Proceedings of the ASME 2010 International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
IDETC/CIE 2010
August 15-18, 2010, Montreal, Quebec, Canada

DETC2010-28567

BIOLOGICALLY INSPIRED DESIGN: A MACROCOGNITIVE ACCOUNT

Swaroop S. Vattam
Design and Intelligence Lab
School of Interactive Computing
Georgia Institute of Technology
Atlanta, GA, USA
svattam@cc.gatech.edu

Michael Helms
Design and Intelligence Lab
School of Interactive Computing
Georgia Institute of Technology
Atlanta, GA, USA
mhelms3@gatech.edu

Ashok K. Goel
Design and Intelligence Lab
School of Interactive Computing
Georgia Institute of Technology
Atlanta, GA, USA
ashok.goel@cc.gatech.edu

ABSTRACT

Biologically inspired engineering design is an approach to design that espouses the adaptation of functions and mechanisms in biological sciences to solve engineering design problems. We have conducted an *in situ* study of designers engaged in biologically inspired design. Based on this study we develop here a macrocognitive information-processing model of biologically inspired design. We also compare and contrast the model with other information-processing models of analogical design such as TRIZ, case-based design, and design patterns.

Keywords: Engineering Design, Bioinspiration, Biomimetics, Cognitive Study, Cognitive Model, Analogy.

INTRODUCTION

Biologically inspired design (e.g., Vincent & Mann 2002) is an important movement in design that espouses the adaptation of functions and mechanisms found in nature to solve human problems. The practice of biologically inspired engineering design involves the identification and application of analogous biological phenomena to develop design solutions to engineering problems. By looking to nature for solutions, new and innovative ideas are being developed in a number of engineering disciplines like aerodynamics, robotics, bio-sensors, material science, biomedical engineering and more (e.g., Yen & Weissburg 2007).

In this paper we develop a *macrocognitive* model of biologically inspired design. Macrocognitive models (Klein et al. 2003) are high-level models of a cognitive task which take a different form and have different purposes compared to the more traditional cognitive models. Cognitive models traditionally describe performance for known, fixed tasks undertaken by human subjects in a laboratory, specified in terms of a causal chain of mental events, and built from relatively low-level mental operations such as short-term memory access and attention shifts. Macrocognitive models, on the other hand, describe major goal-directed functions of cognitive work (e.g., problem identification, solution search, planning) and the cognitive processes that support those functions (e.g., mental model building, memory retrieval, analogical transfer). Macrocognitive modeling is typically based on studies conducted in real world settings where subjects are situated in complex and dynamic situations. Macrocognitive models are also usually created with the intention of helping software system engineers develop better *human-centered* interactive technologies and work methods (Hoffman 2008).

Although a significant body of literature on biologically inspired design already exists, most of this literature reports case studies of specific instances of biologically inspired design, including the challenges and promises of innovation associated with those instances (e.g., Yen & Weissburg 2007). We view this work as a first step in the broader agenda of developing (1) design methodologies that promote a more systematic approach to biologically inspired design and help it gain more traction within the mainstream engineering design community and (2) interactive technologies that facilitate the work of individuals and teams engaged in biologically inspired design.

Table 1: A sample of biologically inspired design problems and solutions documented in the study (adapted from Helms, Vattam & Goel 2009).

Project	Design	Inspiration	Design approach	Design type
Abalone Armor	A self-healing bullet-proof vest that combines the qualities of strength and toughness	Material of abalone shell (nacre)	Solution-driven	non-compound
Traffic Control	A traffic system that reduces congestion on urban roads	Traffic load-balancing in ant colonies	Problem-driven	non-compound
Shell Phone	Cell phone case that is tough and resistant to everyday wear and tear	Material of abalone shell (nacre)	Solution-driven	non-compound
BioFilter	Portable, stand-alone, home air filtration system	Adhesive properties of spider silk + porous properties of diatoms	Problem-driven	compound
BriteView	Electronic display that is resistant to drowned illumination in bright sunlight	Hummingbird feathers + Morpho butterfly wings	Solution-driven	compound
Eye in the Sea	Underwater micro-bot with stealthy motion	Copepod locomotion + squid locomotion	Solution-driven	compound
InvisiBoard	Surfboard that does not produce silhouette when seen from underwater to prevent shark attacks	Counter-illumination mechanism in pony fish + photo-capture mechanism in Brittle star	Problem-driven	compound
iFabric	A thermally responsive and adaptive fabric for clothing that provides thermoregulation for the wearer	Bee hive material + blood circulation system of arctic wolves	Problem-driven	compound
RoboHawk	Aerial bomb detection device	Chemical sensing in dogs + scent tracking movement of sea gulls	Problem-driven	compound

The development of interactive environments for aiding biologically inspired design is a growing trend in design computing (e.g., Chakrabarti, et al., 2005; Shu, Stone, McAdams & Greer 2007; Vincent et al. 2006; Chiu & Shu 2007; Sarkar & Chakrabarti 2008; Nagel et al. 2008). In contrast to this existing literature, we want to ground our work on interactive biologically inspired design in cognitive studies from start. Through the present work, we wish to contribute to the relatively small but growing body of literature (e.g., Linsey, Wood & Markman 2008; Mak & Shu 2008; Helms et al. 2008; Vattam, Helms & Goel 2008; Helms, Vattam & Goel 2009; Vattam, Hemls & Goel 2009) that investigates biologically inspired design from a cognitive perspective.

Our approach for developing a high-level cognitive model of biologically inspired design employs two strategies: (1) conduct *in situ* studies of design processes and products of designers engaged in biologically inspired design, grounding our model in data obtained from the real world, and (2) use existing cognitive and AI models as lenses to examine the processes of biologically inspired design. Our earlier papers (e.g., Vattam, Helms & Goel 2008; Helms et al. 2008; Helms, Vattam & Goel 2009; Vattam, Helms & Goel 2009) describe detailed findings from cognitive studies of biologically inspired design. In contrast, this paper develops a macrocognitive information-processing model of biologically inspired design based on those findings. In the first part of this paper, we will briefly summarize the main findings from the cognitive studies because they form the basis for the subsequent analysis. In the second and main part of the paper, we will compare the processes of biologically inspired design with existing cognitive and AI models of analogical design, and develop a macrocognitive model of biologically inspired design. Finally, we will compare this model against other relevant models of analogy-based design.

BIOLOGICALLY INSPIRED DESIGN: INITIAL STUDY

This section briefly summarizes our findings about the practices and products of biologically inspired design through *in situ* studies of designers engaged in biologically inspired design. These findings form the basis for our subsequent macrocognitive analysis. Helms, Vattam & Goel (2009) provides a more detailed account of these studies.

The Context of the Study

ME/ISyE/MSE/PTFe/BIOL 4803 is a project-based undergraduate class, in which 45 students, 41 of whom were seniors, work in small teams of 4-5 designers on assigned projects. The class was interdisciplinary, composed of 6 biologists, 25 biomedical engineers, 7 mechanical engineers, 3 industrial engineers, and 4 from other majors. The projects involve identification of a design problem of interest to the team and conceptualization of a biologically inspired solution to the identified problem. Each team wrote a 15-20 page report and made an oral presentation near the end of the semester. In Fall 2006, ME/ISyE/MSE/PTFe/BIOL 4803 was jointly taught by six faculty members from Georgia Tech's Schools of Biology, Chemistry, Mechanical Engineering, Industrial & Systems Engineering, and Polymer, Textile and Fiber Engineering. The course also included guest lectures by several prominent researchers from other schools.

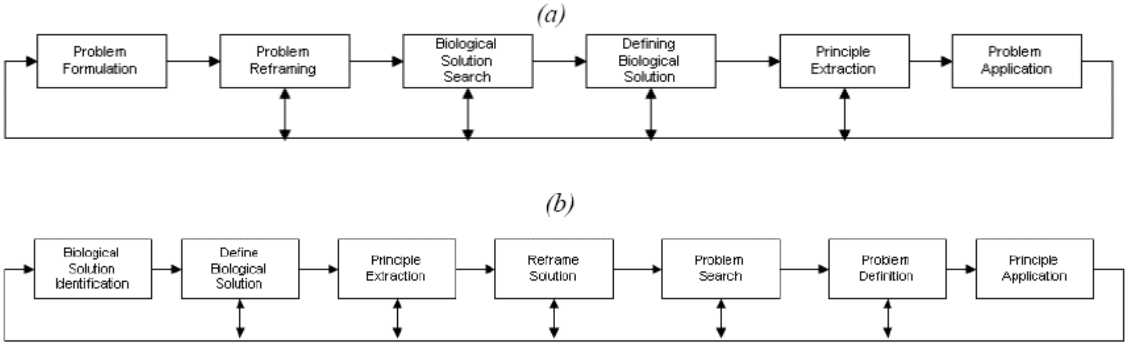


Figure 1: Observed biologically inspired design processes. (a) Problem-driven process, (b) Solution-driven process (adapted from Helms et al. 2008).

The ME/ISyE/MSE/PTFe/BIOL 4803 class was structured into lectures, found object exercises, journal entries, and a term design project. 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 semester-long design projects. Each design project grouped an interdisciplinary team of 4-5 designers together based on interest in similar problems or solutions. Each team had at least one designer 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. The teams presented their final designs during the last two weeks of class and submitted a final paper, which combined represented a majority of their semester grade. Table 1 highlights the nine design projects in the Fall 2006; the third and fourth columns in the table are explained in the next subsections.

Selected Findings

Here we provide a summary of selected findings from the above study, focusing only on findings that are directly relevant to the development of our information-processing model of biologically inspired design. (One potential issue associated with the classroom context we have chosen to study is how truly does it reflect a "naturalistic" setting of biologically inspired design. While we acknowledge this issue, we also think that it is reasonable to assume that this particular classroom context represents a microcosm of a real biologically inspired design setting for two reasons: (1) the project-based nature of the class where the students work on one serious project the whole term, and (2) the involvement of "real" biologically inspired designers as mentors. In the future, our observational studies will need to include design laboratories and other professional settings.)

Biologically inspired design processes: We observed the existence of two high-level processes for biologically inspired design based on two different starting points – *problem-driven* and *solution-driven* process. As depicted in Figure 1(a), in a problem-driven approach, designers identified a problem which formed the starting point for subsequent problem-solving. They usually formulated their problem in functional terms (e.g., stopping a bullet). In order to find biological sources for inspiration, designers "biologized" the given problem, i.e., they abstracted and reframed 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?). They used a number of strategies for finding biological sources relevant to the design problem at hand based on the biologized question. They then researched the biological sources in greater detail. Important principles and mechanisms that are applicable to the target problem were extracted to a solution-neutral abstraction, and then applied to arrive at a trial design solution.

As depicted in Figure 1(b), in the solution-driven approach, on the other hand, designers began with a biological source of interest. They understood (or researched) this source to a sufficient depth to support extraction of deep principles from the source. This was followed by finding human problems to which the principle could be applied. Finally they applied the principle to find a design solution to the identified problem.

Compound analogical design: We found that biologically inspired design often (in 66% of the observed projects) involved compound analogies in which a new design concept was generated by composing the results of multiple cross-domain analogies (Vattam et. al., 2008). This process of compound analogical design relies on an opportunistic interaction between two processes: problem decomposition and analogy. 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 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) source. For example, in the InvisiBoard project (see Table 1) the design goal was to conceptualize surfboard technology that prevented the formation of the surfboard silhouette to prevent hit-and-run shark attacks. The final solution was a combination of (1) the concept of ventral light glow (inspired by *pony fish*) that gives off light proportional to the ambient surface light for the purposes of counter-illumination and (2) the principle of photo-reception from surrounding light in the *brittle star* (echinoderms that are closely related to starfishes) for providing the counter-illumination rather than having to use energy to self-produce light.

In another example of compound analogical design, the BriteView project (see Table 1), the goal was to design a display screen that was resistant to drowned illumination in bright sunlight. The final solution was generated, as illustrated in Figure 2, by incorporating the following design concepts: (1) a thin-film structure composed of alternating layers of materials with different refractive indices to achieve iridescence and (2) a variable air gap that can be changed to reflect red, green or blue wavelengths. The former was inspired by structural coloration principles used in hummingbird plumage. The latter was inspired by the behavior of light within the air gaps found among nanostructures lining the Morpho butterfly wings.

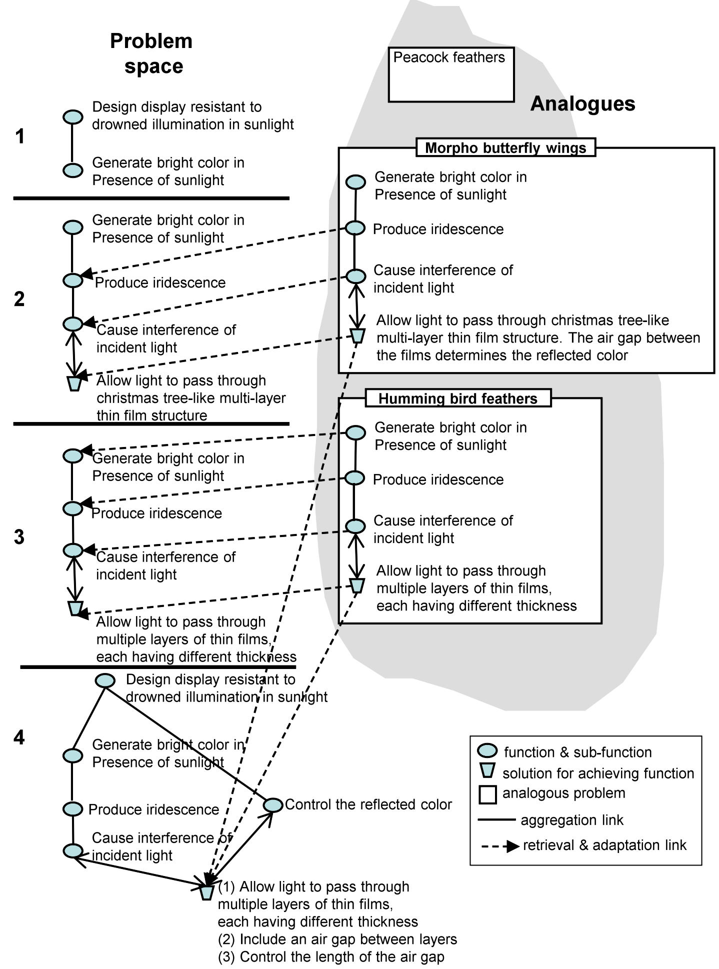
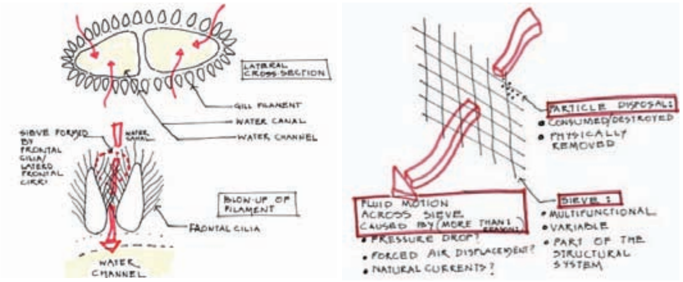


Figure 2: Design trajectory of one of the projects that exemplify compound analogical design (adapted from Vattam, Helms & Goel 2008).

Analogical design with multi-modal representations:

We observed that designers consistently used a combination of textual descriptions, pictures, graphs, and mathematical representations throughout the design process. These representations span not only multiple modalities (textual, diagrammatic, and pictorial) but also multiple levels of abstraction (pictures and diagrams of specific structures or parts of a biological system, to graphs and mathematical equations representing more abstract processes). Further, the use of multi-modal representations extended across disciplinary and level-of-experience boundaries.



(a) **(b)**

Figure 3: An example of the use of multi-modal representations obtained from design journals. (a) Filtering mechanism in Zebra mussel. (b) Conceptual model of a filtering mechanism inspired by the mussel.

This suggests that the rich representations the designers use are multimodal in nature and are organized at different levels of abstraction. One instance of this can be seen in the examples from the BioFilter project (see Table 1) presented in Figures 3a and 3b. This figure, reproduced from the designers' journal, gives us insight into some of the knowledge requirements for successful biologically inspired designing. The biological source (on the left) and the design solution (on the right) are both represented using a combination of textual and pictorial representations, and thus are multimodal. Additionally, the representations are explicitly capturing: (1) the relationship between the biological function and the biological mechanisms that achieves that functions on the one hand, and the engineered function and the engineered mechanisms for achieving that function on the other hand, and (2) the affordances and constraints posed by the physical structures for enabling the mechanisms in both biological and engineering designs. Designer's extensive use of multimodal representations also suggests that information represented in different modalities have their own unique advantages for analogy-making during biologically inspired design. A cognitive model of biologically inspired design should account for how knowledge represented in different modalities affords and constrains analogical reasoning in the context of design.

ANALOGICAL DESIGN AND BIOLOGICALLY INSPIRED DESIGN

The vast literature on design computing contains many macrocognitive information-processing models of design (e.g., Alexander, Ishikawa & Silverstein 1977; Altshuller 1984; Chandrasekaran 1990; Brown & Chandrasekaran 1989; Gero & Kannengiesser 2004; Campbell, Cagan & Kotovsky 2003; Tomiyama et al. 1989; Goel 1997; Goel & Bhatta 2004; Pahl & Beitz 1996; Suh 1990; However, since biologically inspired design is fundamentally analogical in nature, in this paper we focus on information-processing models of analogical design. In this section, we first summarize a generic information-processing model of analogical design. We will then elaborate this generic model to incorporate our findings presented in the previous section to obtain an information-processing model of biologically inspired design.

A generic model of analogical design

Figure 4 illustrates a generic information-processing model of analogical design that is consistent with information-processing models of analogical reasoning in general (such as Clement 2008; Falkenhainer, Forbus & Gentner 1989; Gentner, Holyoak & Kokinov 2001; Goel 1997; Hofstadter 1995; Holyoak & Thagard 1996; Kolodner 1993; Maher & Pu 1997; Nersessian 2008; Winston 1979). The overall *task* is design (see Figure 4). 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 (see Figure 4). 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.

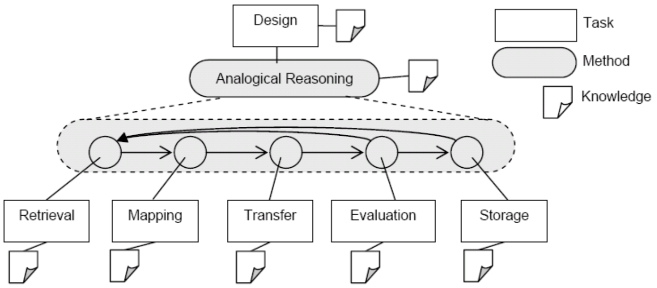


Figure 4: A generic model of analogical design

A Model of Biologically Inspired Designing

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

Incorporating problem-driven and solution-driven methods: 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-driven methods. These methods should incorporate tasks that were noted in their respective processes, depicted in Figure 1. 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-driven 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 model and the subtasks in our observed biologically inspired design process models (see Figure 5). For example, the "biological solution search" in the problem-driven method and "problem search" task in the solution-driven method corresponds to the "retrieval" subtask in the generic analogical design model. The aggregate of "defining biological solution," "principle extraction" and "principle 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 model. There are sets of subtasks that are considered preparatory to the subtasks of retrieval, mapping and transfer that follow. These include "problem abstraction" and "solution abstraction" in the problem-driven and solution-driven processes respectively (see Figure 6).

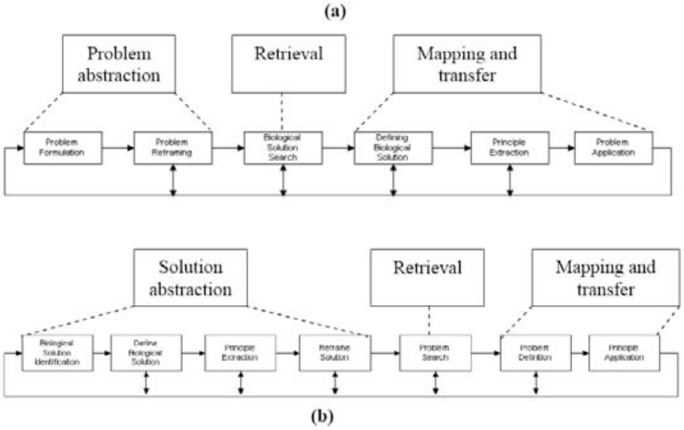


Figure 5: Correspondences between (a) problem-driven and (b) solution-driven processes and the generic analogical design model

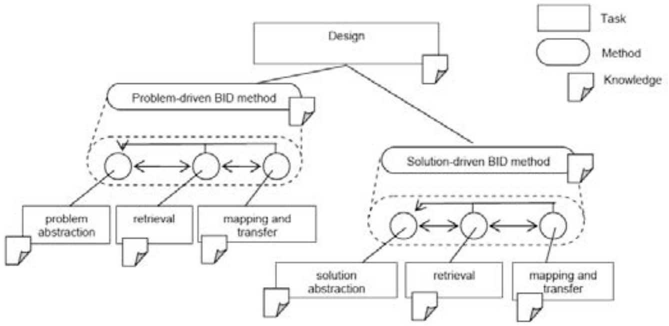


Figure 6: A generic biologically inspired design model after incorporating the two process models

Incorporating compound analogy: The second aspect of our observations that our model must account for is the notion of compound analogy. In previous section we described compound analogy in the context of biologically inspired design and provided two examples. Our pilot study analysis also suggested 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 surfboard problem mentioned in the previous section on compound analogy, they initially retrieved the case of the pony fish and transferred the phenomenon of counter-illumination to obtain a solution that included placing a ventral light source on the surfboard. Second, when they evaluated this initial solution, they identified additional constraints that needed to be met. Addressing these additional constraints became a design sub problem in itself, for which they underwent another cycle of biologically inspired design to obtain a sub-solution. For example, when they evaluated their initial design of the surfboard, they realized that they needed to include a power source for the light included in the design, which made the surfboard heavy and was not desirable. This introduced a constraint of finding an alternative source of power, which became a design problem in itself. To address this problem, they retrieved the case of the brittle star and transferred the phenomenon of photo-reception from ambient light to power the light source. This sub solution is incorporated into the initial solution to obtain a more complete solution.

Incorporating compound analogy into the biologically inspired design model incrementally expands the model as shown in Figure 7. Here, S1 represents the initial solution obtained. The new subtask "evaluate" added to both problem- and solution-driven 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.

Incorporating multi-modal representations: In previous section regarding multi-modal representations, we stated that our designers consistently used a combination of textual descriptions, pictures, graphs, and mathematical representations. These span representations across multiple modalities (textual, diagrammatic, and pictorial) and across multiple levels of abstraction (pictures and diagrams of specific structures or parts of a biological system, to graphs and mathematical equations representing abstract phenomena).

The general analogical design model presented in Figure 4 illustrates that *tasks* and *methods* are associated with *knowledge*. Specifically, these tasks and methods are coupled with the knowledge inputs and outputs required for their processing. The generic analogical design model can place constraints on the *content* (e.g., knowledge should contain teleological models of devices) and the *representation* of that knowledge (e.g. teleological models should be represented in schema-based representations) based on the requirements of the task or method with which that knowledge is associated. However, it is neutral to the *modality* of the representation. In order to incorporate multi-modality into the biologically inspired design model, at the very least certain tasks and methods should allow for and use knowledge represented in different modalities. For example, consider the task of retrieval. This task requires a knowledge base of various biological cases from which to suggest a particular source(s). Our results imply that representations of these systems can contain not only textual/linguistic modalities but also various kinds of diagrammatic/pictorial modalities. The task of retrieval should incorporate techniques that will also take advantage of knowledge that is present in these other modalities, for example diagrammatic reasoning (Glasgow, Narayanan and Chandrasekaran 1995; Davies, Goel & Yaner 2008; Davies, Goel & Nersessian 2009). The incorporation of multi-modal representations is minimally captured in our developing model shown in Figure 7. This model shows that all the tasks and methods can potentially be associated with, and make use of multi-modal knowledge. Further research is required to determine the exact role played by multi-modal representations in achieving the intended functions of tasks and methods.

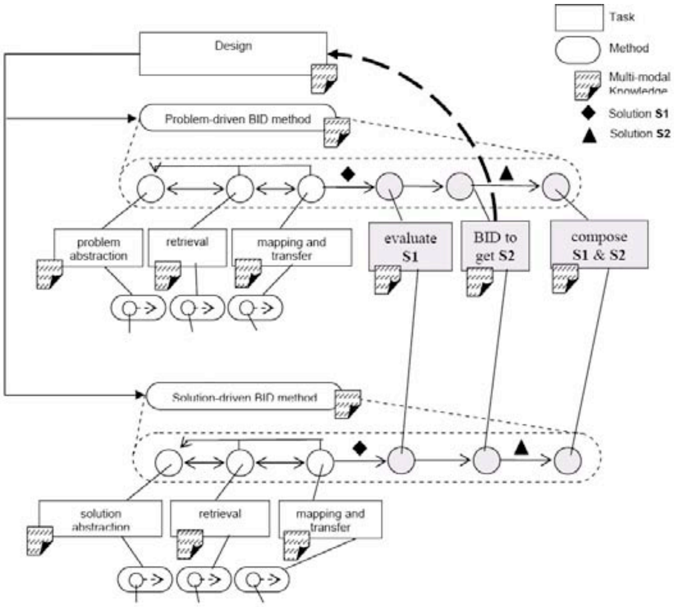


Figure 7: Incorporation of compound analogy into biologically inspired design model

COMPARISON TO OTHER FRAMEWORKS

In this section we will compare some existing theories and models against the five issues that we identified as being important for biologically inspired design: (i) making cross-domain analogies, (ii) accounting for two processes of biologically inspired design, viz. problem-driven and solution-driven processes, (iii) compound analogy, and (iv) multi-modal representations. We hope to show that while all of them provide some theoretical coverage with respect to the above issues, none account for all of them.

Case-based design

Case-based reasoning provides one general answer to how new problems (including design problems) are solved by referring to familiar problems with known solutions (Goel & Chandrasekaran 1992; Goel, Bhatta & Stroulia 1997; Kolodner, 1993; Maher & Pu 1997; Wills & Kolodner 1996). Given a problem P_{new}, first the designer is reminded of a familiar problem P_{old} with a solution S_{old}, where P_{old} and P_{new} are so similar that S_{old} is an approximate solution for P_{new}. The designer then modifies the selected components in S_{old} to obtain a candidate solution S_{new} to P_{new}. Thus in case-based design, the entire solution S_{old} is transferred to S_{new} and modified to fit the specifications of P_{new}. Case-based design thus appears to be a limiting case of the general analogical design model presented earlier in which (a) P_{new} and P_{old} are very similar and (b) the mapping is a non-issue and the question of transfer reduces to the question of what to modify. A model of case-based design is shown in Figure 8.

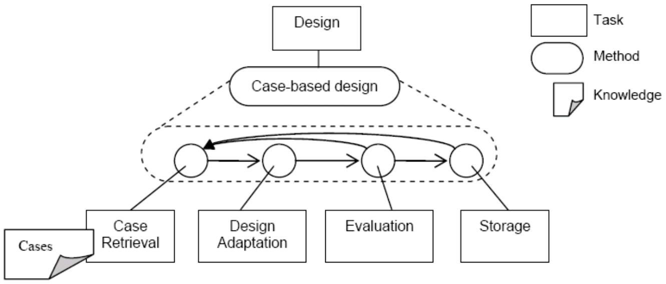


Figure 8: A model of Case-based Design

A comparison of Figures 7 and 8 reveals the following similarities and differences between the biologically inspired design model and case-based design:

- Case-based design always starts with a problem, whereas biologically inspired design can also start with a solution.
- Case-based design does not account for some of the tasks and methods that are required to approach a biologically inspired design problem from a solution-driven perspective, including solution abstraction to obtain a transferable principle, and problem search and application of a known principle to a new problem.
- Case-based design has no notion of compound analogy, as it assumes that P_{new} and P_{old} are so similar that the solution S_{new} can be obtained by directly adapting S_{old}, emphasizing that entire solutions are transferred in case-based design.
- Case-based design does not emphasize the multi-modality of its representations. As a result, there have been few attempts in case-based design to produce models that employ multi-modal representations.
- Case-based design, requiring similar P_{new} and P_{old}, does not usually address cross-domain analogies, which is required for biologically inspired design by definition.

There are other theories and models related to analogical design that do address the issue of cross-domain retrieval, mapping and transfer. These theories typically employ *generic abstractions* to achieve cross-domain transfer. The analogical reasoning literature in both AI and cognitive science (e.g., Clement 2008; Falkenhainer *et al.*, 1989; Gentner, Holyoak & Kokinov 2001; Goel 1997; Goel & Bhatta 2004; Holyoak & Thagard 1996; Nersessian 2008; Winston 1979) suggests that these generic abstractions are not merely abstractions over features of objects, but they capture relational structure among objects and processes. This implies that the availability of these generic patterns through learning (or otherwise) is an important characteristic of cross-domain analogical design.

Design patterns

Design patterns (Alexander, Ishikawa & Silverstein 1977) are a kind of generic abstractions that capture knowledge of relations among objects and processes. Design patterns can be of many types depending on the kinds of relations they capture, for example, spatial and structural relations (e.g., Griffith, Nersessian & Goel 1996, 2000) and functional and causal relations (e.g., Bhatta & Goel 1997; Goel & Bhatta 2004). Recent work on design computing has led to computer systems that use design patterns to perform analogical design such as the IDEAL program (Bhatta & Goel 1997; Goel & Bhatta 2004). Similar to case-based design, IDEAL also requires a repository of design cases with known solutions. These cases are indexed by functions in IDEAL. In addition to cases, IDEAL also requires generic abstractions called *design patterns* to facilitate cross-domain knowledge transfer. Design patterns in IDEAL are generic, solution-neutral abstractions over multiple designs that IDEAL *learns* from the design cases in its repository. For example, a number of designs in its repository might implement some form of feedback. Therefore, it learns the abstract "feedback" concept, omitting the specifics of individual cases. Each case in IDEAL contains knowledge about a particular device and the function that the device achieves.

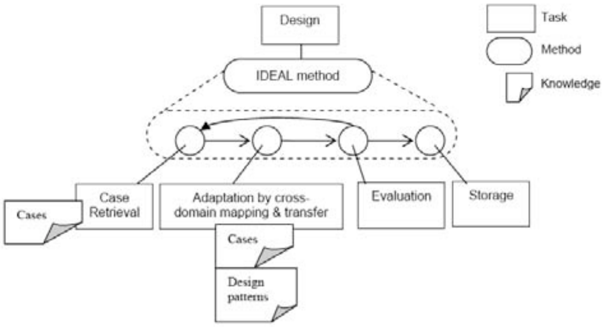


Figure 9: A model of IDEAL

In the IDEAL model, given a specification of the desired function, the designer first retrieves a source design case from the repository that delivers the function closest to the desired function. For example, let us assume that the goal is to design a device that produces an angular momentum with some magnitude $L_{avg} \pm \delta$ (where δ represents a small fluctuation over an average value L_{avg}). The designer probes the memory of design analogues and retrieves the design and SBF model specification of a simple gyroscope. The function of the retrieved design is similar to the desired function except that the output angular momentum fluctuations can fluctuate over a range greater than δ.

Next the designer must modify the retrieved design to achieve the required function. IDEAL supports two kinds of modifications: (1) local modifications, characterized by changes only with respect to the parameters of the source design (while retaining the design elements and the design topology), and (2) non-local modifications, characterized by changes to the design topology itself. We suspect that design adaptation from biology to engineering domains will almost always involve non-local changes.

In order to perform a non-local modification the designer uses an analogy, facilitated by design patterns. In the above example, when the functional model of the simple gyroscope is analyzed, the designer determines that the output fluctuation of a simple gyroscope is too great. The designer is reminded of the general "feedback" design pattern, which reduces the size of output fluctuation, a direct functional match. The "feedback" design pattern also refers to one or more specific design cases in which the feedback mechanism is implemented. Further, the designs pointed to by the pattern can be from different domains such as an operational amplifier from the electrical domain, which is different from mechanical domain of gyroscopes. The designer then applies the general feedback mechanism to the simple gyroscope design to regulate its output fluctuation. Here the analogue of operational amplifiers is used to adapt the case of a simple gyroscope to achieve the desired function.

A comparison of Figures 7 and 9 reveals the following similarities and differences between the biologically inspired design model and the IDEAL model:

- Retrieval is based on functions in both models.
- Cross-domain mapping and transfer occurs in both models.
- IDEAL is predominantly problem-driven and cannot account for the solution-driven process.
- IDEAL does not address problem decomposition and the subsequent guiding of the analogy process.
- IDEAL does not address the notion of compound analogy.

TRIZ

We interpret TRIZ (Altshller 1984) as a theory of analogy-based design invention. The TRIZ model can be considered an extension of the case-based design model discussed in the last section. In the TRIZ model there is 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. These 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.

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 (Cavallucci, 2002): "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."

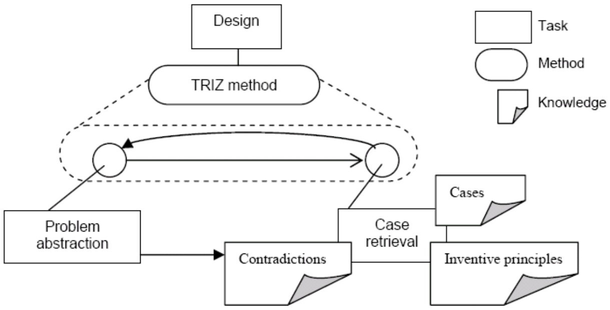


Figure 10: A model of TRIZ

A comparison of Figures 7 and 10 reveals the following similarities and differences between the biologically inspired design model and TRIZ:

- TRIZ provides an account for problem abstraction and cross-domain case retrieval, but it does not address the issue of mapping and transfer.
- TRIZ 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.
- TRIZ does not address the notion of compound analogy.
- TRIZ does not provide any interesting content account or representational account of knowledge of either the cases or the generic abstractions (inventive principles).

CONCLUSION

Our research goal is to understand the cognitive basis of biologically inspired design, and to use this understanding to develop computational methods and tools to support engineering designers. We first conducted a study of biologically inspired design *in situ* and identified salient aspects of biologically inspired design as described in our earlier papers (Vattam, Helms & Goel 2008; Vattam, Helms & Goel 2009). In this paper, we sketched a macrocognitive information-processing model of biologically inspired design (see Figure 7). This model is based on several observations. (1) Biologically inspired design entails cross-domain analogies. (2) Biologically inspired design entails two distinct but related processes: problem-driven design and solution-based design. (3) There is a rich and complex interplay between the process of problem decomposition and the process of analogical mapping and transfer of knowledge from the domain of biology to engineering. (4) Biologically inspired design often involves compound analogies. (5) Successful biologically inspired design requires that designers carry rich representations of the systems they bring to bear during design. Further, these rich representations are multimodal in nature and are organized at different levels of abstraction. These representations also explicitly capture functions and mechanisms that achieve those functions on the one hand, and the affordances and constraints posed by the physical structures for enabling the said mechanisms on the other hand.

We also compared our information-processing model of biologically inspired design with three existing models of analogical design. We found that the compared models do not address all the salient aspects of biologically inspired design that we have uncovered, with different theories having different explanatory strengths and weaknesses. Our next efforts on biologically inspired design include (1) bridging the theoretical gap that exists by extending the existing theories of analogical design to encompass biologically inspired design, (2) developing normative approaches to biologically inspired design based on our theory-building to increase the success rate of biologically inspired design and to accelerate the innovation accompanied by this approach to design, and (3) designing and developing computer-based support tools to enhance and facilitate the process of biologically inspired design. Recently, we have developed an interactive tool called DANE (for Design by Analogy to Nature Engine) and introduced it within the biologically inspired design classroom we discussed earlier. We are presently analyzing the results of this intervention.

ACKNOWLEDGEMENTS

We thank the instructors and students of the ME/ISyE/MSE/PTFe/BIOL 4803 class in Fall 2006, especially Profs Jeannette Yen and Marc Weissburg, This research is supported by an NSF Creative IT Grant (#0855916) entitled MAJOR: Computational Tools for Enhancing Creativity in Biologically Inspired Engineering Design.

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