An Information-Processing Account of Creative Analogies in Biologically Inspired Design

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ABSTRACT
Biologically inspired design perhaps is one of the most important movements in engineering design. The paradigm espouses use of analogies to biology in generating conceptual designs for new technologies. In this paper, we briefly summarize some empirical findings about biologically inspired design, and then develop an information-processing theory of creative analogies in biologically inspired design. We also compare our theory with similar theories. In addition, we examine how biologically inspired design is fundamentally different from other design paradigms.

Author Keywords
Analogy, Biologically Inspired Design, Biomimetics, Creativity, Innovation, Task Analysis, Task Models.

ACM Classification Keywords
J.6 Computer-aided engineering: Computer-aided design

General Terms
Design

INTRODUCTION

Biologically inspired design [5,13,23,26] perhaps is one of the most important movements in engineering design. The paradigm espouses use of analogies to biology in generating conceptual designs for new technologies. This paradigm has inspired many designers in the history of design, such as Leonardo da Vinci, the Wright brothers, etc. But it is only over the last generation that the paradigm has become a movement, pulled by the growing need for environmentally sustainable design and pushed by the desire for creativity and innovation in design. The design of blades of windmill turbine mimicking the designs of tubercles on flippers of humpback whales is one example of biologically inspired design [2,12]. As seen in Figure 1, the tubercles are large bumps on the leading edges of the flippers, which create even, fast-moving channels of water flowing over them. The whales thus can move through the water at sharper angles and turn tighter corners than if their flippers were smooth. When applied to wind turbine blades, they improve lift and reduce drag, improving the energy efficiency of the turbine [7].

Note that the design of biologically inspired energy-efficient wind turbine blades illustrates both sustainable design as well as creative design. However, although biologically inspired design is rapidly growing as a design movement, its practice is *ad hoc*, with little systemization of either biological knowledge from a design perspective, or of the processes of biologically inspired design. Transformation of the promising paradigm of biologically inspired design into a principled methodology requires development of theories of biologically inspired design, e.g. [27].

Theories of biologically inspired design can be of many types and take many forms. Vincent et al. [27], for example, describe a theory of biological designs in terms of material, energy, information, structure, substance, space and time. Their analysis suggests that while biological systems at some spatio-temporal scales often use information for achieving many functions, technological systems at the same scales typically use energy for similar functions. In contrast, our goal is to develop *an information-processing theory* of biologically inspired design. Information-processing theories themselves can be

Figure 1. Two examples of humpback whale flippers, adapted from [3,4]. The structure of the flippers inspired an improved windmill turbine design.

of several types. Some information-processing theories propose cognitive models of specific tasks such as problem solving and decision-making. Newell & Simon [21], for example, describe particular memory, inference and attention processes of human problem solving. In contrast, we seek to conduct a cognitive task analysis (e.g., [10]) and describe a task model of biologically inspired design based on the analysis. A task model describes the processes, knowledge and representations that result in the accomplishment of open-ended tasks such as design (e.g., [16]). Further, an information-processing theory of biologically inspired design may describe the behaviors of an individual designer, the interactions among a team of designers, or the behaviors of a design team viewed as a unit. Although in general we are interested in all three levels of aggregation, in this particular paper we focus on interdisciplinary design teams of biologists and engineers viewed as units.

To summarize, then, our goal in this paper is to develop a task model of cross-domain analogies from biology to engineering in the conceptual phase of biologically inspired engineering design. Through this work, we wish to contribute to the relatively small but growing body of literature (e.g., [17,18,20,24,28]) that investigates biologically inspired design from an information-processing perspective. We view this work as a step in the broader agenda of developing (1) a design methodology that promotes systematization of biologically inspired design, (2) pedagogical techniques for fostering education and training in biological inspired design, and (3) interactive technologies that facilitate the work of individuals and teams engaged in biologically inspired design.

In this paper, first we briefly summarize some empirical findings about biologically inspired design. Then we conduct a task analysis and develop a task model of creative analogies in biologically inspired design. Next, we compare our theory with the two best-known information-processing theories of biologically inspired design. Finally, we examine if and how biologically inspired design is fundamentally different from other design paradigms.

RESEARCH CONTEXT AND METHODOLOGY

Since 2006, we have observed ME/ISyE/MSE/PTFe/BIOL 4740, a yearly, interdisciplinary, project-based undergraduate class taught by jointly biology and engineering faculty at Georgia Institute of Technology, in which mostly senior-level design students work in small teams of 4-5 on design projects. The class is composed of students from biology, biomedical engineering, industrial design, industrial engineering, mechanical engineering, and a variety of other disciplines. The projects involve identification of a design problem of interest to the team and conceptualization of a biologically inspired solution to the identified problem [30].

Although it changes slightly every year, the class is consistently structured around lectures, found object exercises, journal entries, and one or more design projects (usually a single project that lasts the entire term). Most lectures focused on exposing the designers to existing biologically inspired design case studies. Other lectures were devoted to the design processes involved in biologically inspired design work: reframing engineering problems in biological terms, functional analysis of a problem, optimization, and the use of analogy in design. Some lectures posed problems for the students to solve in small group exercises.

The focal point of our data collection was the design projects. Each design project grouped an interdisciplinary team of 4-5 students together. Each team had at least one student with a biology background and a few from different engineering disciplines. Each team identified a problem that could be addressed by a biologically inspired solution, explored a number of solution alternatives, and developed a final solution design based on one or more biologically inspired designs.

In this paper, we analyze two such design projects from the Fall 2010 section of the course: the SNAP project and the NOLA4NOLA project. The same design team within the class conducted both projects, and each consisted of about a month-long design episode. We report on this team because one of the authors (Wiltgen) performed a participatory ethnography of the class in Fall 2010, and the course instructor assigned him to be a member of this team during that study. Through participating in the team's design activities, we were able to gain insight into the particulars of this team's designs and design processes. Although we report in detail only on this team, our analysis of these two projects will illustrate how a rich task model is required to encapsulate the variety of design processes that occur within biologically inspired design. We refer the reader to [25] for additional examples of projects in this class context.

The SNAP Project

In this project, the students first selected a set of biological organisms, did research to understand those organisms, and then were asked to find a human-related problem that the functionality of one or more of those organisms could help solve. SNAP, which stands for Shrimp-inspired Non-harmful Attack Prevention, was directed at preventing shark attacks off the coast of the United States without harming the sharks. The students designed an underwater sound-based shark repellant device inspired by the snapping shrimp [22], a small shrimp with the ability to create loud, underwater sound waves using one of its claws. The device worked by emitting sounds, generated by the same mechanism that the snapping shrimp uses to emit sound, but at a frequency that sharks dislike. By placing a line of these devices between human beach-goers and shark populations, the design team envisioned creating something akin to an "invisible fence," a field that would repel sharks without harming them.

The NOLA4NOLA Project

For this project, the students were first asked to come up with a set of human-related problems, decide upon and investigate a single one of those problems, and then to find organisms whose functionality could help solve that problem—the opposite methodology of the first project. The goal of the NOLA4NOLA project, which stands for Novel Optimized Levee Architecture for New Orleans, Louisiana, was to prevent another disaster like 2005's Hurricane Katrina by strengthening the levee system in New Orleans. The design team identified several modalities of failure for the levees in New Orleans, such as scouring, overtopping, and joint cracking, and devised biologically inspired solutions for each. For example, the team designed a better joint system for concrete levees inspired by the iron snail [29] that would be resistant to incoming water forces by being multi-layered like the snail's shell.

BIOLOGICALLY INSPIRED DESIGN: A TASK ANALYSIS

In this section we analyze a set of tasks that we have observed in biologically inspired design.

Cross-Domain Analogies

By definition, biologically inspired design engages cross-domain analogies, e.g., analogies from biology to engineering. Although we have observed that extended episodes of biologically inspired design involve both within domain and cross-domain analogies [24], it is the essentialness of cross-domain analogies that defines it.

Problem-Solution Co-Evolution

Conceptual design in biologically inspired design undergoes problem-solution co-evolution as described by Maher et al. [19] and Dorst & Cross [11]. That is, the design process iterates between defining and refining the problem and the solution, with both influencing each other. As a solution (S) is developed and evaluated for a given problem (P), it reveals additional issues, spawning a new conceptualization of the problem (P+1). The process continues with the development of a new solution (S+1) and will iterate until a final solution is decided upon, which in our examples was driven primarily by instructor-mandated deadlines.

For example, the original design problem of the SNAP project was simply to prevent coastal shark attacks. Inspired by the snapping shrimp, the team designed a decoy-like device that would attract the sharks to a location away from human population using sound. However, the team discovered new problems upon evaluation of the idea, such as durability of the decoy if sharks were going to attack it instead of humans. The overall problem then evolved to account for these newly identified issues (e.g., that one must prevent shark attacks with a design that doesn't get eaten by sharks), resulting in a changed solution from a shark-attracting to a shark-repelling device.

Problem Decomposition and Multifunctional Design

A central challenge in biologically inspired design is how to leverage biological knowledge in service of an engineering problem. At the heart of this problem is how to understand and represent the engineering problem and biological solutions such that analogical transfer is facilitated, allowing for the development of a design solution. Functional decomposition of the problem and biological solution is one such method to overcome this challenge.

When developing these decompositions, each function can be used as a cue to retrieve known solutions that achieve that function, thus expanding the number of alternative solutions. Solutions are transferred to the current problem, and aggregated to generate the overall solution. We show how an analysis of snapping shrimp provided inspiration for prevent shark attacks in Figure 2.

Here both the natural solution and the problem have been decomposed into functions until a level is reached where functions overlap and a crossover can occur. In this example, the ability of the snapping shrimp to defend itself

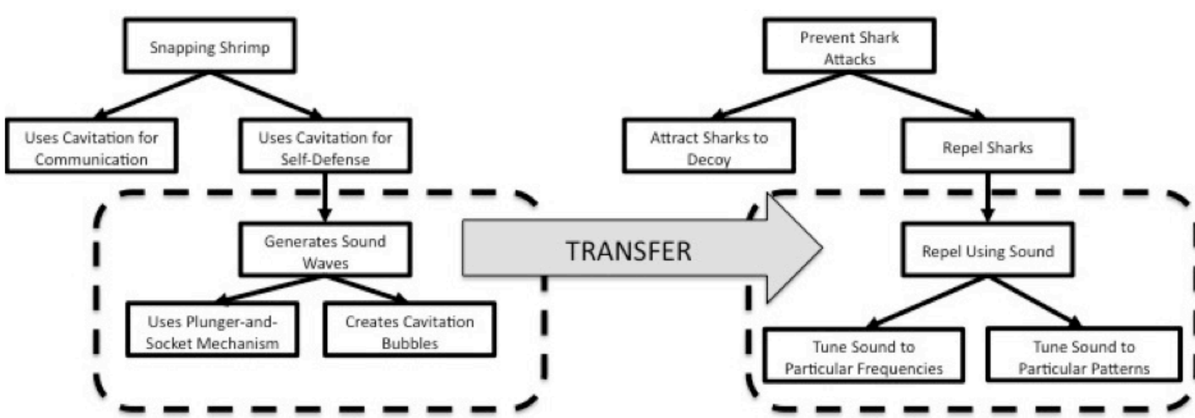

Figure 2. The functional decomposition of the snapping shrimp's ability to defend itself with cavitation was constructed in parallel to similar analyses of the design challenge of preventing shark attacks. By decomposing the biological solution and the problem, the designers were inspired by way the snapping shrimp defends itself to prevent shark attacks on humans by generating shark-repelling sounds and patterns using cavitation.

using sound was an inspiration for a sound-based shark repellent device.

Memory Processes and Compound Analogies

We have found that biologically inspired design often involves compound analogies in which a new design concept is generated by composing the results of multiple cross-domain analogies [17, 24]. This process of compound analogical design relies on an opportunistic interaction between two processes: problem decomposition and memory. Of course, that designers decompose a large, complex design problem into smaller, simpler problems is not a new finding. Equally unsurprising is the fact that designers retrieve and use analogies to generate new designs. However, an interesting aspect of biologically inspired design that we noted was how these two processes interacted and influenced each other, resulting in generation of a compound solution: the overall solution is obtained by combining solutions to different parts of the problem where the solution to each part is derived from a different (biological) analog retrieved from memory.

For example, in the NOLA4NOLA project (see Figure 3), the design goal was to strengthen levees against floods. During their research, the designers identified four sub-problems that were related to levee failure: scour (the eroding of soil by water), regional failure (local levee failures causing whole regions to flood), levee joint cracking (water forces breaking through the joints between levee sub-structures), and foundation destruction (water undermining the foundation of non-earthen levees). The team could not identify a single solution that would overcome all four of these sub-problems, so the final design solution incorporated (1) foundation strengthening underground structures inspired by riparian buffers and *Bacillus pasteurii* bacteria, (2) multi-layered, force-resistant structures to improve the levee walls and joints inspired by the iron snail, and (3) overall levee placement inspired by *Polyrachis sokolova* ant nests, which prevent complete flooding by localizing failure points. Note that Figure 3 only displays how analogical design followed for scour and cracking sub-problems.

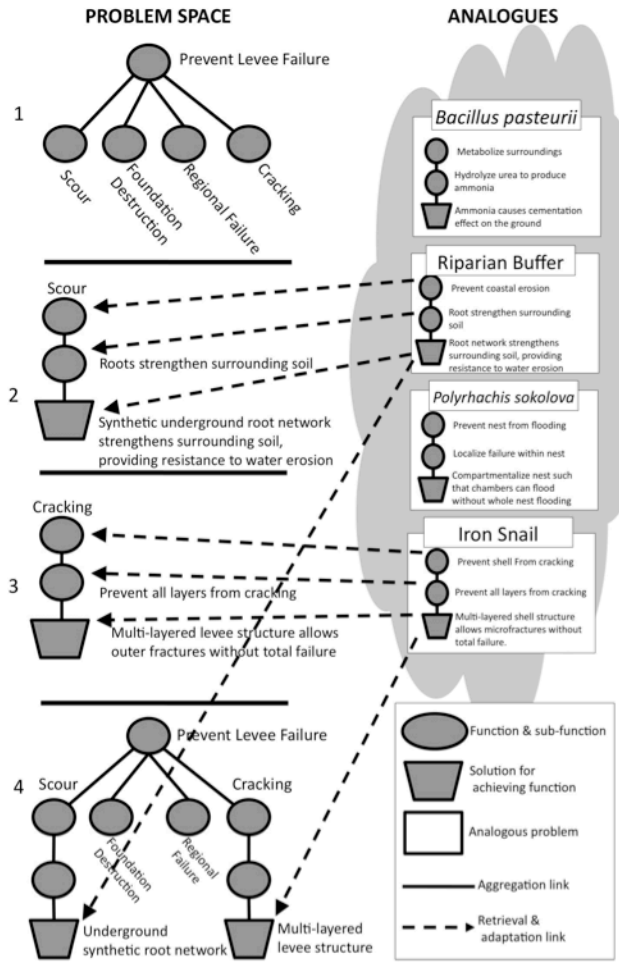

Figure 3. Design trajectory of the NOLA4NOLA project, which exemplifies compound analogical design. Note that only two of the four analogies made by designers are shown.

Problem-Driven and Solution-Based Processes

We observed the existence of two high-level processes for biologically inspired design based on two different starting points – *problem-driven* and *solution-based* [17,24,28]. As depicted in Figure 4(a), in a problem-driven approach, designers identify a problem that forms the starting point for subsequent problem solving. They usually formulate their problem in functional terms (e.g., stopping a bullet). In order to find biological sources for inspiration, designers "biologize" the given problem, i.e., they abstract and reframe the function in more broadly applicable biological terms (e.g., what characteristics do organisms have that enable them to prevent, withstand and heal damage due to impact?). Designers use a number of strategies for finding biological sources relevant to the design problem at hand based on the "biologized" question, and then they research the biological sources in greater detail. Important principles and mechanisms that are applicable to the target problem are then extracted to a solution-neutral abstraction and applied to arrive at a trial design solution.

The NOLA4NOLA project is an example of the problem-driven process. The design team began with the general problem of preventing levee failure, "biologized" their problem (e.g., "protect against incoming forces" and "prevent erosion"), and then conducted a solution search. The search returned such organisms as the iron snail and riparian buffers. Principles were extracted from these solutions (hierarchical, multilayered structures and dense underground networks, respectively), which were then applied to the design problem.

On the other hand, in the solution-based approach, as depicted in Figure 4(b), designers begin with a biological source of interest. The designers understand (or research) their biological source to a sufficient depth to support the extraction of deep principles from it. Then they find human

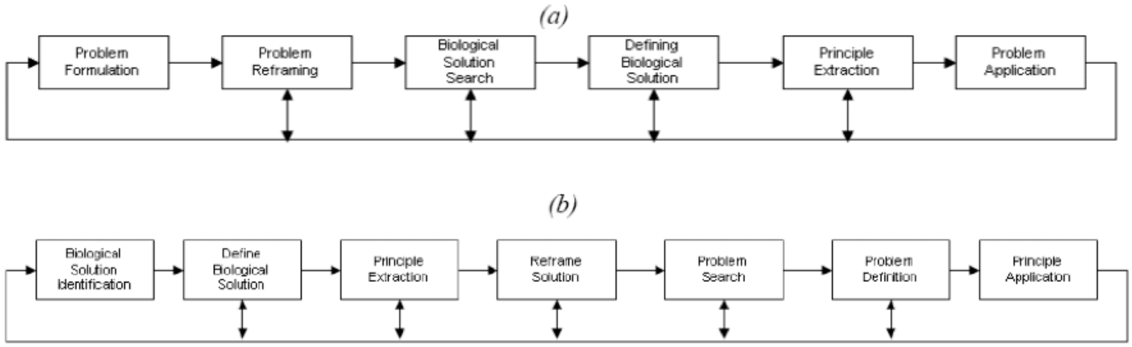

Figure 4. Observed biologically inspired design processes. (a) Problem-driven process. (b) Solution-based process.

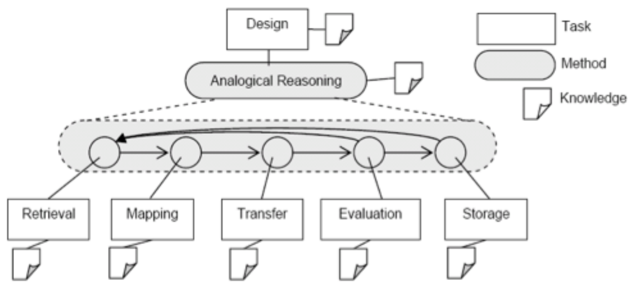

Figure 5. A generic model of analogical design.

problems to which the principle can be applied. Finally they apply the principle to develop a design solution to the identified problem.

The SNAP project is an example of the solution-based approach. The team began with knowledge of the snapping shrimp. From that organism, they extracted the principle of cavitation as a means to both defend oneself and to create sound. Next, the team sought out human problems to utilize the principle, whereby the retrieved shark attacks. By applying their knowledge of cavitation along with its functional use in defense and sound-generation, the team designed a device that repelled sharks in defense of humans using sounds generated by cavitation bubbles.

BIOLOGICALLY INSPIRED DESIGN: A TASK MODEL

In this section, we first summarize a generic task model of analogical design. We will then elaborate this generic model to incorporate the findings presented in the previous section to obtain a task model of biologically inspired design.

Figure 5 illustrates a generic information-processing theory of analogical design (based on [15]) that is consistent with information-processing theories of analogical reasoning in general (such as [14]). The overall *task* is design (see Figure 5). This is accomplished by using the *method* of analogical reasoning. The analogical design method sets up further *subtasks* like retrieval of a source analogue, mapping and transfer of relevant knowledge across source and target to obtain the new solution, and evaluation and storage of the new solution. Each subtask (e.g. retrieval) might, in turn, be accomplished by one of several methods (e.g. feature-based similarity matching for retrieval). *Knowledge*, here, refers to the knowledge inputs and outputs associated with the processing of each task, subtask or a method. For example, the knowledge associated with the subtask of transfer includes what may get transferred between the source and the target design situations; this can include, among others, elements of a previous design like components and relationships between components.

Our task model of biologically inspired design is based on the above generic theory of analogical design, but will extend the generic theory to incorporate the two key findings from our study described above: (i) problem-driven and solution-based design and (ii) compound analogies.

Incorporating Problem-Driven and Solution-Based Analogies

Earlier we identified two processes followed by designers engaged in biologically inspired design, suggesting two *methods* for the *task* of biologically inspired design: the problem-driven and solution-based methods. These methods should incorporate tasks that were noted in their respective processes, depicted in Figure 4. See Figure 6 for an updated task model that incorporates problem-driven and solution-based methods. The problem-driven method incorporates the design subtasks: problem formulation, problem reframing, biological solution search, defining biological solution, principle extraction and principle application. Similarly, the solution-based method incorporates the design subtasks: defining biological solution, principle extraction, solution reframing, problem search, problem definition, and principle application.

As one might expect, there are correspondences between many of the subtasks in the generic analogical design theory and the subtasks in our task model of biologically inspired design processes (see Figure 7). For example, the "biological solution search" in the problem-driven method and "problem search" task in the solution-based method corresponds to the "retrieval" subtask in the generic analogical design theory. The aggregate of "defining biological solution," "principle extraction" and "principle

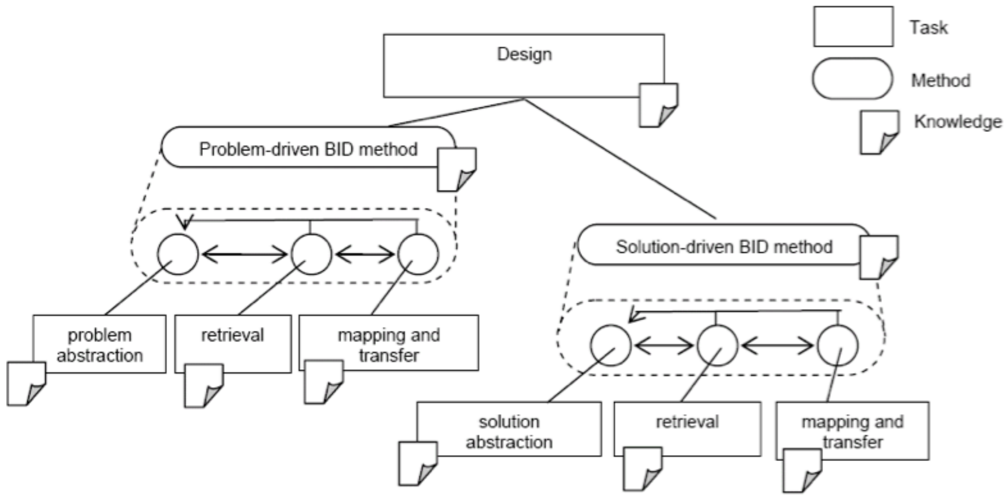

Figure 6. A generic task model of biologically inspired design after incorporating the two processes of problem-driven and solution-based design.

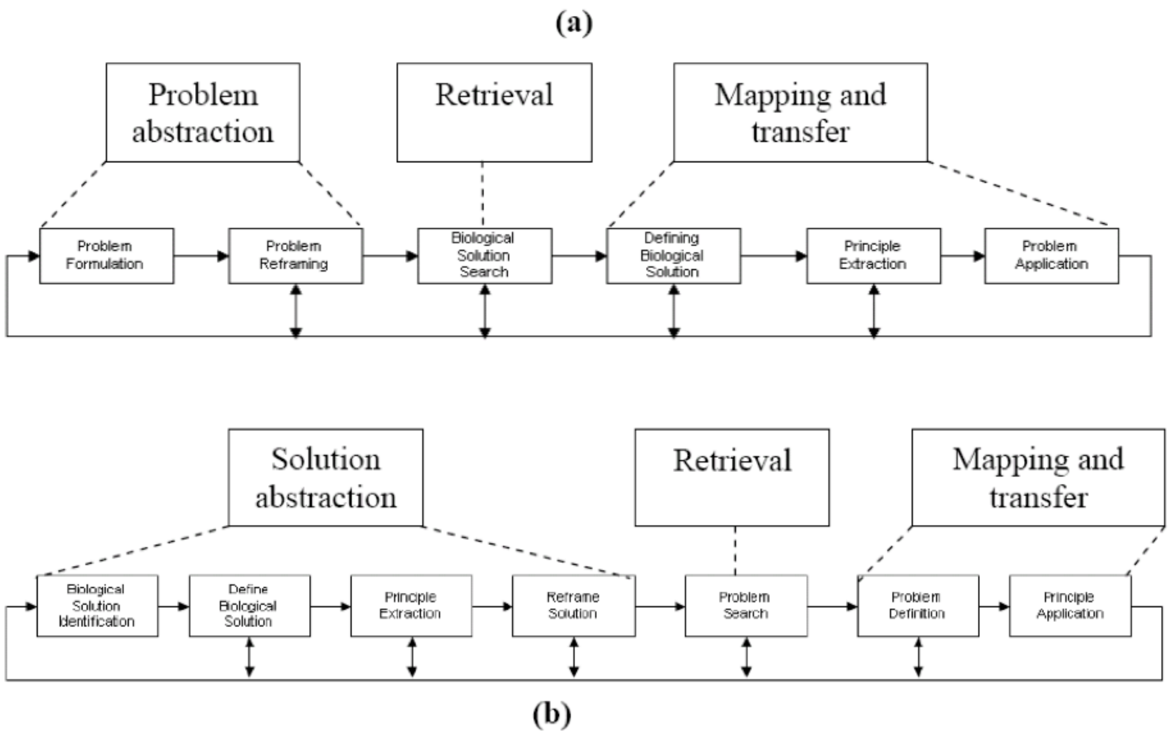

Figure 7. Correspondences between (a) problem-driven and (b) solution-based processes and the generic task model of biologically inspired design.

application" subtasks in the problem-driven method corresponds to the "mapping" and "transfer" subtasks; similarly, the aggregate of "problem definition" and "principle application" tasks results in mapping and transfer between source and target design situations.

On the other hand, there are elements of our observed biologically inspired design processes that are not addressed by the general analogical design theory. There is a set of subtasks that are considered preparatory to the subtasks of retrieval, mapping and transfer that follow. These include "problem abstraction" and "solution abstraction," which are pre-pended to the problem-driven and solution-based processes respectively.

Incorporating Compound Analogies

The second aspect of our observations that our task model must account for is the notion of compound analogy. Above we described compound analogy in the context of biologically inspired design and provided two examples.

Our observations also suggest a pattern of occurrence as far as compound analogy is concerned. In this pattern, compound analogy occurred as a result of the evaluation of initial design solution. First, the designers retrieved and transferred a biological source to propose an initial solution to the design problem at hand. For example, in the NOLA4NOLA project mentioned above, the team determined that multiple sub-problems caused the levees to fail in New Orleans (scour, joint cracking, etc.). After transferring one biological source to generate a design (e.g., transferring the complex underground network principle from riparian buffers to design a synthetic underground root network), the team evaluated their design and realized it was not sufficient to cover all the sub-problems. Addressing these additional problems became a design sub-problem in itself, for which they underwent another cycle of biologically inspired design to obtain a sub-solution. For example, they transferred the principle of multi-layered structures from the iron snail and redesigned the concrete levees to be multi-layered to solve the sub-problem of joint cracking. This sub-solution is incorporated into the initial solution to obtain a more complete solution. The process continued until all design challenges were met.

Incorporating compound analogy expands the task model of biologically inspired design model into the one shown in Figure 8. Here, S1 represents the initial solution obtained. The new subtask "evaluate" is added to both problem- and solution-based methods evaluates this initial solution. If a partial failure occurs, a new biologically inspired design subtask is added to address this failure as a new design sub problem. This in turn suggests a new sub solution S2. The subtask "compose" composes S1 and S2 to obtain a more complete solution to the original problem. For expediency, it is assumed here that subtask execution for compound analogy is sequential, represented by one-way arrows between the circles denoting the evaluation, designing and composition. The actual process may in fact involve more complex interactions.

COMPARATIVE ANALYSIS

In this section we will compare our task model of biologically inspired design with existing information-processing theories in terms of the four issues that we identified as being important for biologically inspired design: (i) making cross-domain analogies, (ii) accounting for the two processes of biologically inspired design, viz. problem-driven and solution-based design, (iii) problem decomposition, and (iv) compound analogy. We will show that while all current theories provide some theoretical coverage with respect to the above issues, none account for all four of these characteristics.

Design Spiral

Perhaps one of the most popular processes used for biologically inspired design is the Biomimicry Guild's "Design Spiral" [6]. The Design Spiral is a prescriptive theory for an iterative design process, where each design iteration informs the next. The basic idea of design spiral has been around in the design literature for some time (e.g., [8] in the domain of software design).

Within an iteration, the Design Spiral sub-divides biologically inspired design into six steps [6]: Identify, Interpret, Discover, Abstract, Emulate, and Evaluate. Each step has a set of prescribed actions associated with it. For example, the designer is advised in the Interpret step to

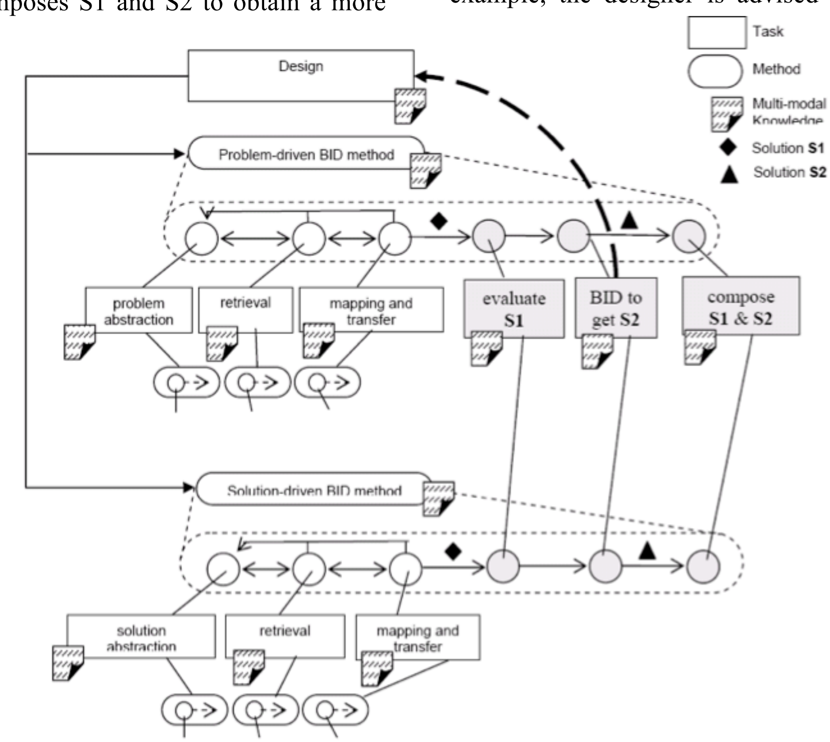

Figure 8. Incorporation of compound analogy into biologically inspired design model.

“[t]ranslate the design function into functions carried out in nature. Ask ‘How does Nature do this function?’ ‘How does Nature NOT do this function?’”

A comparison between our task model and the Design Spiral reveals the following similarities and differences:

- The Design Spiral is a prescriptive theory for biologically inspired design, presumably derived from best practices in other kinds of design. In contrast, our model is a descriptive theory that is based on *in situ* observations of biologically inspired design.
- Like our model, the Design Spiral characterizes biologically inspired design as an iterative process. The Design Spiral implies that one should pursue an entire iteration before beginning a new iteration (e.g., to return to Identify, one must go through all Interpret, Discover, etc. steps), whereas our model suggests that one could interrupt the process at any point to return to an earlier phase of design.
- The Design Spiral is problem-driven. The Identify and initial step assumes the designer begins with a design problem or desired function. Our model accounts for both problem-driven and solution-based design processes.
- The Design Spiral is silent on compound analogy *per se*, whereas our model explicitly accounts for this phenomenon. However, the iterative nature of the Design Spiral suggests that compound analogies may be possible within the framework.

Design Matrices

BioTRIZ [27] is a recent and preliminary information-processing theory of biologically inspired design derived from the earlier theory of engineering invention known as TRIZ [1]. The TRIZ theory begins with a repository of design cases with known solutions, where each case is indexed by contradictions that arose in the original design situation. For example, consider a case in the repository that represents the design of an airplane wing. In this case the designer faces the contradiction of obtaining a material that is both strong and light-weight, and solves it using a solution, say S_1. This case is then indexed by the contradiction “strong yet light-weight material.” Additionally, if the particular solution S_1 belongs to a more general way of resolving contradictions of a particular kind, it may be categorized as a generic abstraction, such as “use porous materials (to resolve the contradiction of strong yet light-weight material)”. TRIZ posits the existence of forty such generic ways of resolving conflicts, called inventive principles. The inventive principles were extracted by dropping the domain specifics and retaining the essence of how a particular class of contradictions is solved, so we can imagine each principle pointing to numerous cases (potentially belonging to different domains) in which that principle was used to resolve a conflict.

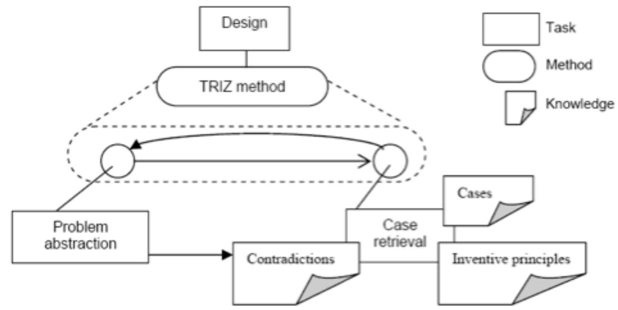

Figure 9. A model of TRIZ.

When the designer is presented with a design problem, she reformulates the problem to identify certain key contradictions in the requirements of the design. For each contradiction, she is reminded of a general inventive principle that is applicable for resolving that conflict. In addition to suggesting the essence of a solution for resolving that conflict, the inventive principle also points to a number of cases in which that general principle was instantiated. These cases can originate from domains different from the one in which the designer is currently working. TRIZ however does not address the issue of how transfer occurs [9]: “Then the creative skills of the designer are dedicated to interpret these models with their industrial realities in order to build a concrete given solution.”

Although TRIZ facilitates cross-domain design, it was developed primarily to work within engineering. Therefore, Vincent et al. [27] developed a modified version of TRIZ called BioTRIZ specifically for biologically inspired design. The primary difference between the two theories is a change in the features that compose the contradiction matrix. Whereas TRIZ defines 39 features with which to determine contradictions and index into innovative principles, BioTRIZ abstracts to six “operational fields”: substance, structure, space, time, energy, and information. The authors claim that these fields better characterize biological systems.

A comparison of Figures 8 and 9 reveals the following similarities and differences between BioTRIZ and our task model of biologically inspired design:

- BioTRIZ is a prescriptive theory of biologically inspired design, derived from best practices in engineering design. In contrast, our task model is a descriptive theory based on *in situ* observations of biologically inspired design in our classroom context.
- BioTRIZ provides an account for cross-domain case retrieval, but it does not address the issue of mapping and transfer.
- BioTRIZ is problem-driven. It does not address the question of how, given a design solution, one can find and solve other interesting problems that this solution is applicable to. Our task model accounts for both problem-driven and solution-based design.

IS BIOLOGICALLY INSPIRED DESIGN DIFFERENT?

This brings us to the question of if and how biologically inspired design is different from other kinds of creative design, or, put another way, what precisely makes it a new design paradigm? Note that the question is not whether or not biology and technology are different. As Vincent et al. [27] note, "biology and technology solve problems in design in rather different ways." French [13] makes a detailed analysis of the similarities and differences between biology and technological systems. Instead, the question here is whether or not the information *processes* of biologically inspired design are different from other kinds of creative and innovative design.

The design spiral and the design matrix theories of biologically inspired design certainly can be, and have been, applied to many kinds of design. In fact, the TRIZ design matrix theory arose out of engineering inventions, and it has been applied to many kinds of design. Similarly, the design spiral is used extensively in software design. Thus, according to the design spiral and the TRIZ design matrix theories, the processes of biologically inspired design are fundamentally the same as that of other kinds of creative design.

However, our task analysis offers some insights into what makes biological inspiration a new design paradigm from an information processing or cognitive perspective. Firstly, biologically inspired design is by definition based on cross-domain analogies. While other creative design can also sometimes engage in cross-domain analogies, and while biologically inspired design also engages within domain analogies, there are not many other kinds of design that are by definition based on cross-domain analogies. Secondly, many biologically inspired designs often entail compound analogies. Once again other kinds of creative design sometimes engage in compound analogies as well, but this seems to be a stronger characteristic of biologically inspired design. Finally, and perhaps most importantly, biologically inspired design engages in two very different creative design processes, namely, problem-driven and solution-based design. Insofar as we know, there are at present few theories of solution-based analogies in other kinds of creative design. Solution-based design appears to be another definitional characteristic of biologically inspired design.

CONCLUSIONS

In this paper, we first presented a task analysis of biologically inspired design based on our empirical observations of its practice. (1) Biologically inspired design by definition engages cross-domain analogies. (2) Problems and solutions in biologically inspired design co-evolve. (3) Problem decomposition is a fundamental process of biologically inspired design. (4) Biologically inspired design often involves compound analogies, entailing a complex interplay between the processes of problem decomposition and the processes of analogical retrieval from memory. (5) Biologically inspired design entails two distinct but related processes: problem-driven analogies and solution-based analogies.

We then described a task model of biologically inspired design. Due to lack of space, our description of the task model focused on only two results of our task analysis: that biologically inspired design involves compound analogies, and that biologically inspired entails both problem-driven and solution-based design. Insofar as we know, our task model of biologically inspired design is novel and unique.

Next, we compared our task model with the two best-known information-processing theories of biologically inspired design in the field: the design spiral and the design matrix TRIZ. Both the design spiral and the design matrix models address cross-domain analogies and admit problem decomposition. We can also see how the design spiral can admit problem-solution co-evolution and how the design matrix can admit compound analogies. However, both the design spiral and the design matrix are limited to problem-driven analogies; neither address solution-based analogies.

Finally, we analyzed what makes biologically inspired design a new design paradigm, and, in particular, how the process of biologically inspired design differs from other kinds of design. The design spiral and the design matrix theories view the process as fundamentally the same. In contrast, our task model of biologically inspired design suggests that it differs from other kinds of design in the use of cross-domain analogies, the use of compound analogies, and the use of both problem-driven and solution-based analogies. We are presently investigating the methodological, technological and pedagogical implications of our task model of creative analogies in biologically inspired design.

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