving up in the hierarchy answers questions of why from the previous level, while moving down answers questions of how. Chakrabarti's et al. defined five analogical transfer abstraction levels based on the analysis of 20 bio-inspired design case studies in literature using the State-Action-Part-Phenomenon-Input-oRgan-Effect (SAPPhIRE) model of causality [21,62]. The five levels identified are attributes, organs, parts, state changes, and resulting transfer. Attributes and organs are properties not associated with physical effects.

Parts are the physical components and interfaces. State changes are descriptions of interactions or behaviors. The resulting transfer captures analogies not correlated to SAPPhIRE, thus is not included in Table 2. This comparison shows analogical reasoning occurs with physical and non-physical biological characteristic information in bio-inspired design. Furthermore, Table 2 demonstrates that the proposed categories could serve as a unifying categorization across bodies of research and are applicable regardless of design method preference.

Table 2. Analogy Categories Compared to Supporting Work.

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

Multiple process models for bio-inspired design exist and vary depending on the tools used, level of automation involved, theory basis, or the intended audience. A generic process for bio-inspired design, irrespective of theory basis and audience, is given in Figure 1 [21]. This generic process model includes the fundamental steps that are necessary to start from a problem and arrive at a conceptual design that meets the needs of the problem. Similar to bio-inspired design tools supporting knowledge transfer such as the four box method [63] or causal relation templates [64], the analogy categories are recommended for use during the analyze and transfer steps. Using the categories during these steps assists with establishing deeper biological knowledge, which helps to overcome fixation on observable physical characteristics so that associated principles can be transferred. Moreover, as a design method independent tool, they can be used with multiple bio-inspired design methods (e.g., function-based design, concept-knowledge theory, Biomimicry Institute).
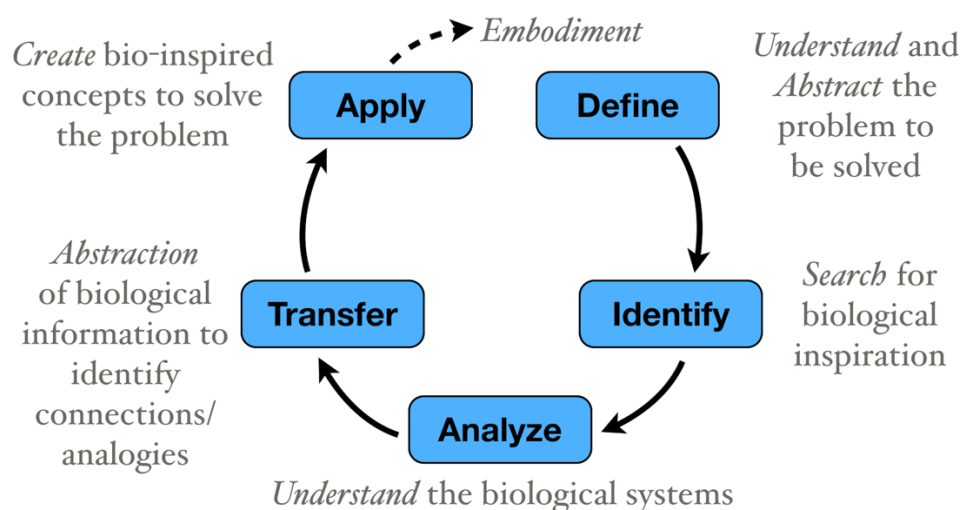

Figure 1. Generic Bio-inspired Design Process.

The advantages of the analogy categories are:

- fostering and contextualizing the analogy with respect to the biological information transferred in bio-inspired design;
- providing direction for recognizing the different information a biological system may provide when forming analogies for artifact design;

- encourages learning about the variety of biological system characteristics to push designers beyond fixating on the obvious knowledge; and
- applicable for professional product design, research, and teaching purposes.

3. Materials and Methods

This work consists of two studies to explore the use of the analogy categories in bio-inspired design. The first study analyzed the analogies used in commercialized products. The second study investigated analogies used to generate a design inspired by a particular biological system: a terrapin turtle. A control group was asked to complete their design using simple information about the turtle. The experimental group had the same task but was given the analogy categories as depicted in Table 1. In both studies, analogies were characterized using relational predicates of the base analogy similar to the approach by Gentner and Landers [1]. The following subsections review the studies. While the categories are recommended for use during biological system analysis and transfer as in the study with a control and experimental group, they are also applied in both studies to analyze the knowledge transferred.

3.1. Analogy Study of Products in a Database

The analogy study of products in a database surveyed the commercialized products found in the AskNature database, the largest publicly accessible database of biomimicry information. Because the database is an open source project and community, entries can be of published research, commercial products, or simply a great idea. Only products in the AskNature database that were sponsored by a company were chosen for application and analysis. This is to ensure an adequate level of information about the bio-inspired product is given. Often is the case that a product is protected through a trademark, copyright, or patent before going to market, and once it does make it to market, the technology or any unique features, such as bio-inspired design, are heavily advertised.

The categories of analogical transfer were applied to the identified commercialized bio-inspired products in the AskNature database. The database entry for each product was analyzed and characterized. Analogies were identified through analysis of the written descriptions and images were used as supplementary information to verify the characterization. For example, the description of the Mirasol™ display technology states, "Wing scales diffract and scatter light," which is characterized as the analogy of architecture. This characterization was further supported by the provided image of the butterfly wing. Additionally, the statement, "These highly developed structures reflect light so that specific wavelengths interfere with each other to create nature's purest, most vivid colors" explains how the structure of the wing scales supports the function of color modulation. Thus, the product is characterized by the analogies of architecture and function.

3.2. Analogy Study of Student Work

The study of student design work includes data collected from twenty-four subjects participating in Engineering Design Methods, a graduate engineering course taught by Schmidt. Participants included students pursuing both research-based and terminal master's degrees in mechanical engineering. A small number of professional engineers were part of the groups. Students in the course have diverse mechanical engineering research interests (e.g., robotics, automotive engineering, micro-electromechanical systems (MEMS), and thermal fluid sciences). The Engineering Design Methods course provides instruction in multiple methods of performing engineering design and contemporary philosophies of design. All participants (N = 24) consented to allow their work to be included as data in this study. The students were randomly divided into two equal sized groups of twelve (N = 12).

A design task of creating a "Terpee" was given to students as homework in the second week of the course and was due one week later. The design task required the students to create the idea of a product called a "Terpee" (in reference to the University of Maryland mascot the terrapin turtle).

The Terpee had to fulfill a list of design requirements and constraints. The assignment was introduced to the students through a YouTube video (http://tinyurl.com/terpie-video) of a Carolina diamondback terrapin. This short video displayed the terrapin body. A view from the top down showed the shell, scute pattern, the head, and all limbs. The video also displayed the terrapin walking through the grass, and retracting and extending limbs. This suggests that all students had a view of the form of the terrapin and of some functions. Also, some form and function details of the terrapin are common knowledge to students. For example, students "know" that the shell provides the function of protection to the inside of the turtle. The hypothesis of this study was that the Terpee designs of students who had descriptions of the analogy categories given in Table 1 would be inspired to use analogies from these categories in addition to "form" analogies. This would imply that knowledge of multiple analogies possible from biological systems would lead to the use of less obvious analogies.

The wording of the design task was as follows: "Design a commercial personal convenience product that will be marketed in Brookstone-type stores and catalogs." The requirements and constraints given for the device were as follows:

- This product must be based on some characteristic of the terrapin turtle.
- This product must meet a need that is common to middle-class adults in the USA.
- This product must serve a need that is unmet by any current product of this size.
- It must be small enough to be stored in a 12 fl. oz. soda can.
- It must not need a sophisticated computer control system. It may make use of a small on-board computer on a chip.
- It must retail for under $150.

Students had the additional instruction to "Record all your notes and sketches during the work you do on this assignment. Upload scanned copies of all of the pages you use leading up to and including your final design page which has labeled sketch(es) of the design and a written description of how it accomplishes its purpose." The assignment records show that students generated lists of terrapin characteristics as part of their evaluation process for choosing what to focus on during concept development.

All materials submitted for the Terpee assignment were analyzed. The emphasis of the review was characterizing the category of each analogy used in the design process of each student. The analogies appeared in the form of written notes such as "The phone case is hard like a turtle's shell." or in sketch form as seen in Figure 2a. Figure 2a is the final Terpee design of a soap dish that displays the shape of a turtle. This was the work of a student in the control group. The design was characterized as being a form analogy focused on "general turtle shape." Figure 2b is the final Terpee design of a multi-tool (like a type of army knife). This student was part of the experimental group and received information on the variety of analogies from biological systems. Several analogy transfers from the terrapin turtle to the Terpee can be referenced in the design. They include (1) the head and stylized face of the Terpee are form analogies; (2) the multi-tool tools are stored inside the Terpee body and deployed when needed derived from the notion of retractable limbs, which is a function category analogy. The Terpee designs in Figure 2a,b are representative of products designed in the control and experimental groups, respectively.

Every recorded instance of an analogy was recorded and identified using the categories in Table 1. These included analogies appearing in design notes made before the student's final design was described. Two authors coded the analogy categories. A score on the inter-coder reliability test indicated that the reliability was good.
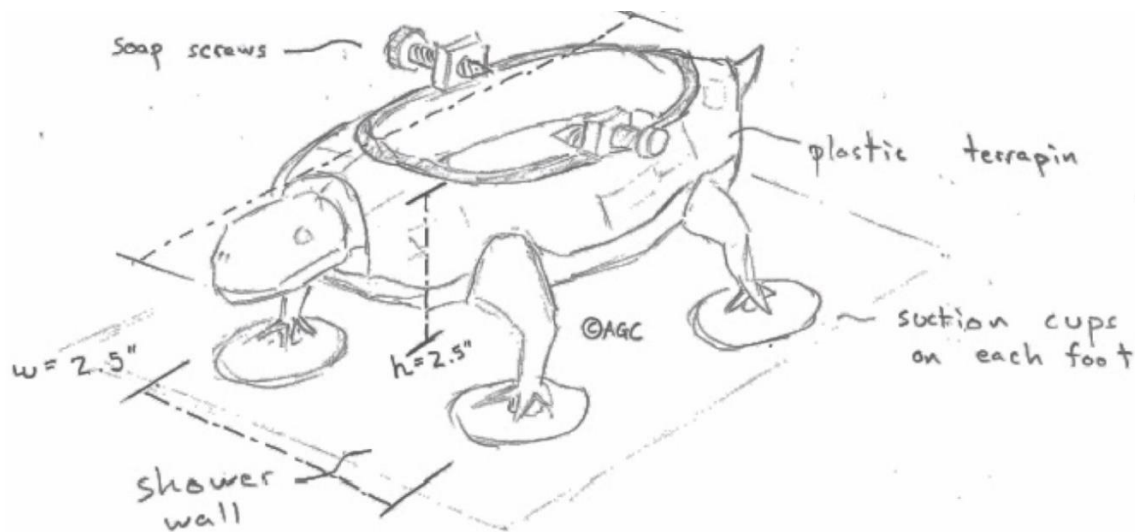
(**a**)
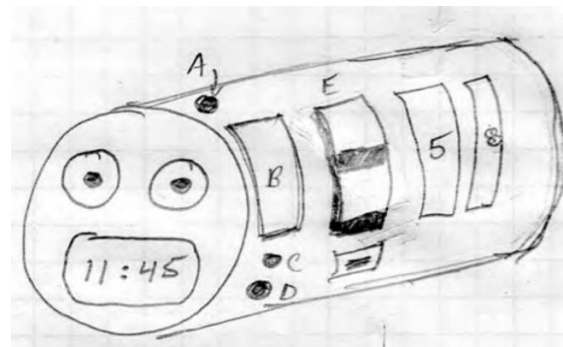
(**b**)

Figure 2. Excerpts from the analogy study of student work: (**a**) an example from Student 2 in the control group, and (**b**) an example from Student 12 in the experimental group.

4. Results

The results of both studies offer valuable information and insights into the discovery of non-conventional solutions to engineering problems. Presented in the following subsections are the results of both studies.

4.1. Database Products Study Results

Twenty-four (N = 24) commercialized, bio-inspired products were identified for analysis. Table 3 provides the list of products analyzed along with summary information about the inspiring biological system. All categories of analogical transfer were represented across the 24 products analyzed. The category of function was the highest represented analogy in the products at 67%, while material was the least represented category among the set at 13%. Biological form and function are often highly coupled, which is not always the case in engineering. Understanding biological function offers insight into the purpose of the observable, physical characteristics and can assist with establishing analogies between the biology and engineering domains. Interestingly, three biological systems (morpho butterfly, bull kelp, and sacred lotus) offered multiple analogies that resulted in different products, including different products from the same inspiration. For example, the way morpho butterfly wing scales diffract and scatter light inspired digital display technology and color-shifting paint.

Table 3. Analogy Categories Applied to Commercialized Products in the AskNature Database.

Product Name	Inspiring Biological System(s)	Specific Inspiration	Form	Surface	Architec.	Material	Function	Process	System
Mirasol™ display technology	butterfly	wing scales diffracting/scattering light			X		X		
μMist® Platform Technology	bombardier beetle	combustion chamber sprays scalding liquid					X		
All PAX Scientific Technologies	bull kelp	spiral-shaped flow	X				X		
i2™ Modular Carpet	forest floor	pattern diversity	X				X		X
PureBond® technology	blue mussel	sticky proteins				X	X		
Tubercle Technology blades	humpback whale	flippers providing lift	X				X		
Lotusan® paint	morpho butterfly	self-cleaning wing surface		X			X		
	sacred lotus	hydrophobic self-cleaning surface							
Biolytix® water filter	soil ecosystem	multiple organism ecosystem						X	X
ORNILUX	orb-web spider	spider silk	X			X	X		
ChromaFlair Color-Shifting Paints	morpho butterfly	wing scales diffracting/scattering light			X		X		
bioSTREAM™ tidal energy	yellowfin tuna	efficient propulsion system					X		X
GreenShield™ fabric finish	morpho butterfly	self-cleaning wing surface		X			X		
	sacred lotus	hydrophobic self-cleaning surface							
Sharklet AF™	shark	skin inhibits microbes		X			X		
Joinlox™	clams/shellfish	mechanical method for joining components	X				X		
Eco-Clad® anti-fouling paint	fish	drag reducing slime				X		X	
SunPoint Technologies Inc. solar tracker	sunflower/plants	tilting towards the sun					X		
Nikwax® Directional Fabrics	fur from living in cold, wet climates	repelling water; pushing water vapor and liquid away from the body				X	X		
Fog-harvesting mesh	namib desert beetle	water vapor harvesting		X			X		
Byetta® and Bydureon® diabetes injections	gila monster	saliva regulates digestion					X	X	
BioMimics 3D™ stent technology	cardiovascular system (human)	helical geometry of the arterial system				X			
BioHaven® floating islands	wetlands	ecosystem functions							X
Flat Rainshower from Moen®	bull kelp	spiral-shaped flow patterns							X
Power Plastic® solar cell technology	cooke's koki'o	photosynthesis						X	
TX Active® cement	microbes	dealing with toxins via oxidation						X	
		Total	5	4	4	3	16	6	5

In 71% of the products, multiple categories of analogical transfer were present, which signifies that analogical transfer in bio-inspired design is complex. Fifteen, or 63%, of the products relied on physical characteristic analogies. All but one instance of single analogy inspiration was based on a non-physical characteristic of function, process, or system. From this analysis, it is evident that the majority of products that were considered bio-inspired and unique enough to commercialize did not rely on physical characteristic-based analogies alone. All but one product that utilized an analogy based on a physical characteristic (form, surface, architecture, material) also utilized an analogy based on a non-physical characteristic (function, process, system). Furthermore, this study demonstrates that the breadth of the analogy categories is sufficient to capture the knowledge transferred by analogy to a new target needed for bio-inspired design.

4.2. Student Work Study Results

The Terpee design task provided data on student use of bio-inspired analogies. Results are summarized in Table 4 and in Figures 3 and 4. The portfolio of products, given in Table 4, proposed by all participants had only two duplications. In addition, there were no duplications in the control group or the experiment group. This result may be surprising to some considering the narrow assignment. This can be explained by the number and variety of terrapin characteristics available as inspiration.

Table 4. "Terpee" Product Concepts.

Control Group		**Experimental Group**	
Student	**Product**	**Student**	**Product**
1	Miniature Safe	1	Card Holder
2	Soap Holder	2	Multi-Tool
3	Multi-USB Charger	3	Bottle Opener
4	Lumbar Back Support	4	Hidden Camera
5	Universal Phone Case	5	Phone Case
6	Handheld Massager	6	Charging Device
7	Screw Removal/Storage Tool	7	Diver Pocket Watch
8	Projector	8	Aquatic Item Retriever
9	Travel Companion	9	Computer Mouse
10	Miniature Stove	10	Water-Proof Phone Case
11	Portable Wireless Router	11	Water-Proof Flashlight
12	Hidden Camera	12	Multi-Tool/Puzzle

A simple reading of the Terpee product list shows some difference in complexity. The control group suggested projects that were heavily based on only form analogies and were less sophisticated designs. Many of the products conceptualized by the control group were devices that simply mimicked a turtle's aesthetics or physical characteristics to no functional benefit, rather than truly utilizing the turtle as a source of design inspiration. Three of the more complex products are found in the experimental group including the multi-tool (Figure 2b), diver pocket watch, and the aquatic item retriever.

Figure 3 presents a list of the different analogies used by the student groups. The analogies are classified by the categories given in Table 1. Major observations of the stacked bar chart are as follows:

- There were 26 different analogies identified across the categories by students as a whole group. If the same analogy was repeated in the work of a student, it was only counted once.
- The counts indicate the number of each analogy considered by a student. For example, the most used analogy was the turtle shell at 18 instances. This means the shell as an analogy was identified by 18 out of 24 participants.
- Large proportions of participants explored form analogies. Forty percent (40%) of participants considered head analogies; 37.5% considered analogies based on the limbs; and 33.3% of participants considered the overall turtle shape.

- Nearly half of participants (45.8%) identified function category analogies during their design. The function analogies were protection, retraction of limbs, and movement (speed). Two or three of these functions can be considered as "common knowledge" about turtles so they are remembered without any special research into turtle biology.
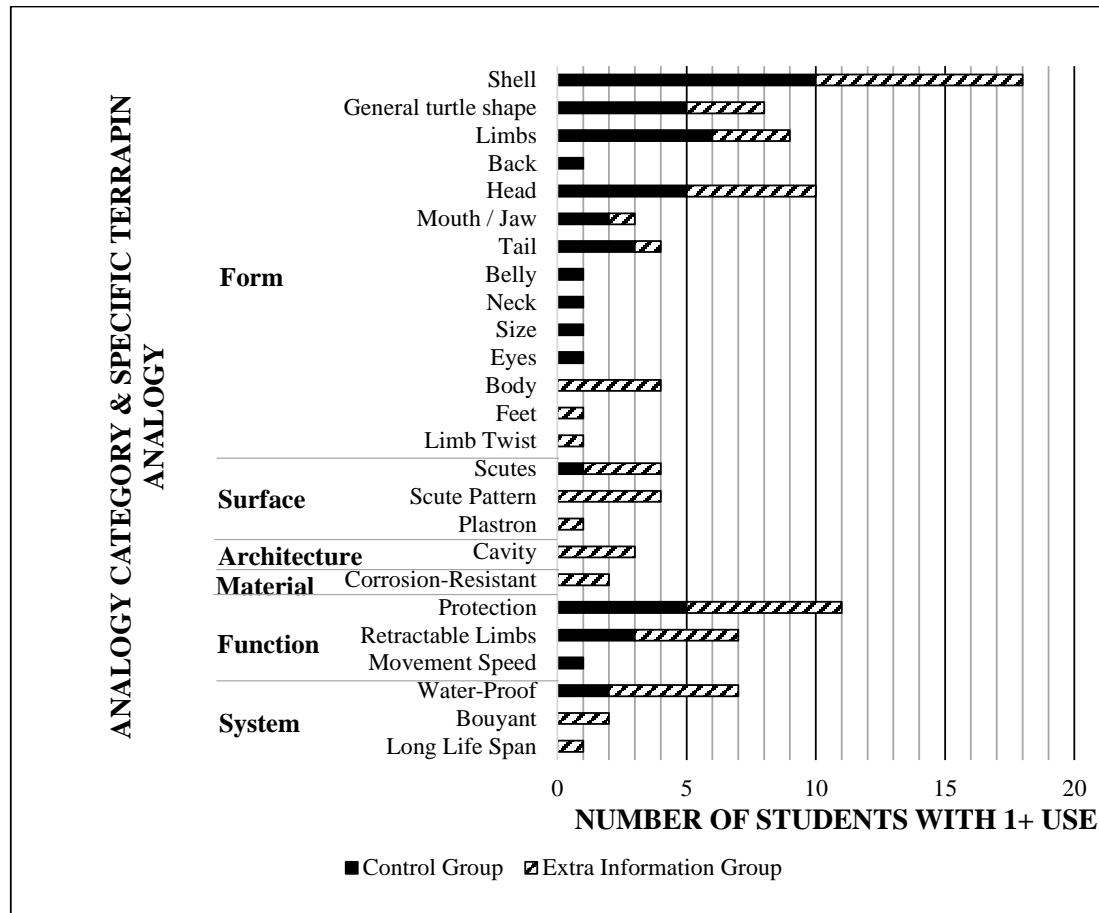

Figure 3. Analogy usage across all study participants. Specific terrapin analogies are grouped based on analogy categories found in Table 1.

Figure 4 presents the total number of instances an analogy is reported in the Terpee assignment. For example, if the analogy to the form of terrapin shell was recorded four times, it was counted four times. The number of times an analogy was noted indicated the frequency that the student was *thinking about the analogy*. The data in Figures 3 and 4 provide more observations on the different uses of analogy between the two groups. Major observations from the two Figures are as follows:

- Students in the control group considered about 3.5 *different* categories of terrapin analogies while students in the experimental group considered about 4.5.
- Nine of the 26 analogies in Figure 3 were exclusively identified by participants of the experimental group. The analogies were: form-body, feet, and limb twist; Surface—scute pattern and plastron; Architecture—internal cavity; Material—corrosion resistance; and System—buoyant and long life-span.
- The control group averaged 8.7 total analogies per proposed product, while the work done by students in the experimental group averaged 13.4 total analogies, over a 50% increase.
- The control group noted form analogy categories 75% of the time in their work. Students in the experimental group had only 47%.

- There was practically no difference in the function category of analogies noted. This might be attributed to common knowledge of some turtle functions, including protection and retractable components, or perhaps attributed to their training as engineers, which is a discipline that values the use of function in design.
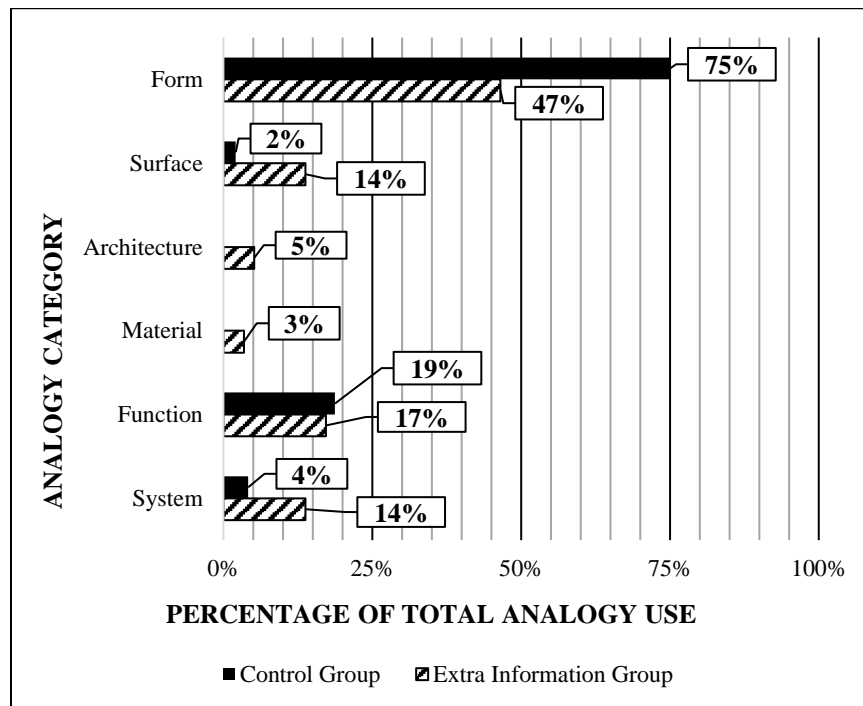

Figure 4. Population of analogy category breakdown for both groups.

5. Discussion

The results of both studies confirm that compound analogy, i.e., multiple analogies contained within a single solution, identified by Vattam et al., is a fundamental process of bio-inspired design [65,66]. Furthermore, the analogy categories provide an approach to characterizing the compound analogy, which offers insight into how to achieve biological inspiration versus biological imitation. Imitation often results from copying observable aspects, as shown with the control group from the student work study. Inspiration involves learning from nature rather than copying, as shown with the experimental group from the student work study and the commercialized product study.

Results from the study on commercialized products indicate that (1) biomimetic innovation is not based on observable form-based or physical characteristics alone, and, in most cases, involves the transfer of physical and non-physical characteristics; (2) understanding biological function is key as it provides purpose to the physical characteristics, which are often highly coupled; (3) a single biological system can offer multiple analogies that result in different products including different products from the same inspiring biological system; and (4) the breadth of the analogy categories is sufficient to capture the knowledge transferred via analogy from biology to engineering for bio-inspired design.

Results from the study on student work indicate that (1) students seem to readily identify and transfer form-based or physical characteristics to their designs, which is consistent with the literature; (2) a single biological system embodies multiple characteristics and behaviors that can serve as analogies for transfer to a new concept that result in different engineering inspiration for design; (3) biological information from multiple categories can be transferred during concept generation; and (4) anecdotal evidence exists that non-physical characteristics may inspire more sophisticated engineering concepts than those based on physical characteristics alone.

Results of the experiment can be compared to prior work. The BioM Innovation Database catalogs products that are labeled as inspired by biological systems [67]. BioM includes just under 400 cases

and classifies the cases by their developer, point in their product lifecycle (i.e., prototype, commercially available, etc.), and their biological inspiration. In BioM, 61.8% of product designs displayed analogies based on physical characteristics and half of those included only physical characteristic analogies. This result indicates the surface nature of transfers of biological phenomena in product development and is similar to the trends we saw in the studies. These trends are also an indicator that better methods are needed to facilitate analogical reasoning for bio-inspired design.

Biological systems have evolved into complex yet elegant systems that exhibit multi-functionality, highly coupled form and function, and multifaceted behaviors necessary to fulfill the existence imperative and the multi-scale physical nature of living organisms. Thus, the possibilities for analogical transfer are equally rich and diverse, and are what we see in the student work when given extra information and the commercialized products. Multiple category transfer is possibly attributed to the complexity of biological systems, where it is hard to isolate certain inspiring features, as well as exposure to the categories of analogy. The analogy categories capture the diversity or the context of the analogical transfer, as well as push designers to consider biological characteristics beyond what they can see.

To assist with explaining the fourth observation from the study of student work, we look to the work of Gentner. Gentner and Landers [1] used structure-mapping theory to identify types of analogy to identify corresponding objects in the base to objects in the target. Three types of analogical correspondence are identified: *true analogy* in which all higher order relations (e.g., causal, temporal, and functional) between objects of the base are mapped to objects in the target; *mere-appearance* match in which object attributes are mapped to the target; and *literal similarity* in which some objects attributes and some relations are mapped.

Considering the classification established by Gentner and Landers, the analogy categories of Table 1 can be correlated as follows. True analogies are identified using the transfer of non-physical attributes, such as those of the function, process, or system analogy categories. With respect to the terrapin, inspiration drawn from the act of fighting dehydration goes beyond the obvious characteristics and results in a higher order relational transfer. Only four projects (or 33.33%) of the control group were true analogies in this sense, as opposed to seven projects (or 58.33%) from the experimental group. Mere appearance analogies are identified by the transfer of physical attributes, such as form, material, surface, or architecture. Creating a product design that looks like a turtle with four limbs, a head, a tail, and shell, but does not embody any other characteristics of the biological system, would be considered mere appearance. The majority of the control group (N = 8 or 66.67%) created concepts that can be classified as mere appearance transfers, while less than half (N = 5 or 41.67%) of the extra information group did likewise. If, however, the turtle was mimicked by its physical characteristics, functions, and processes, such as creating a robotic turtle, then the result would be considered a literal similarity. Literal similarity analogies are identified by directly copying physical and non-physical characteristics and typically results in the product looking and acting like its source of inspiration. This type of analogy is most commonly seen in artificial organs. No students in this data set created literal similarities.

5.1. Best Practices for Bio-inspired Design

The research findings of the present studies have the potential to influence how bio-inspired design is practiced.

Best Practice 1—Inspiration is derived from a diverse set of biological system physical and non-physical characteristics. Inexperienced designers performing bio-inspired design tend to focus heavily on physical characteristics of a biological system or copying what can be observed at a macro level. The study results in this paper and in prior work support this claim. Often this approach results in solutions that look like or act like the biological system, which are not true analogies. Thus, guidance on exploration of biological systems at deeper levels to truly learn about the biology is needed. As evidenced by our study of student work, simply providing information

regarding multiple inspiration categories resulted in a significant decrease in the fixation on physical characteristics. Although biological form and function are coupled, the bio-inspired solution does not have to be visually like what inspired it. Only considering the biological morphology or form results in a mere appearance analogy and not a true analogy. Therefore, it is possible, and desirable, to consider non-physical biological characteristics, or to consider them in combination with physical biological characteristics.

Best Practice 2—Consider a range of information about familiar biological systems to uncover the less obvious information. The mindset that there is a "right" biological system for solving the design problem can cause endless searching until the information causes spontaneous idea generation. Often paired with this mindset is the inspiration must be from an uncommon biological system, or one that has not been used for bio-inspired design already. As shown by both studies these misconceptions are unfounded. Student Terpees inspired a wide variety in products inspired by the terrapin turtle. A single biological system can and has provided multiple sources for analogical reasoning that have led to multiple different engineering solutions. Working across the domains is challenging in and of itself. Knowing that it is not necessary to search for an uncommon, unique, or right biological system can lower the hurdle to learning non-engineering domain knowledge as well as the associated application. Using the analogy categories, a designer can consider familiar biological systems from different analysis perspectives and the less obvious information can be found.

Best Practice 3—Utilize tools that address issues during certain steps in the bio-inspired design process. Biological systems are not the first source of design ideas for practicing engineers. Applying biological inspiration to engineering problems requires the creation of far-field analogies, which is a complex cognitive process. Tools, however, have been researched and developed for addressing a range of issues encountered during bio-inspired design and are available to aid a designer seeking bio-inspired solutions. Some tools, like the one in this paper, can be applied independently of the design method. The tool presented in this paper aids in guiding analogy formulation and application that fosters bio-inspired solution generation.

5.2. Future Work

Future work includes performing additional design studies and the development of a metric to assess bio-inspired designs. Future design studies will include engineering professionals and engineering students at other institutions. The studies and analysis will focus on understanding analogical reasoning differences between biology-driven and problem-driven solutions. Correlations to the type of problem being solved will also be investigated. Additional future work includes using the analogy categories to create a metric of biomimicry to evaluate the level of inspiration versus imitation of bio-inspired designs. The number and type of analogy transfers could lead to a quantifiable metric of biomimicry.

6. Conclusions

Nature provides a rich set of biological systems that have evolved over billions of years to adapt to changing conditions and can be learned from to inspire engineering innovation. Consequently, a diverse set of analogies from the domain of biology as well as from a single biological system have been used to aid in solving technical problems. The analogy category model established in this paper captures this diversity and provides insight on analogical transfer during bio-inspired design. Connections occur across multiple categories, resulting in a variety of analogical mappings, which can be influenced by alignment with mental representations or mental models [25]. Mental models influence the level of abstraction that designers use when transferring knowledge across domains. We cannot explain why certain analogy categories were dominant over others with respect to the student projects; however, the data shows that when guided to explore both physical and non-physical characteristics, students fixated less on the physical characteristics, and made more less-obvious or unique analogical transfers from biology to engineering. As compared to the control group,

the experimental group given the extra information on analogy categories made wide use of analogy to convey their ideas and design intentions in a more powerful manner. Simply providing the information in Table 1 resulted in a significant decrease in the reliance on biological physical characteristics. Thus, the experimental group given extra information generated concepts that more closely resembled biological inspiration, learning from nature to innovate rather than copying, whereas the control group concepts more closely resembled biological imitation.

Design inspiration can be derived from a diverse set of physical and non-physical characteristics of biological systems. Often a single biological system can lead to multiple analogies that result in different engineering solutions. Without guidance on knowledge transfer through analogy it can be said that bio-inspired ideation is left up to chance, which points to the need for more predictable and successful means to identify and apply promising analogies. The analogy categories established here address this need. They not only demonstrate the breadth of analogy transfers possible from biology to engineering, but also assist with making those analogies more accessible. While the categories are recommended for use during biological system analysis and transfer, they can also be used for design analysis purposes. Furthermore, the analogy categories are envisioned as a design method independent tool for facilitating transfer or understanding the transfer of diverse analogical knowledge between domains to facilitate bio-inspired design.

References

1. Gentner, D.; Landers, R. Analogical reminding: A good match is hard to find. In Proceedings of the International Confernece on Systems, Man, and Cybernetics, Tucson, AZ, USA, 12–15 November 1985.
2. Bar-Cohen, Y. *Biomimetics Biologically Inspired Technologies*; CRC/Taylor & Francis: Boca Raton, FL, USA, 2006.
3. Brebbia, C.A.; Collins, M.W. *Design and Nature ii: Comparing Design in Nature with Science and Engineering*; WIT: Southampton, UK, 2004.
4. Brebbia, C.A.; Sucharov, L.J.; Pascolo, P. *Design and Nature: Comparing Design in Nature with Science and Engineering*; WIT: Southampton, UK; Boston, MA, USA, 2002.
5. Brebbia, C.A. *Design and Nature iii: Comparing Design in Nature with Science and Engineering*; WIT: Southampton, UK, 2006.
6. Brebbia, C.A. *Design & Nature iv: Comparing Design in Nature with Science and Engineering*; WIT: Southampton, UK; Boston, MA, USA, 2008.
7. Brebbia, C.A.; Carpi, A. *Design & Nature v: Comparing Design in Nature with Science and Engineering*; WIT: Southampton, UK; Boston, MA, USA, 2010.
8. Nagel, J.K.S.; Stone, R.B. A computational concept generation technique for biologically-inspired, engineering design. In *Design Computing and Cognition DCC'10*; Gero, J.S., Ed.; University of Stuttgart: Stuttgart, Germany, 2010.
9. Nagel, J.K.S.; Nagel, R.L.; Stone, R.B.; McAdams, D.A. Function-based, biologically inspired concept generation. *AIEDAM* **2010**, *24*, 521–535. [CrossRef]
10. Dieter, G.E.; Schmidt, L.C. *Engineering Design*, 5th ed.; McGraw-Hill: New York, NY, USA, 2013.
11. Cross, N. *Engineering Design Methods: Strategies for Product Design*; John Wiley & Sons: Chichester, UK, 2008.
12. Dym, C.L.; Little, P. *Engineering Design: A Project-Based Introduction*; John Wiley: New York, NY, USA, 2004.
13. Hyman, B. *Engineering Design*; Prentice-Hall: Upper Saddle River, NJ, USA, 1998.

14. Pahl, G.; Beitz, W.; Feldhusen, J.; Grote, K.H. *Engineering Design: A Systematic Approach*, 3rd ed.; Springer-Verlag: London, UK, 2007.

15. Otto, K.N.; Wood, K.L. *Product Design: Techniques in Reverse Engineering and New Product Development*; Prentice-Hall: Upper Saddle River, NJ, USA, 2001.

16. Ullman, D.G. *The Mechanical Design Process*, 4th ed.; McGraw-Hill, Inc.: New York, NY, USA, 2009.

17. Ulrich, K.T.; Eppinger, S.D. *Product Design and Development*; McGraw-Hill/Irwin: Boston, MA, USA, 2004.

18. Voland, G. *Engineering by Design*, 2nd ed.; Pearson Prentice Hall: Upper Saddle River, NJ, USA, 2004.

19. Helms, M.; Vattam, S.S.; Goel, A.K. Biologically inspired design: Process and products. *Des. Stud.* **2009**, *30*, 606–622. [CrossRef]

20. Nagel, J.K.S.; Stone, R.B.; McAdams, D.A. Function-based biologically inspired design. In *Biologically Inspired Design*; Goel, A., Stone, R.B., McAdams, D.A., Eds.; Springer: London, UK, 2014.

21. Sartori, J.; Pal, U.; Chakrabarti, A. A methodology for supporting "transfer" in biomimetic design. *AIEDAM* **2010**, *24*, 483–506. [CrossRef]

22. Badarnah, L.; Kadri, U. A methodology for the generation of biomimetic design concepts. *Archit. Sci. Rev.* **2015**, *58*, 1–14. [CrossRef]

23. Speck, T.; Speck, O. Process sequences in biomimetic research. In *Design and Nature iv*; Brebbia, C.A., Ed.; WIT Press: Southampton, UK, 2008; Volume 114, pp. 3–11.

24. Gentner, D. Structure-mapping: A theoretical framework for analogy. *Cognit. Sci.* **1983**, *7*, 155–170. [CrossRef]

25. Gentner, D.; Markman, A.B. Structural alignment in analogy and similarity. *Am. J. Psychol.* **1997**, *52*, 45–56. [CrossRef]

26. Ward, T.B. Analogical distance and purpose in creative thought: Mental leaps versus mental hops. In *Advances in Analogy Research: Integration of Theory and Data from the Cognitive, Computational, and Neural Sciences*; Holyoak, D.G.K., Kokinov, B., Eds.; New Bulgarian University Press: Sofia, Bulgaria, 1998.

27. Mak, T.W.; Shu, L.H. Using descriptions of biological phenomena for idea generation. *Res. Eng. Des.* **2008**, *19*, 21–28. [CrossRef]

28. Cheong, H.; Shu, L. Effective analogical transfer using biological descriptions retrieved with functional and biologically meaningful keywords. In Proceedings of the ASME International Design Engineering Technical Conference, San Diego, CA, USA, 30 August–2 September 2009.

29. Linsey, J.; Viswanathan, V. Overcoming cognitive challenges in bioinspired design and analogy. In *Biologically Inspired Design: Computational Methods and Tools*; Goel, A., Stone, R.B., McAdams, D.A., Eds.; Springer-Verlag: London, UK, 2014; pp. 221–244.

30. Wilson, J.O.; Rosen, D.; Nelson, B.A.; Yen, J. The effects of biological examples in idea generation. *Des. Stud.* **2010**, *31*, 169–186. [CrossRef]

31. Fu, K.; Moreno, D.; Yang, M.; Wood, K. Bio-inspired design: An overview investigating open questions from the broader field of design-by-analogy. *J. Mech. Des.* **2014**, *136*, 111102. [CrossRef]

32. Benyus, J.M. *Biomimicry Innovation Inspired by Nature*; Morrow: New York, NY, USA, 1997.

33. Biomimicry Institute Nature's Unifying Patterns: Learning from Nature's Overarching Design Lessons. Available online: https://toolbox.biomimicry.org/core-concepts/natures-unifying-patterns/ (accessed on 2 November 2018).

34. Raven, P.H.; Johnson, G.B. *Biology*; McGraw-Hill: Boston, MA, USA, 2002.

35. Chen, D.A.; Ross, B.E.; Klotz, L.E. Lessons from a coral reef: Biomimicry for structural engineers. *J. Struct. Eng.* **2014**, *141*, 2514002. [CrossRef]

36. Schild, K.; Herstatt, C.; Luthje, C. *How to Use Analogies for Breakthrough Innovations*; Technical University of Hamburg: Hamburg, Germany, 2004.

37. Hill, B. *Naturorientierte Lösungsfindung: Entwickeln und Konstruierenvonbiologischen Vorbildern*; Expert-Verlag: Renningen-Malmsheim, Germany, 1999.

38. Vattam, S.; Helms, M.; Goel, A. A content account of creative analogies in biologically inspired design. *AI Eng. Des. Anal. Manuf. Spec. Issue Biol. Inspir. Des.* **2010**, *24*, 467–481. [CrossRef]

39. Wiltgen, B.; Goel, A.K. Case-based reasoning all over the place: The multiple roles of cbr in biologically inspired design. In workshop of human-centered and cognitive approaches to case-based reasoning. In Proceedings of the 19th International Conference on Case Based Reasoning, Greenwich, UK, 12–15 September 2011.

40. Nagel, J.K.S.; Schmidt, L.; Born, W. *Fostering Diverse Analogical Transfer in Bio-Inspired Design*; ASME IDETC/CIE 2015, DEC-47922; ASME: Boston, MA, 2015.

41. Goel, A.K.; Rugaber, S.; Vattam, S. Structure, behavior, and function of complex systems: The structure, behavior, and function modeling language. *Artif. Intell. Eng. Des. Anal. Manuf.* **2009**, *23*, 23–35. [CrossRef]

42. Umeda, Y.; Takeda, H.; Tomiyama, T.; Yoshikawa, H. Function, behaviour, and structure. In *Applications of artificial intelligence in engineering v, Gero, J.S., Ed.*; Computational Mechanics Publications/Springer–Verlag: Southampton/Berlin, UK/Germany, 1990; pp. 177–193.

43. Erden, M.S.; Komoto, H.; Beek, T.J.V.; D'Amelio, V.; Echavarria, E.; Tomiyama, T. A review of fucntional modeling: Aproaches and applications. *Artif. Intell. Eng. Des. Anal. Manuf.* **2008**, *22*, 147–169. [CrossRef]

44. Stone, R.; Wood, K. Development of a functional basis for design. *J. Mech. Des.* **2000**, *122*, 359–370. [CrossRef]

45. Gero, J.S. Design prototypes: A knowledge representation schema for design. *AI Mag.* **1990**, *11*, 26–36.

46. Gero, J.S.; Kannengiesser, U. The situated function–behaviour–structure framework. In *Artificial Intelligence in Design '02*; Gero, J.S., Ed.; Springer: Dordrecht, The Netherlands, 2002; pp. 89–104.

47. Yaner, P.W.; Goel, A.K. Analogical recognition of shape and structure in design drawings. *AIEDAM* **2008**, *22*, 117–128. [CrossRef]

48. Campbell, N.A.; Reece, J.B. *Biology*; Pearson Benjamin Cummings: San Francisco, CA, USA, 2003.

49. The Biomimicry Institute Biomimicry: A Tool for Innovation. Available online: http://www.biomimicryinstitute.org/about-us/biomimicry-a-tool-for-innovation.html (accessed on 10 October 2009).

50. The Biomimicry Institute Ask Nature—The Biomimicry Design Portal. Available online: http://www.asknature.org/ (accessed on 10 January 2011).

51. Forbes, P. *The Gecko's Foot: Bio-Inspiration: Engineering New Materials from Nature*; W. W. Norton & Co.: New York, NY, USA, 2006.

52. Biggins, P.H.J.K.A. *Bio-Inspired Materials and Sensing Systems*; RSC Publishing: Cambridge, UK, 2011.

53. Jay, H. *The Shark's Paintbrush: Biomimicry and How Nature is Inspiring Innovation*; Nicholas Brealey: London, UK, 2013.

54. Macnab, M. *Design by Nature: Using Universal Forms and Principles in Design*; Pearson Education: London, UK, 2011.

55. Mazzoleni, I.P.S. *Architecture Follows Nature: Biomimetic Principles for Innovative Design*; Taylor & Francis Group: Milton Park, UK, 2013.

56. Gruber, P. *Biomimetics—Materials, Structures and Processes*; Springer: Heidelberg, Germany, 2011.

57. Gruber, P. *Biomimetics in Architecture: Architecture of Life and Buildings*; Springer: Wien, Austria, 2010.

58. Pawlyn, M. *Biomimicry in Architecture*; Riba Publishing: London, UK, 2011.

59. Allen, R. *Bulletproof Feathers: How Science Uses Nature's Secrets to Design Cutting-Edge Technology*; University of Chicago Press: Chicago, IL, USA, 2010.

60. Finsterwalder, R. *Form Follows Nature: A History of Nature as Model for Design in Engineering, Architecture and Art = Eine Geschichte der Natur als Modell f¸r Formfindung in Ingenieurbau, Architektur und Kunst*; Springer: Wien, Austria; New York, NY, USA, 2011.

61. Mak, T.W.; Shu, L.H. Abstraction of biological analogies for design. *CIRP Ann.* **2004**, *531*, 117–120. [CrossRef]

62. Chakrabarti, A. Supporting analogical transfer in biologically inspired design. In *Biologically Inspired Design*; Goel, A., Stone, R.B., McAdams, D., Eds.; Springer: London, UK, 2013.

63. Helms, M.; Goel, A. I The Four-Box Method of Analogy Evaluation in Biologically Inspired Design. In Proceedings of the ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Buffalo, NY, USA, 17–20 August 2014.

64. Cheong, H.; Chiu, I.; Shu, L. Extraction and transfer of biological analogies for creative concept generation. In Proceedings of the ASME International Design Engineering Technical Conference, Montreal, QC, Canada, 15–18 August 2010.

65. Goel, A.K.; Vattam, S.; Wiltgen, B.; Helms, M. Information-processing theories of biologically inspired design. In *Biologically Inspired Design*; Goel, A., Stone, R.B., McAdams, D.A., Eds.; Springer-Verlag: London, UK, 2014.

66.　Vattam, S.S.; Helms, M.E.; Goel, A.K. Nature of creative analogies in biologically inspired innovative design. In *Creativity and Cognition (C&C'09)*; ACM: Berkeley, CA, USA, 2009.

67.　Jacobs, S.R.; Nichol, E.C.; Helms, M.E. Where are we now and where are we going? The biom innovation database. *J. Mech. Des.* **2014**, *136*, 111101. [CrossRef]