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SEEKING BIOINSPIRATION ONLINE: A DESCRIPTIVE ACCOUNT

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ABSTRACT

Biologically inspired design, which espouses the use of analogies to biological systems in generating conceptual designs for engineering problems, is emerging as an important movement in modern design. A key initial task in the design paradigm - seeking bioinspiration - identifies relevant biological systems to use as analogies. Current efforts at supporting designers in this task tend to be technology centric and do not take sufficiently into account the actual practices and the everyday context of designers engaged in this task. As a result, there is a disconnect between the reality of seeking bioinspiration and the technological interventions for aiding it. Here we present two studies that focus on describing the current practices and challenges of seeking bioinspiration. We find that seeking bioinspiration is significantly situated in online information environments where designers are confronted with three main challenges: findability, recognizability and understandability. We also indicate how this descriptive account leads to an information-processing model of online bioinspiration seeking which may be leveraged to developing more human-centric approaches for technological interventions.

Keywords: biomimetics, design process, human behaviour in design, analogy, information seeking

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1 INTRODUCTION

Biologically inspired design (Benyus, 1997; Vincent & Mann, 2002; Yen & Weissburg, 2007; Chakrabarti & Shu 2010; Shu *et al.* 2011) espouses the use of analogies to biological systems in generating conceptual designs for engineering problems. Pulled by the growing need for environmentally sustainable design and pushed by the desire for creativity and innovation in design, biologically inspired design is emerging as an important movement in modern design. Recent examples emerging from this design paradigm include Velcro (inspired by the attachment mechanism of burr seeds; Simonton 2004), a new class of adhesives (inspired by attachment mechanism of gecko feet; Lee, Lee & Messersmith 2007), and next generation wind turbine technology (inspired by the structure of flippers of humpback whales; Fish & Battle 1995; Ashley 2004).

Yet, the practice of biologically inspired design at present is largely *ad hoc* with no well-established communities of practice. Best practices, design methodologies, pedagogical techniques, and interactive tools for systematic transfer of knowledge from biology to engineering remain under-researched. The flow of ideas, concepts, and principles from biology to engineering is mostly incidental or solution-based. Incidental flow here means that the origin of the biological source of inspiration is either serendipitous or happens through *ad hoc* associations between biologists and engineers. In solution-based design, the design process starts from solutions rather than other way around: it begins with a biological source and looks for engineering problems to which the solution may be applicable (Helms, Vattam & Goel 2009).

As the biologically inspired design movement gains momentum, increasing numbers of engineering designers are beginning to take an interest in the paradigm. However, engineering designers are more likely to proactively look for biological sources of inspiration for their design problems rather than start with a biological source or wait for serendipitous encounters with biology. This shifts the emphasis from solution-based to problem-driven biologically inspired design.

Problem-driven biologically inspired design is a complex activity that encompasses many challenging tasks. In this paper, we focus on a key initial task of biologically inspired designing, namely, *seeking bioinspiration*. Given a target design problem, the task of seeking bioinspiration involves finding relevant biological systems that can act as useful analogies. A biological system is considered relevant if the application of the knowledge of its workings can lead to a potentially novel and useful solution to the target design problem. The importance of this task for biologically inspired design cannot be overstated: the design outcomes of biologically inspired design are strongly dependent on the biological systems that are discovered as sources of inspiration.

Although engineering designers may be experts in their engineering disciplines, most designers are not experts in biology. There are millions of species of biological organisms (Mora *et al.* 2011). If one takes into account different levels of organization of biological organisms like the molecular-, cellular-, organ-, and ecosystem-levels, then the estimated number of biological systems may increase by more than an order of magnitude. However, engineering designers typically are not fully familiar with the scope and richness of biology. Most of them may be aware of only a tiny fraction of the vast space of biological systems that can be drawn upon in order to develop design solutions. The near limitless availability of biological systems to draw upon coupled with engineering designers' lack of knowledge of the vast space of biological systems makes seeking bioinspiration a challenging task.

We need to better understand the information needs of engineering designers in order to systematize biologically inspired design. The question then becomes: How do engineering designers in fact find relevant systems from the vast space of available biological systems that belong to a completely different and mostly unfamiliar domain? Currently, there are a number of technology-building efforts to help designers find their biological sources of inspiration, including web portals and organize databases (e.g., www.asknature.org; http://dilab.cc.gatech.edu/dane/), information retrieval tools based on natural language (e.g., Chiu & Shu 2007) and engineering-to-biology thesauri to facilitate this retrieval (e.g., Nagel, Stone & McAdams 2010), and digital libraries that capture knowledge of biological and technological systems in a formal language and use navigation techniques to connect the two domains (e.g., Chakrabarti *et al.* 2005; Goel *et al.* 2012). However, the basic question about how do engineering designers in fact find relevant biological systems has not been studied in its own right. As a result, current technology-centric efforts to aid the practice of biologically inspired design are driven largely by trial and error. In this paper, we present two *in situ* studies of designers engaged in biologically inspired design that aims to bridge this gap, and provide a foundation for developing a more human-centric, data-driven approach to aiding biologically inspired design.

2 THE CONTEXT OF THE STUDIES

We conducted the two *in situ* studies of designers in the context of a Georgia Tech senior-level course on biologically inspired design (ME/ISyE/MSE/PTFe/BIOL 4740) in Fall 2006 and Fall 2008 respectively. This interdisciplinary project-based course is offered in the Fall semester of every year, and typically is taught jointly by biology and engineering faculty. Yen *et al.* (2011) provide details of the teaching and learning in the course.

The most important element of ME/ISyE/MSE/PTFe/BIOL 4740 for us is the semester-long design project. Each design project groups an interdisciplinary team of 4-6 designers together based on similar interests. It is ensured that each team has at least one designer with a biology background and a few from different engineering disciplines. Each team identifies a problem that can be addressed by a biologically inspired solution, explores a number of solution alternatives, and develops a conceptual design solution based on one or more biological sources of inspiration. All teams present their conceptual designs during the last two weeks of class and submit a final design report.

3 THE METHODOLOGY OF THE STUDIES

In this section we briefly describe our methodology for data collection and analysis in the two studies. Vattam (2012) describes the studies, the data, and the methodology in detail.

3.1 Fall 2006 study

In Fall 2006, ME/ISyE/MSE/PTFe/BIOL 4740 attracted 45 students, 41 of whom were seniors. The class was composed of 6 biologists, 25 biomedical engineers, 7 mechanical engineers, 3 industrial engineers, and 4 from other majors. Most students, although new to biologically inspired design, had previous design experience. Out of the 45 students, at least 32 had taken a course in design and/or participated in design projects as part of their undergraduate education. The students were grouped into nine design teams, resulting in nine biologically inspired design projects by the end of this term.

In the Fall 2006 study (Vattam, Helms & Goel, 2007), we adopted an observational approach. Two researchers, including the first author of this paper (Vattam), externally observed participant activities both inside and outside the classroom setting. Inside the classroom, we attended all classroom sessions that included lectures, individual and group “found object” exercises, presentation and critiquing of design ideas, discussion of practical challenges of engaging in bio-inspired design, in-class team design meetings, and formal presentations after completing different milestones in the project, etc. Outside the classroom, we attended many design meetings of various teams. During these meetings we were able to observe the interactions among members of the design teams. We were also able to observe and document various kinds of external representations (e.g., diagrams, equations, graphs) that were created and propagated by various design teams throughout the design episode. Both researchers kept detailed field notes on their observations.

We also collected all the work products generated by all the nine design teams. After each milestone in the design projects (e.g., problem definition, biological search, initial design, or design analysis), design teams were required to submit a document detailing their accomplishments leading up to that milestone. These documents gave us snapshots in the progression of the design over the semester-long duration. The final design report, which captured different aspects of their finished design, also provided another data point for our analysis. We also collected the materials that were used to make formal presentations to the class.

The design idea journals maintained by each team member in the design teams was another source of data. As part of the course requirement, all participants were asked to maintain a free-form journal in which they were required to not only externalize their design thoughts and the biological systems they encountered, but also reflect on the design process and the activities they were undertaking. In order to motivate students to make effective use of the journal, it was collected and evaluated by the instructor every week from a small set of randomly selected students. At the end of the term, the idea journals from all the participants were collected by the instructor, which were subsequently shared with the researchers. To sum up, the data for this study mainly came from three important sources: 1) direct observations of two researchers captured in field notes, 2) work products produced by design teams, and 3) idea journals maintained by individual design team members.

3.2 Fall 2008 study

In Fall 2008, the ME/ISyE/MSE/PTFe/BIOL 4740 course attracted 43 students. The class was composed of 16 biologists, 2 biomedical engineers, 10 mechanical engineers, 7 industrial engineers, and 6 material science engineers, and 2 from other majors. In 2008, students were grouped into eight design teams, resulting in eight design projects by the end of the term.

In the Fall 2008 study (Vattam, Helms & Goel 2010), we adopted a *participatory case study* (Reilly 2010) approach. After the Fall 2006 study we realized that we were not getting enough fine-grained data and that a significant amount of work on seeking bioinspiration was happening in contexts that we were unable to observe (e.g., at the participants' homes). Therefore, the first author of this paper (Vattam) registered for the course and participated in the biologically inspired design projects like all other students. With full participation, the researcher became an integral part of a design team and obtained not only firsthand experience with bioinspiration seeking, but also a chance to closely interact with and understand the experiences of fellow team members who were also engaged in this task. While in the Fall 2006 study we got a bird's-eye view of all the nine design projects, in Fall 2008 we got a much more detailed view of one team's activities.

When the design teams were formed during the initial stages of this course, the researcher became part of a design team called FORO. Upon joining this team, the other team members were made known about the study and their consent was obtained. Precautions were taken to ensure that their participation in this study did not impact or influence their grades in any way.

In terms of data, the participant researcher maintained a field note journal where he noted his observations. His notes included observations of: 1) student-instructor and student-student interactions inside the classroom, 2) team interactions inside the classroom, and 3) team interactions outside the classroom, mostly restricted to design team meetings. With regard to team interactions, he recorded the thoughts expressed by members during the team meetings, the concepts that were discussed, the ideas that were thrashed out, the external representations that were constructed (e.g., diagrams on the white boards), etc. Additionally, he noted his own bioinspiration seeking experiences like the keywords that were used, the results that information environments returned, the problems that he faced, how long it took him to find information sources, etc. Then he discussed some of the issues that he faced with his team members and noted their reflections on those issues in the field journal. All electronic communication between team members was yet another source of data.

Similar to the earlier Fall 2006 study, each team member of FORO design team maintained his or her own idea journal, which provided another source of data. Also similar to the Fall 2006 study, we collected all the work products generated by team FORO as well as the final design report.

3.3 Data analysis

The general data analysis strategy used in these studies was development of case descriptions (Eisenhardt 1989; Yin 2009). This qualitative analytic strategy involves developing a descriptive framework for organizing and presenting the data from a study. It is considered an alternative to the approach of starting with theoretical propositions; it is applicable to situations when researchers collect data without having settled on an initial set of research propositions. In Fall 2006, we observed nine design teams and hence we developed nine high-level case descriptions. In Fall 2008, we observed and participated in one design project and hence we developed one very detailed and rich case description. All these case descriptions can be found in Vattam (2012).

This general qualitative analytic approach was operationalized using more specific analytic techniques like time-series analysis, and cross-case synthesis. The guidelines for time-series analysis suggest tracing, in detail, the salient events that occur over time (Yin 2009). In this case, the events within individual design teams related to design information processing were traced from the project beginning to the end in order to develop design trajectories. These events could have had its origins either in direct observations or in observations gleaned from work products and idea journals or both.

Cross-case synthesis (Yin 2009) is an analytical technique that applies to situations where more than one case descriptions are developed, aggregating findings across multiple individual cases. Cross-case synthesis is usually performed when the individual case studies have previously been conducted as independent research studies (authored by different researchers). But it can also be performed when multiple case studies are predesigned as part of the same research study. Cross-case synthesis is considered to yield more robust findings rather than findings obtained from a single case description.

4 FINDINGS FROM OUR STUDY

In this section, we briefly describe the main findings from the two studies. Vattam (2012) describes the findings in detail.

4.1 Cross-domain and compound analogies

Biologically inspired engineering design by definition is based on cross-domain analogies from biology to engineering. Our case descriptions further show that a single design solution may sometimes require multiple biological sources of inspiration (Vattam, Helms & Goel 2008). One single biological source was not always available to help solve a target design problem in its entirety. In such cases, the design solution was generated in a piecemeal or modular fashion by composing the resultants of multiple analogies to smaller sub-problems, while the target design problem evolved with each application of an analogy. This implies that the act of actively seeking bioinspiration is not a one-time exercise in a given design episode. In the Fall 2006 study, 6 out of 9 (66%) design solutions were generated by composing the results of multiple cross-domain analogies. Similarly, in the following year (Fall 2007), 4 out of 10 (40%) of the design solutions were compound solutions.

One implication of such cases of compound biologically inspired design situations is that a single design episode requires multiple undertakings of the task of seeking bioinspiration. Due to this any improvements in giving support to designers accomplish this task can have a multiplier effect, resulting in greater payoff for designers.

4.2 Online search for cross-domain analogies.

Designers searched online for biological information about systems that are analogous to the target design. Based on our observations, this was one of the predominant approaches for finding biological sources of inspiration. Designers reported using a range of online information environments to seek information resources about biological systems. These included: 1) online information environments that provided access to scholarly biology articles like Web of Science, Google Scholar, ScienceDirect, etc., 2) online encyclopedic websites like Wikipedia, 3) popular life sciences blog sites like Biology Blog, 4) biomimicry databases like AskNature, and 5) general web search engines like Google. But the most frequently used environments were the ones that provided access to scholarly biology literature like Web of Science and Google Scholar. Biology articles, both scholarly and otherwise, were the predominant types of media or information resources consumed during the process of online bio-inspiration seeking.

4.3 Strategies for online search for cross-domain analogies

The target problem and the sources of inspiration in biologically inspired design are situated in different domains. If cues from the target problem alone are employed during search, then designers are likely to find information resources that belong to the engineering domain rather than biology. We observed several strategies used by designers in order to bridge the engineering-biology divide.

The first strategy was to “biologize” the problem. Biologizing the problem involved redefining the problem by taking the key concepts in the design problem and substituting them with similar biological concepts. Then the concepts from the biologized problem were used as cues in order to search for biological systems. For instance, in one of the projects, the concept of a light-emitting material that resisted drowned illumination in sunlight was biologized to organisms producing iridescent colors in the presence of sunlight. Then the concept of iridescence was used to find biological systems that had this feature. Although this process of biologizing the problem was observed in all the design projects, it remains a black box: there were no explicit rules for how to do this, but relied on the tacit knowledge of designers. The other strategies that were used are shown in Table 1.

It should be noted that the core of the strategies in Table 1 involve using certain abstractions to bridge the domain of technology and the domain of biology. These abstractions include *functions* (e.g., strategies like biologizing, inverse functions, multi-functionality involves abstracting and/or transforming the functions), *operating environment* (e.g., the strategy of champion adapters), *mechanisms/physical principles* (e.g., the strategy of variation within solution family involves similarity across mechanisms and principles), and *constraints* (e.g., the strategy of changing constraints).

Table 1. Strategies for seeking bioinspiration

Strategy	**Description**
Change constraints	If the problem is narrowly defined, such as ‘keeping cool’, change the constraints to increase the search space, for instance to ‘thermoregulation’.
Champion adapters	Find an organism or a system that survives in the most extreme case of the problem being explored. For instance, for ‘keeping cool’, look for animals that survive in desert or equatorial climates.
Variation within a solution family	Where multiple organisms have faced and solved the same problem in slightly different ways, e.g. bat ears and echolocation, look at the small differences in the solutions and identify correlating differences in the problem space.
Multi-functionality	Find organisms or systems with single solutions that solve multiple problems simultaneously.
Inverse functions	If a particular function is not yielding many biological solutions, inverse the function. For instance, if the function is ‘keeping cool,’ look for organisms that achieve the function ‘keeping warm.’ In some cases, the inversed function might yield many potential systems. Learning about the mechanism for the inverse function can sometimes yield insights into accomplishing the original function.

4.4 Challenges of online bioinspiration seeking

The online information environments on which designers relied upon did not adequately support the task of online bioinspiration seeking. It took a long time for designers to find their biological sources of inspiration using the online approach (several weeks of searching). Designers complained that the inspiration-seeking process was frustrating because the search process consumed a lot of time but yielded very few articles containing biological systems that were actually useful in addressing their target problem. We also observed that although designers spent a lot of time searching for novel material, in many cases they ended up using biological systems that they were already exposed to during their class lectures because their search process did not yield any new sources. This issue of difficulty of online bioinspiration seeking was exasperated by the fact that, in many cases, designers had to undertake this task multiple times in the course of their design episode due to the use of compound analogies we mentioned above.

Three main difficulties were noted in the process of online analogy seeking for the purpose of finding biological sources of inspiration. These difficulties were encountered irrespective of the type of information environment used and contributed greatly to the inefficiency of the information seeking process, causing designers to experience some degree of tedium and frustration.

The first challenge was the *findability* issue: designers often went for long periods without finding a useful or relevant information resource in the online search process. In other words, the relative frequency of encountering useful information resources in this context was typically very low. This can be contrasted with our everyday online information seeking experiences where we frequently find useful information in response to our information needs and do so with relative ease. Anecdotal evidence for this issue can be found in comments such as these from designers:

> *“I really had a lot of trouble completing [the] assignment last night. They really need to come up with a better way for people for looking up information [based] on function. [I] wasted so much time looking everywhere but found only one [article] which is just so-so”*
>
> *“I am not about to give up on aquaporins because it took me a long time to find that damn thing”*

A rough back-of-the-envelope calculation also suggests that designers spent approximately three person-hours of search time in order to find a single relevant article. Team FORO, consisting of 6 people, collected 39 articles over the 7 week period, where each designer reported spending an average of 2 to 3 hours per week on this task.

The second challenge was the *recognizability* issue: designers were prone to making errors in the judgment about the true utility of information resources that they encountered in the search process. It was noted that in almost all online environments, search queries brought back a ranked list of search results (a set of information resources). One important aspect of the search process was assessing and selecting promising information resources from this list for further consumption. But, this decision had to be made based on *proximal cues* - hyperlinks and pieces of text that are intended to represent the distal information resources.

In many instances, designers picked up on low-utility articles and spent a lot of time and effort trying to understand their contents, only to realize later that they were not actually very useful articles (false positives). In the Fall 2008 study where the researcher maintained notes about his search experiences, 53 instances of false positives were identified. False positives lead to wasted time and effort (resource cost). False positives also have opportunity costs associated with them – by handling less profitable items one loses, in that time, the opportunity to go after more profitable items. Conversely, one can imagine situations where designers might dismiss a resource that they encounter during the search as having low utility even though in actuality it might have contained useful information about a potential biological source (false negatives). Unfortunately, even though such situations are highly probable, it is practically impossible to observe them in the field because the rejected items are not tracked and independently assessed for their true utility. Although false negatives do not have resource cost associated with them, they represent lost opportunities. The resource and opportunity cost of recognition errors, coupled with the fact that there is a tendency among designers to fixate on the biological sources that they find initially, can potentially lead to suboptimal choice of analogies.

The third challenge was the *understandability* issue. Design has its own distinct ‘things to know, and ways of knowing them (Cross 1982, p. 221).’ However, designers often struggled with ‘designerly’ ways of coming to know biological systems during the information seeking process. Developing an understanding of the workings of unfamiliar biological systems from the information resources that one encounters is an integral part of the online bioinspiration seeking task. Furthermore, developing the right kind of understanding of these systems is also important – the kind that allows designers to “see” in what ways a biological system is similar or dissimilar to the technology that is being designed and how its mechanisms, strategies, principles, etc., can or cannot be transferred and adapted to solve the target design problem. This highlights the fact that learning and information seeking are inextricably intertwined in the context of the bioinspiration seeking task.

Coming to a reasonably good understanding of systems from online information resources presented one of the biggest challenges for designers (especially for non-biologists in our study). That it was difficult to comprehend biology articles was one of the common complaints that got expressed. This was in part due to the scholarly nature of the articles that were being sought and used. A majority of such articles are produced by experts and for experts in the biology community, whose focus is on communicating what, why, and how the researchers did their work, presenting key data (often in figures, tables, and charts), and discussing the results of their analysis. More importantly, the focus is not always on providing a step-by-step guide to how a biological system works. The level of abstraction at which the targeted biological systems are discussed in these articles are often too detail-oriented, obfuscating the “big picture” of their workings. This issue, combined with the technical and domain-specific nature of the vocabulary used, and the implicitness or omission of key concepts required for constructing understanding, hinder the sense-making process and the construction of the kind of mental models of biological systems that are required for the design activity.

One consequence of this difficulty is that the process of sense making itself spawns off new information needs and contributes additional cycles of information seeking. In other words, search cycles can lead to sense making issues, which in turn can lead to more search cycles. This property of information seeking adds to the complexity of online bioinspiration seeking process and can sometimes vastly increase the cost of the process.

5 DISCUSSION

In order to explain the identified challenges of online bioinspiration seeking, we have to first model the phenomenon at some level of depth. Biologically inspired design is a kind of analogical design. The task of seeking bioinspiration involves obtaining biological analogues to target design problems. Therefore, the task of seeking bio-inspiration is a kind of analogical retrieval. Current theories of analogical retrieval (Forbus, Gentner & Law 1995; Kolodner 1993; Thagard *et al.* 1990) provide the first starting point for understanding this phenomenon. However, they are not sufficient. Analogical retrieval has traditionally been portrayed as an internal cognitive process of an individual mind, occurring over the long-term memory, with little room for the external environment in its description. In contrast, online bioinspiration seeking is *situated*, involving the individual, the external information environment, and the interaction between the two. Therefore, we need a new theoretical framework, which not only incorporates elements from traditional theories of analogy, but also includes elements of human-information interaction theory.

We are exploring the development of a theoretical account of online bioinspiration seeking (Vattam 2012). This account combines the theories of *Analogical Retrieval by Constraint Satisfaction (ARCS)* (Thagard *et al.* 1990), and *Information Foraging Theory* (Pirolli 2007). ARCS is conventional model of analogical retrieval which posits that in order to access sources (schemas held in long-term memory) that are considered analogous to a target (a target problem/situation schema held in short-term memory), the access mechanism should simultaneously consider three constraints: *semantic similarity* (the overlap in terms of the number of similar concepts between the target and potential sources), *structural similarity* (the overlap in terms of the higher-order relationships between the target and potential sources), and *pragmatic similarity* (the overlap in terms of the relative weightage given to overlapping functions between the target and potential sources). It is these three pressures acting simultaneously that distinguish analogical retrieval from other kinds of information access mechanisms.

Information foraging theory (Pirolli 2007) was developed to explain the general information seeking behavior of people in online information environments. According to this framework, information seeking in online environments is analogous to how animals forage for food in their natural environments. Similar to their animal counterparts, this theory posits that information seekers navigate from one *information region* to another in an information environment that is inherently patchy in nature, from one *information patch* to another within a region, and use *information scent* to guide this navigation process. Furthermore, this theory has also demonstrated that information seekers adapt their behavior to the structure of information environment in which they operate such that the system as a whole (comprising of the information seeker, the information environment, and the interactions between the two) tries to maximize the ratio of expected value of the knowledge gained to the total cost of interaction.

The model of bioinspiration seeking we are developing takes the general model of information foraging and specializes it to situations where the information seeker is seeking source analogues for target problems or situations. This is done by introducing the notion of the three pressures of analogical retrieval (from the ARCS model) into the general model of information foraging. We believe that such deep understanding of the biologically inspired design practice is more likely to lead to interactive technologies useful for supporting the paradigm. Thus, we are using our model of bioinspiration seeking as the basis for developing an interactive tool called *Biologue* for supporting the practice of seeking bioinspiration (Vattam & Goel 2011).

6 CONCLUSION

We know that design in general is situated in the external world, (Cross 1982; Schon 1983). Schon (1992), for example, describes designing as a reflective conversation of the designer with the materials of the design situation, where the materials of a design situation include not only physical materials and prototypes but also design artifacts such as documents and drawings. More recently, Kulinsky & Gero (2001) have pointed out that analogies in design too are situated in the external world. Thus, it should not be a big surprise that biologically inspired design is situated in the external world. Yet, the situatedness of biologically inspired design has so far received little attention in the design literature.

Our studies of biologically inspired design practice indicate that the task of seeking bioinspiration is situated in online information environments, i.e., the task of finding biological analogies relevant to an engineering design problem entails accessing information about biological analogies from the Web and the generation of a design concept is mediated by the information accessed from the Web. Our studies also suggest that the online information environments on which engineering designers rely upon do not adequately support the task of seeking bioinspiration. Thus, in spite of having online access to vast amounts of biological information, designers often struggle to find the biological analogies relevant to their design problems. The reliance on online information environments coupled with the lack of adequate support in those environments makes the intellectually challenging task of seeking bioinspiration even more difficult to achieve.

In particular, our studies identify three related, distinct, and major difficulties with seeking bioinspiration online: (i) *findability:* finding biological analogies relevant to a design problem is difficult because of the cross-domain nature of the analogies and the lack of a vocabulary that can act as a bridge between biology and engineering; (ii) *recognizability*: even when a biological system that may potentially act as the source of analogy is somehow found, recognizing the relevance and usefulness of the analogy is difficult; and (iii) *understandability:* even when a biological system is somehow recognized as being relevant, understanding the biology article that describes the biological system in detail is difficult because engineering designers typically are not experts at biology. Although our *in situ* studies were conducted in the context of a classroom environment, we posit that these cognitive challenges are quite general: the same challenges are likely to occur in actual practice of biologically inspired design because although practicing designers are experts in their own domain, they are likely to be novices in biology.

Biologically inspired design is an important emerging movement in modern engineering design. Thus, there is a major push in engineering design to develop interactive tools for supporting the task of seeking bioinspiration. However, *in situ* research of how designers actually seek bioinspiration is practically nonexistent. As a result, there exists a gap between our understanding of the biologically inspired design practice and our technology-building efforts for aiding the practice: “what is” has failed to inform “what ought to be.” Symptomatic of this gap, current technology-building efforts tend to be technology-centric whose design and development are trial and error-driven. The studies presented in this paper aim to bridge this gap and provide a foundation for developing more human-centric, theory-driven approach to developing information systems for supporting the practice of biologically inspired design.

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