

Using biomimetic design in a product design course

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ABSTRACT: In this research, the authors propose a systematic procedure for biomimetic design that helps students carry out the transformation of the concept of biological characteristics in a product design course. This systematic procedure is mainly based on wording transformation and morphological analysis in which interchanging a series of graphics and words may enable students to undertake abstract thinking for form, and through morphological analysis, they derive optimal and feasible solutions. A six-week biomimetic design course has been used to verify how this systematic procedure helps students conduct the transformation of the concept of biomimetic design and complete product design works in the process.

INTRODUCTION

The ancient Chinese observed the universe and animals, and through simple lines depicting the forms of these natural organisms, the earliest Chinese hieroglyph was created. The Wright brothers pointed to soaring birds as their inspiration for the first aircraft steering mechanisms. Observations began, followed by imitation and learning. *Biomimetic design* was born from this motivation and the features of creatures are duly applied in the design of products as a transforming mechanism. The natural world has provided human beings with optimum solutions to their problems and biomimetic design is the best means in realising these [1].

Biomimetic design occurs through artificial means by transforming the essence of biological and organic evolution into a practical and functional product. In this process, the product designer must apply many methodological approaches and face many transformation problems.

As organic beings are of sophisticated forms, physical constructions and movements, *simplification* is thus a key concept for the transformation of form in biomimetic design. It is also the first problem that product designers face in analysing and extracting key biological features from a large number of organic forms and structures before obtaining elements for artificial design and manufacture, as well as for simplifying complex organic structures into product features that are suitable for artificial material and manufacture. This type of simplification procedure requires designers to possess associative abilities through profuse abstract thinking. At the same time, this design procedure is time- and thought-consuming, thereby requiring continuous modification and experimentation.

In product design courses implemented in the field of industrial design, biomimetic design is often utilised in training students' observation and association abilities. Another purpose of biomimetic design is to allow students to extract design inspirations through the natural world, thereby creating products that can expand the level of convenience in human lives. However, many biomimetic design instructions have followed standard product design procedures or encouraged thinking through product semantics. There is a deficiency in teaching materials that are capable of instructing students about organism form transformation or abstract associative thinking [2].

In this article, the authors propose a biomimetic design procedure and accompanying teaching materials that will help students in exercising systematic thinking to simplify biological features and transform design concepts. A six-week biomimetic design course has been implemented to explain how the procedure and teaching materials allow students to complete biomimetic design works. Furthermore, the course demonstrates the design efficacy of both the systematic procedure and accompanying teaching materials.

BIOMIMETIC DESIGN

The study of bionics was first proposed by US Air Force Major Jack E. Steele [3]. Steele believed that the purpose of bionics is to acquire knowledge on biology, and by inducing such knowledge through mathematical methodologies, various types of engineering problems can be resolved.

Since bionics denotes the imitation of biological features, Benyus introduced the concept of biomimicry in his book, *Biomimicry: Innovation Inspired by Nature* [4]. Biomimicry is a term constructed from *bio* and *mimicry*. Mimicry is a biological term that refers to the form or behavioural imitation by one species of another. Jones introduced the concept of biodesign in the book *Industrial Design: Reflection of a Century*, regarding organic design and biomorphic modes as the main approaches in the biomimetic design of products [5].

The product designer, through organic curvature and biomorphic approaches, creates bio-friendly products that appeal to aesthetic sensibilities and enhance operational comfort for human use [5]. Based on Benyus's concept, Vakili and Shu gave the following definition for biomimetic design: *Biomimetic design is a design that, fully or partially, imitates or evokes some biological phenomenon* [1].

Steele's bionic concept basically focuses on imitating the biological form and physiological structure of biological organisms, while utilising induced biological features as the basis for new technical development. Jones's biodesign primarily imitates the form and features of organisms, while Benyus' biomimicry, aside from form, includes the concept of replicating the behaviour of biological organisms.

Summing up the aforementioned concepts, biomimetic design has three important application aspects as follows:

- Form biomimicry: the basic product shape arises from imitating and transforming according to the biological organism's form or physical features;
- Behavioural biomimicry: the basic style of product operation or motion arises from imitating and transforming the biological organism's behaviours and functions;
- Structural biomimicry: the basic structure of product form or motion arises from imitating and transforming the biological organism's body construction or the special structure of its individual parts.

RESEARCH METHODS

Product Semantics

Direct transformation in the implementation of biomimetic design is impossible due to the great differences between the target organism and the products' basic features (organic versus human-made products), material (natural material versus human-made material), and form (organic curvature versus rational curvature). Within the process of biomimetic design, the results from observing the objectively mimicked organism must undergo conceptual transformation (Figure 1).

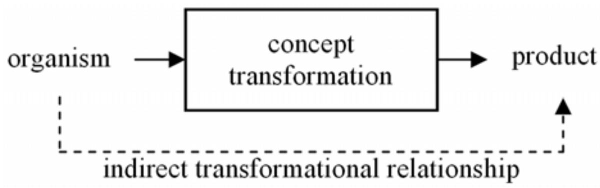

Figure 1: The transformation process of biomimetic design.

Since the early 1980s, product semantics has been perceived by the field of industrial design as an optimal means of delivering the meaning and purpose of product form [6][7]. A product form comprising of semantics can augment users' understanding of the underlying emotions and meanings, and allow for the proper usage of the product.

The concept of product semantics originated from the design symbolism course at the Ulm Design School in Germany. In 1962, Prof. Reinhard Butter of the Ohio State University formally coined the term *product semantics*. Towards the end of the 1980s, owing to McCoy's promotion at the Cranbrook Art Institute, it became the mainstream methodological approach in the field of industrial design [8]. Krippendorff and Butter defined product semantics as follows:

> *Product semantics is the study of the symbolic qualities of man-made forms in the context of their use and application of the knowledge to industrial design* [9].

Product semantics primarily employs the wording of semantics. Through *connotation* and *denotation*, it conveys the meaning of the product given by the designer.

Connotation is related to the morphological symbols and attributes of the referenced object, which are described mainly through the use of adjectives. Denotation refers to the referenced object's function and motion through which people describe the product features [7]. Association through symbolic words and phases of product semantics includes the senses of *vision*, *touch* and *motion*. Among these, association through *vision* is the most direct and effective [10]. Thus, through visualised images (illustration, graphics), design ideas can arise from the symbolic meaning that the designer attempts to bestow upon the product and allow product users to easily understand the given meaning.

Morphology Analysis

After acquiring product form imagination by employing product semantics, the authors utilise a morphological chart of morphology analysis to help converge and make a decision for the biomimetic design concept.

Morphology is the study of an object's physical configuration or form. Morphology analysis is a systematised method of analysing the potential functions or forms of the product. A morphological chart presents the summary of the process of morphology analysis [11].

Morphology analysis is a method in which the problem is broken down and recombined. The problem is broken into numerous sub-problems (functions), and potential solutions are sought for each sub-problem (function). The morphological chart arranges and combines all the potential solutions through graphics, pictures or other visualised elements through which the best solution is found through formulaic combinations [11].

Fundamentally, biomimetic design is a process that involves the transformation of physical or metaphorical features in biological phenomenon through meaningful wording. During this process, the symbolic meaning of the biological organism is the main factor that the designer must handle. At the same time, it is also the critical factor in the creation of a successful biomimetically designed product. Thus, product semantics should become the main approach in the conceptual transformation of biomimetic design. Through the aid of a morphological chart, the designer thereafter develops a visualised solution (illustration or graphic) according to the established words and phrases through which the optimum design solution formula can be found. According to this concept, the conceptual transformation shown in Figure 1 can be further extended into the contents of Figure 2.

COURSE DESIGN

In order to allow students to transform easily the features of biological organisms into concepts of product design, this research devised a six-week biomimetic product design course. Teaching materials were also designed to guide students in gradually developing their ideas while completing the initial product design assignment.

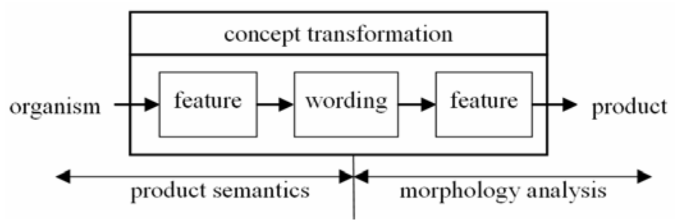

Figure 2: Contents and application of concept transformation process in biomimetic design.

This biomimetic design course includes two stages:

- Stage 1: biological research; duration: two weeks:
  Students choose a familiar or interesting organism (animal or plant) and conduct detailed data collection, discussion and classification of the physiological structure, habits and behaviours of their chosen organism. An oral presentation of the biological research is carried out during the second week;
- Stage 2: product biomimetic design; duration: four weeks:
  Based on the research results from Stage 1 along with the teaching materials of this research, students progressively carry out the extraction and transformation of the organism's biological features and develop their primitive product design accordingly. During this stage, students must be guided by the teaching materials and they then present a proposal for a product design by the end of the course. They should also create an actual physical model to present the works of their design, as well as provide an oral presentation.

TEACHING MATERIALS

According to the concept and construct of Figure 2, this research developed a *Diagram for Biomimetic Product Design* (DBPD) to guide students in the extraction and transformation of the aforementioned biological features during Stage 2. It further develops students' ideas for product design.

The DBPD is a systematic procedure for biomimetic product design, which is derived from the choice of an organism, the extraction of its features, selection of keywords and transformation of imagination to the final product idea drawings. With a total of 10 steps, the diagram has directions and an assignment format, which are indicated in Table 1.

Step 2 is the essential phase in the DBPD that penetrates the entire design process because the resulting product must keep a minimum degree of the original organism's features so that the product can evoke a user's retrospective association by its forms and then recall the original organism from which the product is patterned. From a product semantics perspective, this is a very important human-machinery relationship of the product [9]. The diagram encourages students to choose a feature that adequately represents the organism in Step 2. The result must also be successfully incorporated in Step 8 with the various wording and imagery meanings from Step 7. Essentially, the objective is that students can sustain the organism's features throughout the whole process of their product design.

Table 1: The detailed instructions of the *Diagram for Biomimetic Product Design* (DBPD).

Procedure	Direction	Representation		
		Text	Graph / Photo	Object
Step 0	Describe organism name and photo.	●	○	
Step1	Use photos, pictures, or illustrations to explain the features of the organism.		●	
Step2	Depict unique features that most represent the organism using photos, pictures, or illustrations.	○	●	
Step3	Depict other features, habits, behaviors, and motion mechanisms of the organism using photos, pictures, or illustrations.	○	●	
Step4	Describe the various features, habits, behaviors, and motion mechanisms in Step 3 using appropriate written wordings.	●		
Step5	Categorize the keywords selected from Step 4 into nouns, adjectives, and verbs.	●		
Step6	Illustrate the meaning of the three types of keywords in Step 5 using pictures, photos, or available objects.		●	●
Step7	Reproduce the pictures, photos, or available objects from Step 6 in each grid.		●	●
Step8	Use the established features from Step 2 as basis, and then select numerous pictures, photos, or available objects from Step 7 to formulate several possible conceptual solution groups. Utilize these possible solutions as the basis to draw a product idea sketch for each solution group.		●	●
Step9	Select an idea from Step 8 that is more advantageous for design, production, and market, and produce a more detailed model with a more elaborated function figure description.	○	●	

Remark:
● Primary representational technique for this step.
○ Secondary or non-essential representational techniques for this step.

STUDENT WORKS

Figure 3 is a DBPD and the work of a student taking the course. The organism is a spheroid cactus. In Step 2, he chose the cactus' thorns and thorn base as its representative features. In Step 5, he selected the following nouns as his keywords: leaf, stem, base, fluff, root and surface temperature. His adjective keywords included the following: acicular, spherical, thickset, wide and shallow, and stout. His verb keywords included deteriorate, present, grow independently, store, reduce, decrease, absorb and evaporate. In Step 7, he chose *acicular*, *spherical*, *grow independently* and *store*, in addition to the merged development concept formulated by *thorns* and *thorn base*. The final proposal was a cactus piggy bank. The student stated his insight during his product presentation as follows:

> *The inside of the cactus evolved into a space for storing water, allowing the cactus to adapt to the desert's waterless and hot weather, as it became a hardy plant in the desert. I imagined the cactus as a piggy bank that can store money, transforming the water storage space inside the cactus into a space for storing money. The exterior that is filled with thorns prevents people from seizing this piggy bank and thus discourages them from taking the money. When we can't find water in the desert, we can cut the stem of the cactus to drink the water inside. Similarly, when we don't have money, we can break this piggy bank to meet an urgent need …*

Figure 4 is a DBPD and the work of another student. The organism is an otter. In Step 2, his choice of representative features was an otter swimming on its back on the water surface, holding onto a rock and knocking the rock with a shell in its hand in order to eat the meat inside. In Step 5, his noun keywords included the following: body, resistance, fish and shrimps, sea urchin, shellfish, seaweed, ocean current, toe, web, fur, rock and hard shell. His adjective keywords included conical, thick and tight, waterproof, and cold resistant. His verb keywords included dine, sleep, entwine, stand, swim, back-stroke, knock and feed. In Step 7, his choice of *ocean current*, *shell* and *backstroke* fused with the otter's shell-cracking

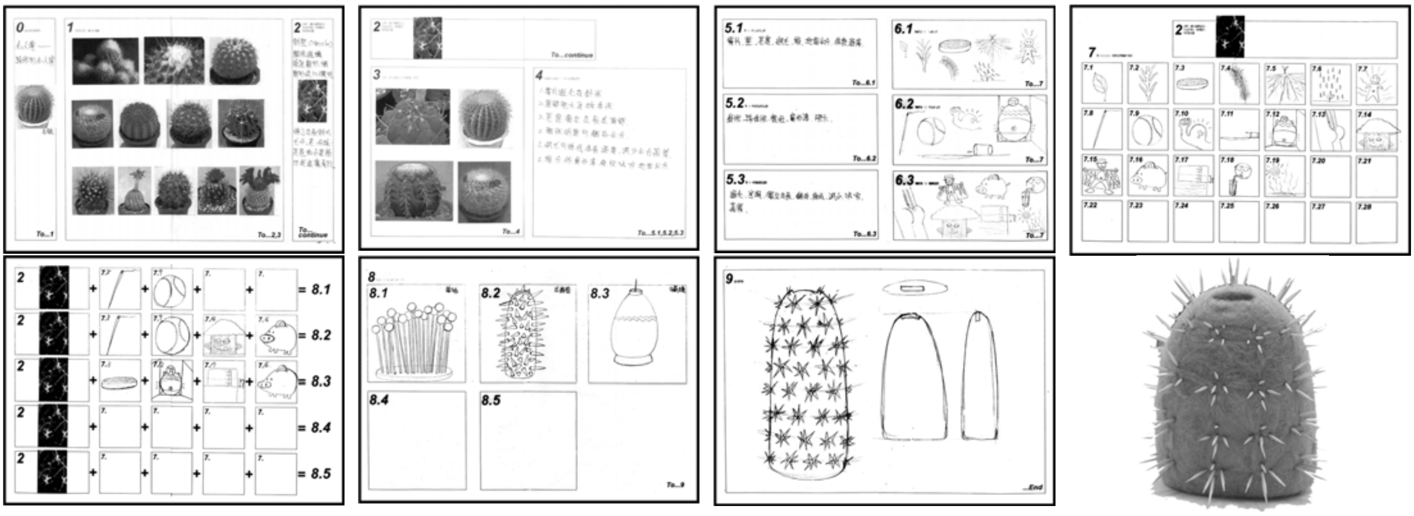

Figure 3: The piggy bank (designed by C.M. Cheng).

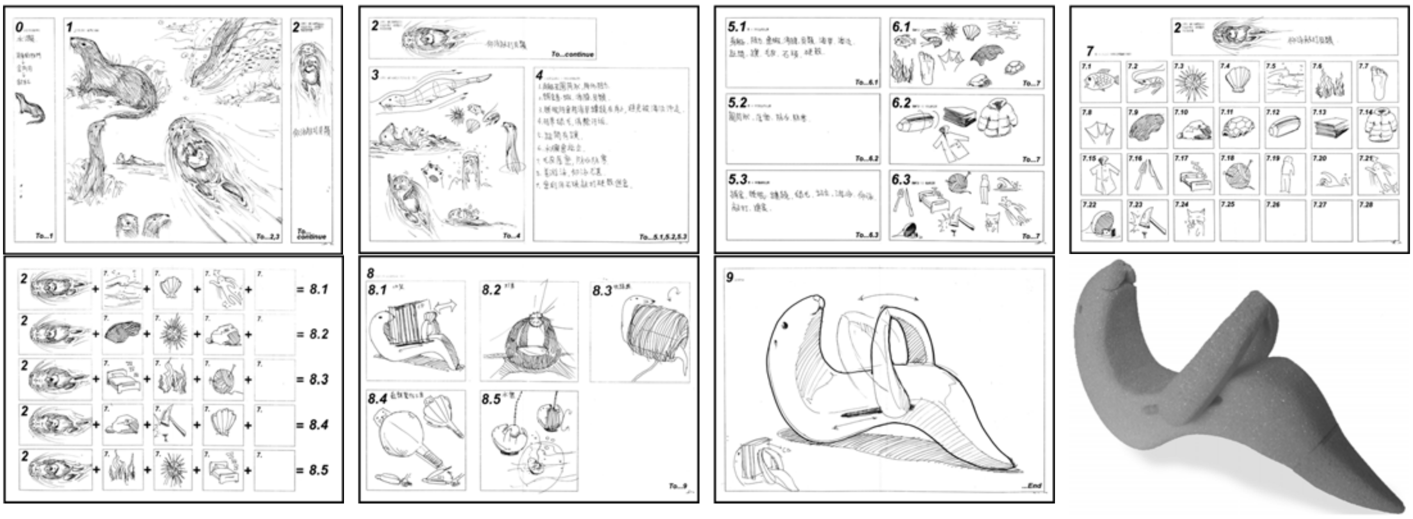

Figure 4: The CD shelf (designed by T.L. Lee).

motion in Step 2, formulated his combined development idea and ended with a product of a CD shelf exterior that utilises the backstroke motion of the otter. He stated the following:

> *The otter's backstroke motion on the water surface, embracing the rock with a shell in hand and knocking the rock to reach the meat within the shell, is a very unique behavior. It reveals that the otter is a clever animal that knows how to use tools. The motion of the otter embracing the rock made me think of a flat storage space; its hands are capable of embracing both the rock and the shell, bringing to mind a CD shelf for storing CDs. Of course, if the dimensions are expanded, it becomes a bookshelf for storing books. When CDs or books are placed on top, it will follow the curvatures of the otter's body, forming a figure like the waves of an ocean current …*

DISCUSSION

In both works by the aforementioned students, the cactus piggy bank imitated the form of a spherical cactus and its water storage function. This product design makes use of both form and structural biomimicry. The CD shelf imitated the otter's feeding behavioural mode and utilised behavioural biomimicry. Through the works of these two students, it can be understood that the teaching method and the proposed *Diagram for Biomimetic Product Design* can manage form, structural and behavioural biomimicry in product design. The key factor for its effectiveness lies in Step 5, which is further subdivided as follows:

- Step 5.1: noun keyword formulation;
- Step 5.2: adjective keyword formulation;
- Step 5.3: verb keyword formulation.

Nouns and adjectives allow the organism's form, structural and functional features to be depicted, while the adjectives and verbs can describe the organism's behavioural or motion features. Students can thus classify the written descriptions from Step 4 into these three parts and then utilise these keywords through the individually visualised images in developing their ideas. The classification of the parts of wording keywords has not been considered in the teaching approach of biomimetic design courses in the past.

Figure 5 is the work of another student. She also selected the cactus as her mimicked organism. In Step 2, she also chose the most important exterior features of the cactus – the thorns. In the latter stages, she similarly focused on the exterior features of the cactus as her developmental basis. Her final product was a toothbrush stand.

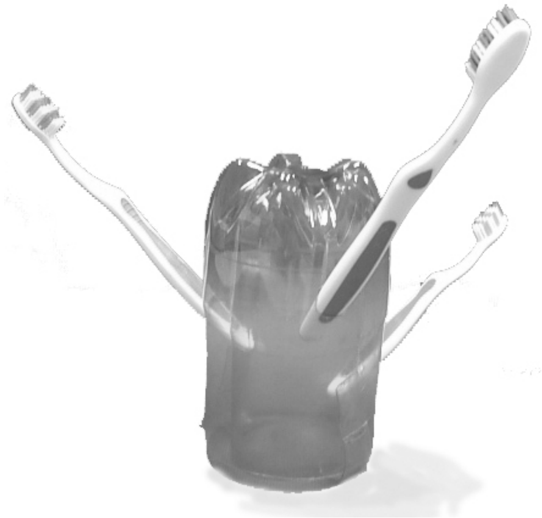

Figure 5: The toothbrush stand (designed by Y.P. Chyau).

Comparing the two products of Figure 3 and Figure 5, it can be discerned that although a similar organism was chosen, the designers' emphasis on different features of the organism resulted in end products that are entirely different (the work in Figure 3 emphasised form and structural biomimicry, while the work in Figure 5 only emphasised form biomimicry).

Another factor that resulted in the difference in outcomes is the alteration from Step 5 to Step 6. This is the transformation stage from written wordings to image conceptualisation. Essentially, the transformation of this stage examines the student's associative ability. In the final week at the end of product presentation, the teacher asked students to share what they had learnt and the majority of students agreed that this stage was the most difficult of the 10 steps. However, they also thought that excluding individual design cognitive abilities during the transformation process, personal life experiences, familiarity towards organisms and a grasp of the form of objects, even the ability to expound language, are all key factors that affect the final quality of the product.

During Stage 2 in this course, the teacher also exerted a lot of effort to explain to students the process of transformation and the key factors that must be grasped. However, there were still some students who had difficulties during the transformation process. Thus, future research should examine and discuss cognitive techniques or modes in transforming wordings to images.

CONCLUSION

This research targets the cause, types, and logical procedure of biomimetic design to propose relevant teaching and learning outcomes. In addition, the research concentrates on a six-week biomimetic design course for college students taking basic product design courses to demonstrate the practicality of the proposed biomimetic design procedure. This research endeavours to allow students to gradually understand the main points of each individual product design stage and obtain the ability to analyse the information gathered through each stage, so that they can conduct a series of conceptual deduction and classification processes. This is meant for them to obtain appropriate product design ideas through a systematic teaching process with the guidance of the proposed teaching materials.

Through a representation of students' product design works in this research, it is also confirmed that the teaching material proposed by this study, the *Diagram for Biomimetic Product Design*, can be utilised in different biomimetic design topics such as form, structural and behavioural biomimicry. The students of this course unanimously agreed that this teaching material can guide learning activity and have positive effects towards conceptual inspiration and assessment. Finally, it can also promote obvious connections between the proposed product and the mimicked organism.

Jones believes that biomimetic products in different eras are indicators that reflect people's perception of natural organisms [5]. Although humans are the most evolved creatures in the world, *imitate from nature* is an important experience for humans to learn humbly from the natural world. Everyday, our lives are deeply connected with the natural world and its infinite inhabitants. This mutual dependence, through the provision of this course, may allow students to understand the quintessence of biomimetic design, while at the same time, providing a broader range of considerations in the subject of product design.

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